Collective fish swimming dynamics: insights from laboratory experiments

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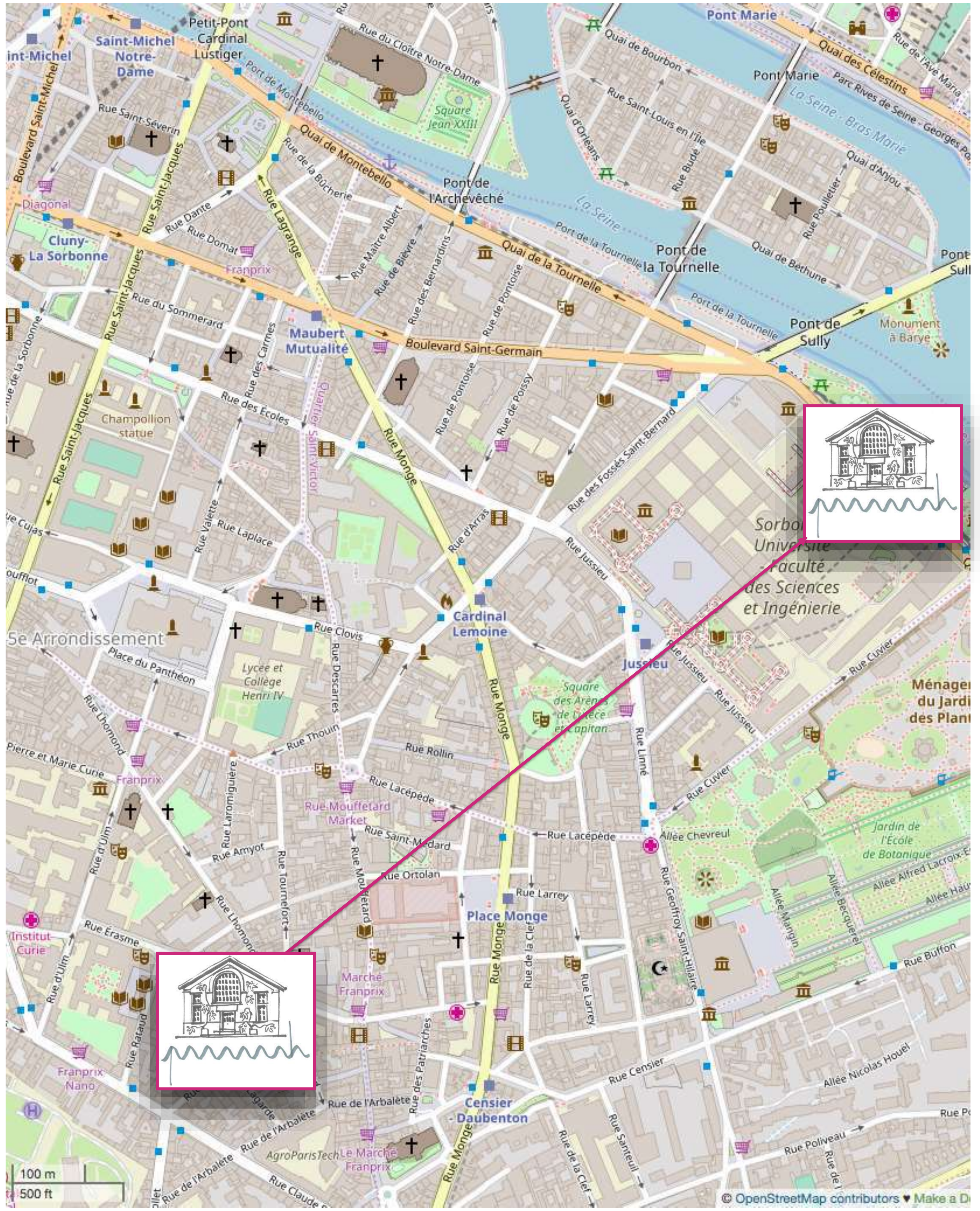
blog.espci.fr/ramiro/

Collective Motions of Animals and Robots, Cargèse, May 27 – 31, 2024

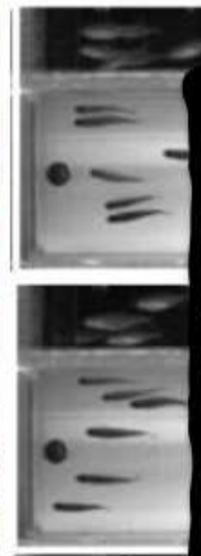
ESPCI Paris renovation project 2018-~~2023~~ 2027?



PMMH lab temporarily relocated at the Sorbonne Université Jussieu campus

BIOMIMetics and Fluid-Structure Interaction

RAMIRO GODOY-DIANA (CNRS) & BENJAMIN THIRIA (UNIVERSITÉ PARIS CITÉ)

wings
arrouste),
Engels)

Intesaaf Ashraf

Verónica Raspa

Baptiste Lafoux

Parts 2 & 3

Part 1

Special thanks to Baptiste for the slides design!

Gen Li
JAMSTEC

Dmitry Kolomenskiy
Skoltech

Hao Liu
CHIBA UNIVERSITY

www.pmmh.espci.fr/Biomimetics-and-Fluid-Structure

10^9 - 10^{10} individuals

Sardine Run, le grand festin (France TV, 2020)

Collective motion: a definition

- **Large number** of **similar** self-propelled agents
- **Interactions** governed by « social » rules
- Emergence of **complex collective behaviour** on large time and space scales

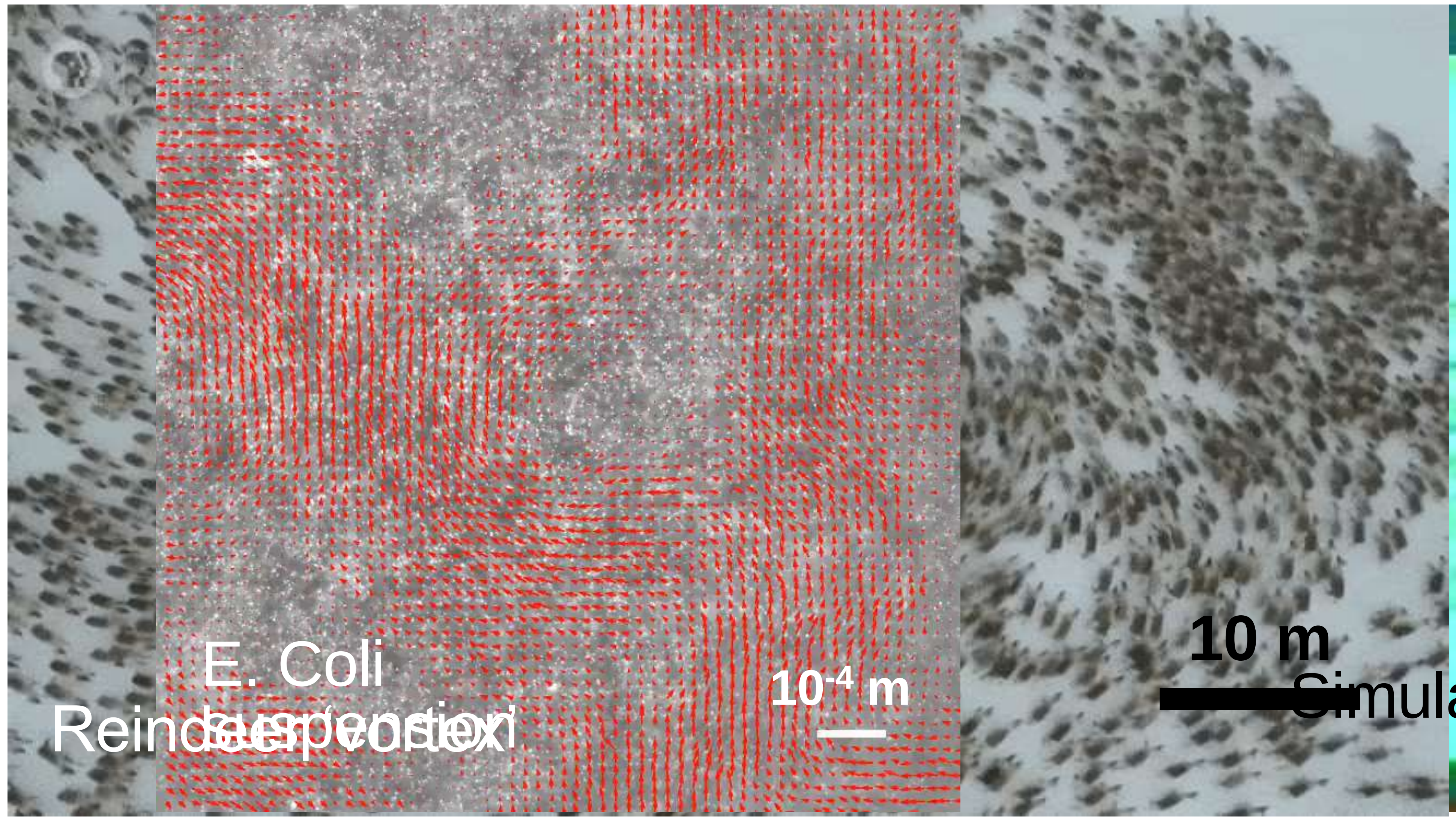
Sheeps - New-Zealand | Cater Clips (Tim Whittaker)

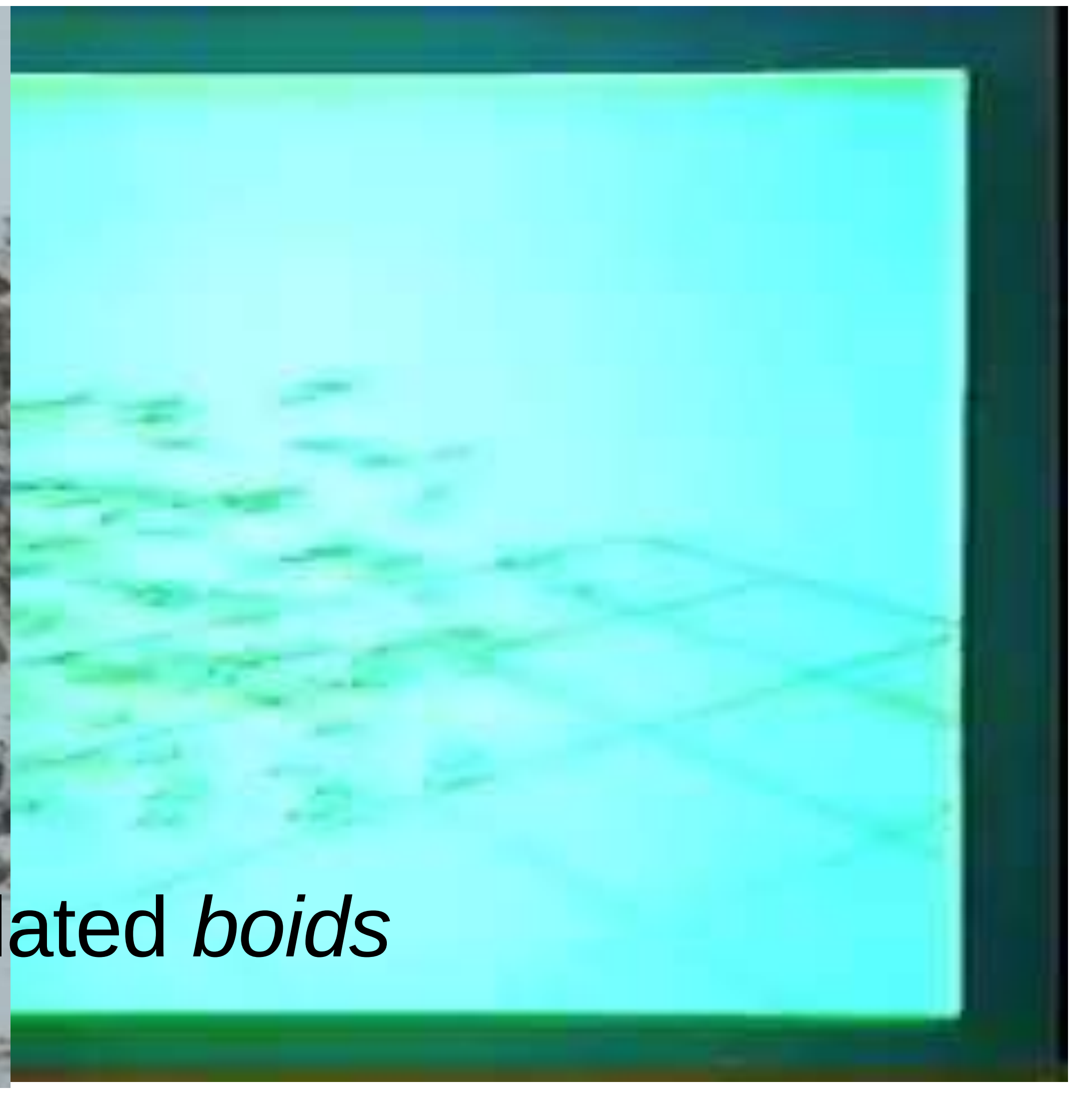
Multidisciplinarity of collective motions studies

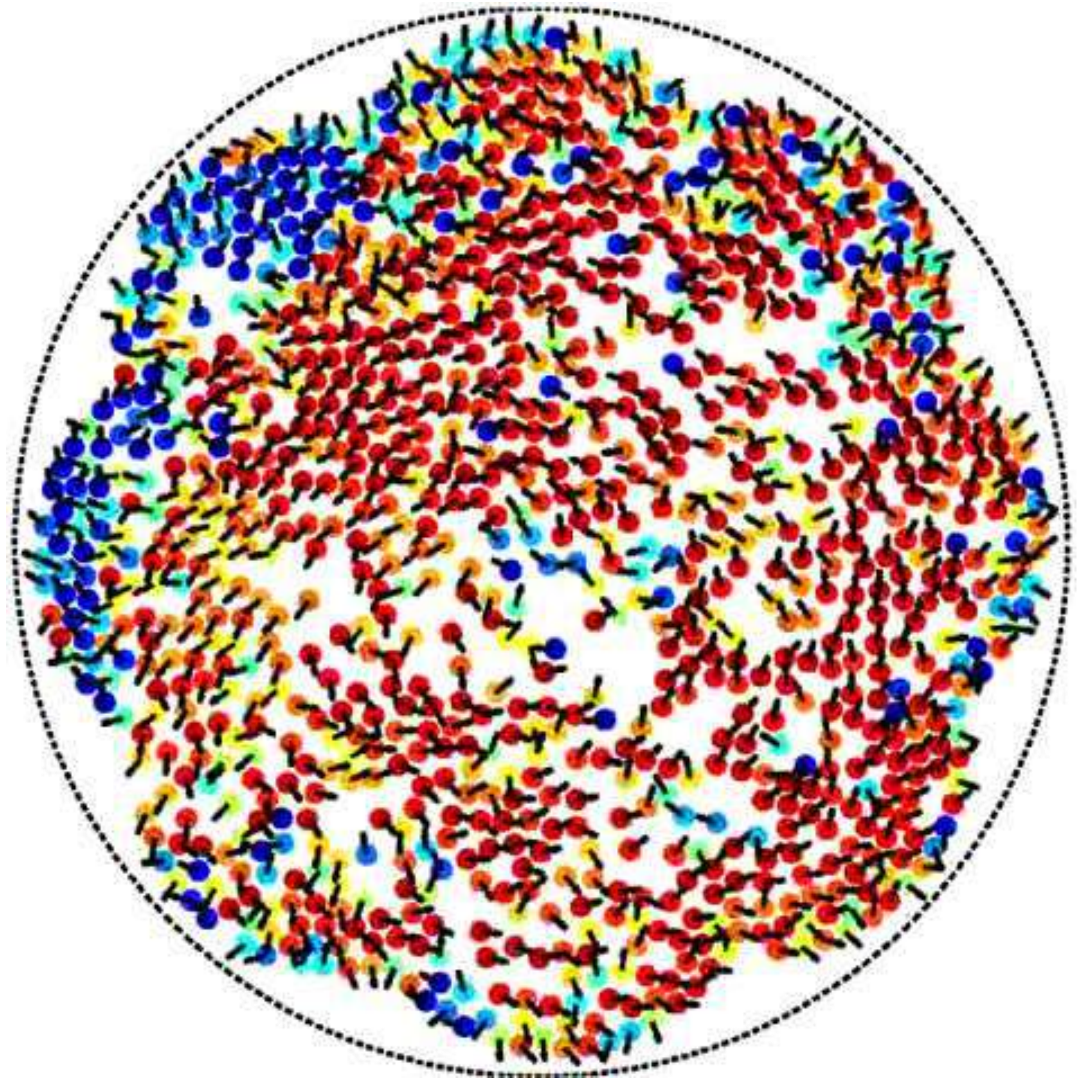
Perez-Estay (2023)

Reynolds (1986), Vicsek *et al.* (PRL, 1995)

Deseigne *et al.* (Soft Matter, 2012)







Biology **Computer science** **Physics**

… and on YouTube

Comment fonctionne un banc de poissons ? [EN 5 NIVEAUX DE DIFFICULTÉ]

225 k vues • il y a 4 jours

Fouloscopie

Pensez à vous abonner et à activer la cloche pour ne pas rater mes futures vidéos Pour soutenir la chaîne : ➡️ sur Tipeee ...

Nouveau Sous-titres

Collective motion

PHYSICAL PARALLELS

Fluid-like behaviour	Stochastic excitable systems	Faster-is-slower
		
Bain, Bartolo (Science, 2019)	Gomez-Nava *et al.* (Nat. Phys., 2023)	Garcimartín (PRE, 2014) *et al.* (Sci. Rep., 2023)

Today's starting point

The interaction between neighbouring swimmers constitutes the fabric of the very rich collective dynamics that is observed in a fish school in nature.

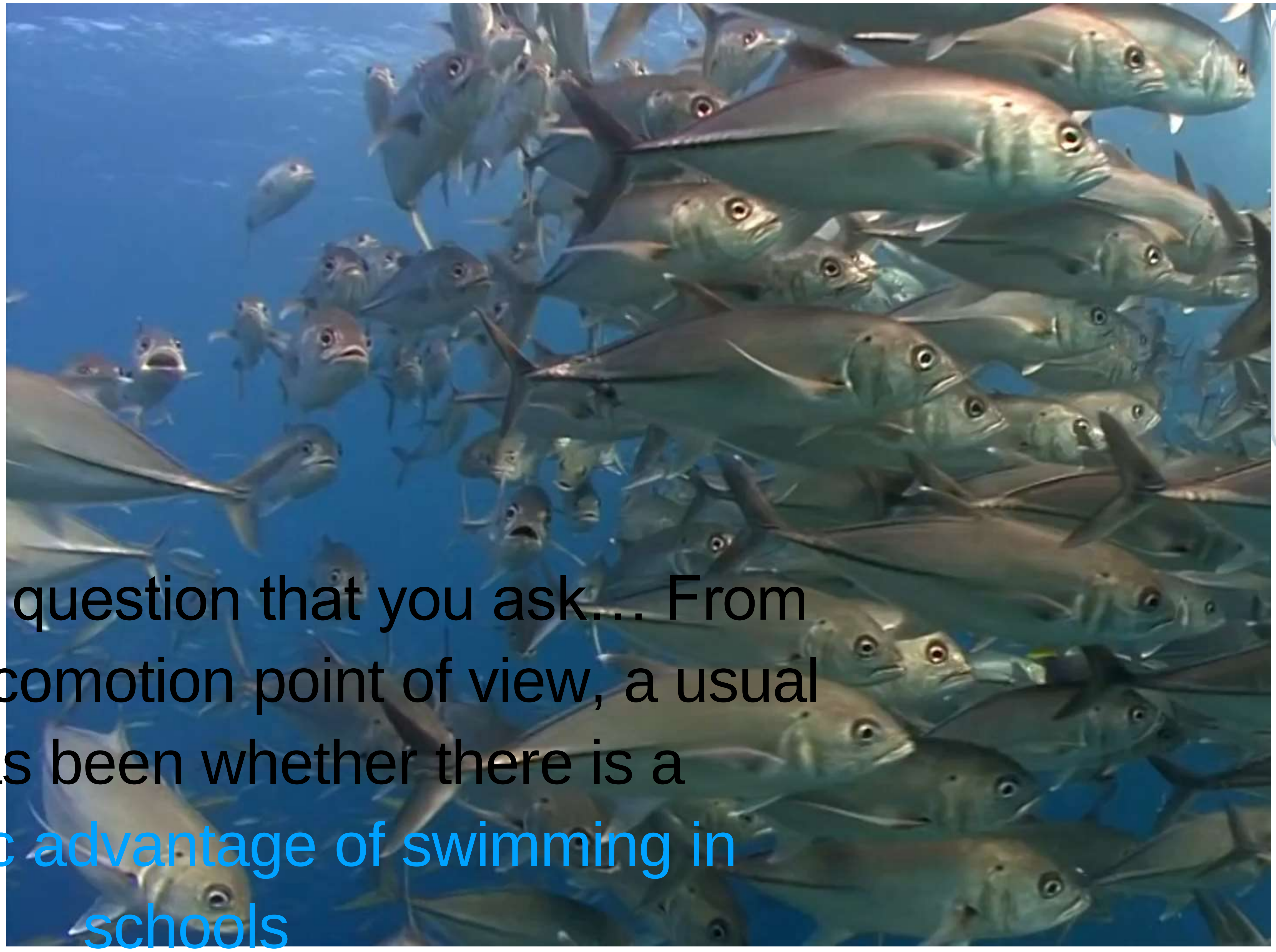
Video: Blue World Academy

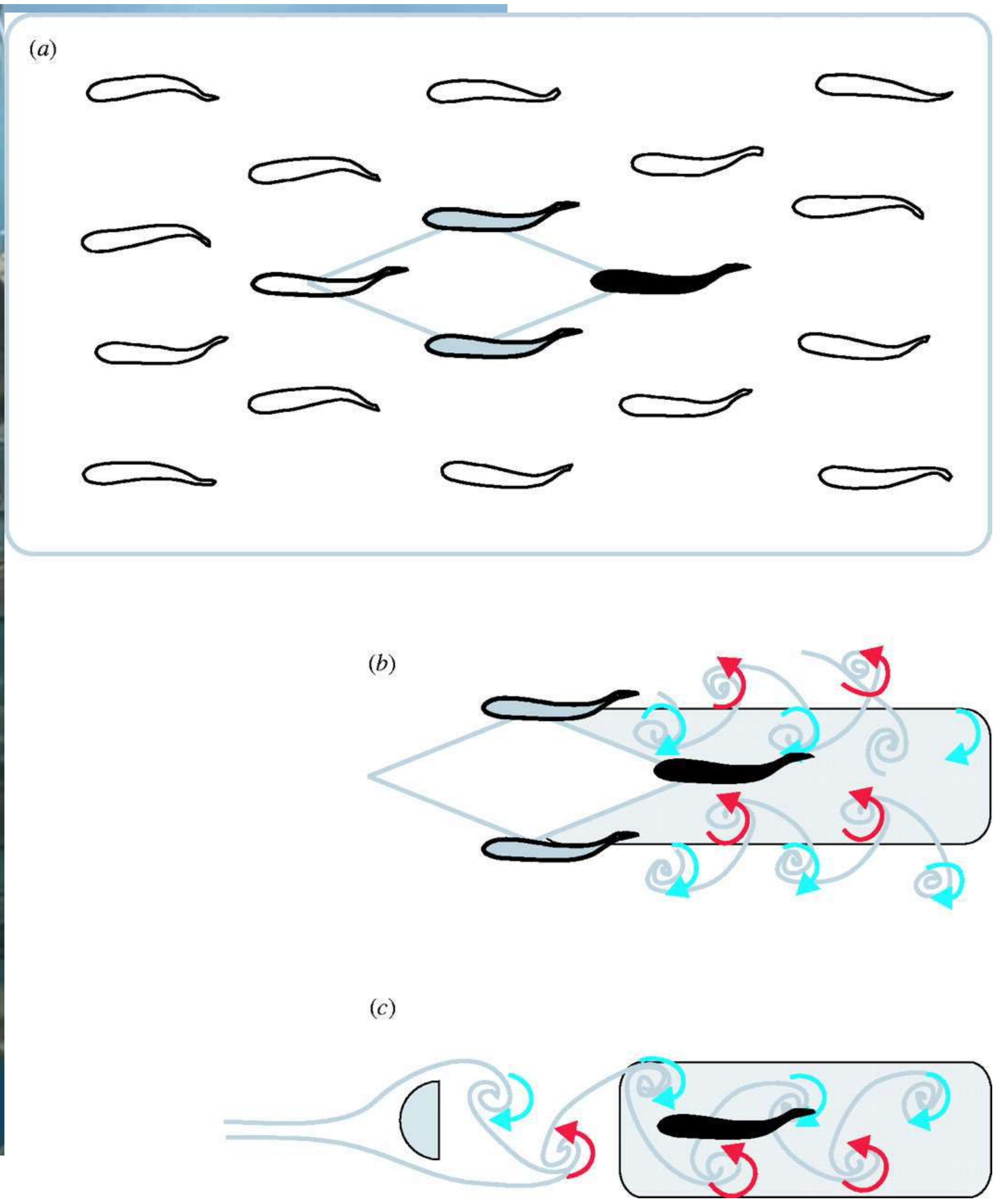
What model experiment?

Weihs’ idealized 2D fish school

-> The diamond-shaped pattern

(Weihs, *Nature* 1973)





Depends on the question that you ask… From the physics of locomotion point of view, a usual question has been whether there is a hydrodynamic advantage of swimming in schools

Figure from: Liao, *Phil. Trans. Roy. Soc. B* (2007)

What model experiment?

Depends on the question that you ask…

How do fish school?

- Vision

- Hydrodynamic interaction

- Chemical cues

Partridge *et al.1980*, McKee *et al. 2021*

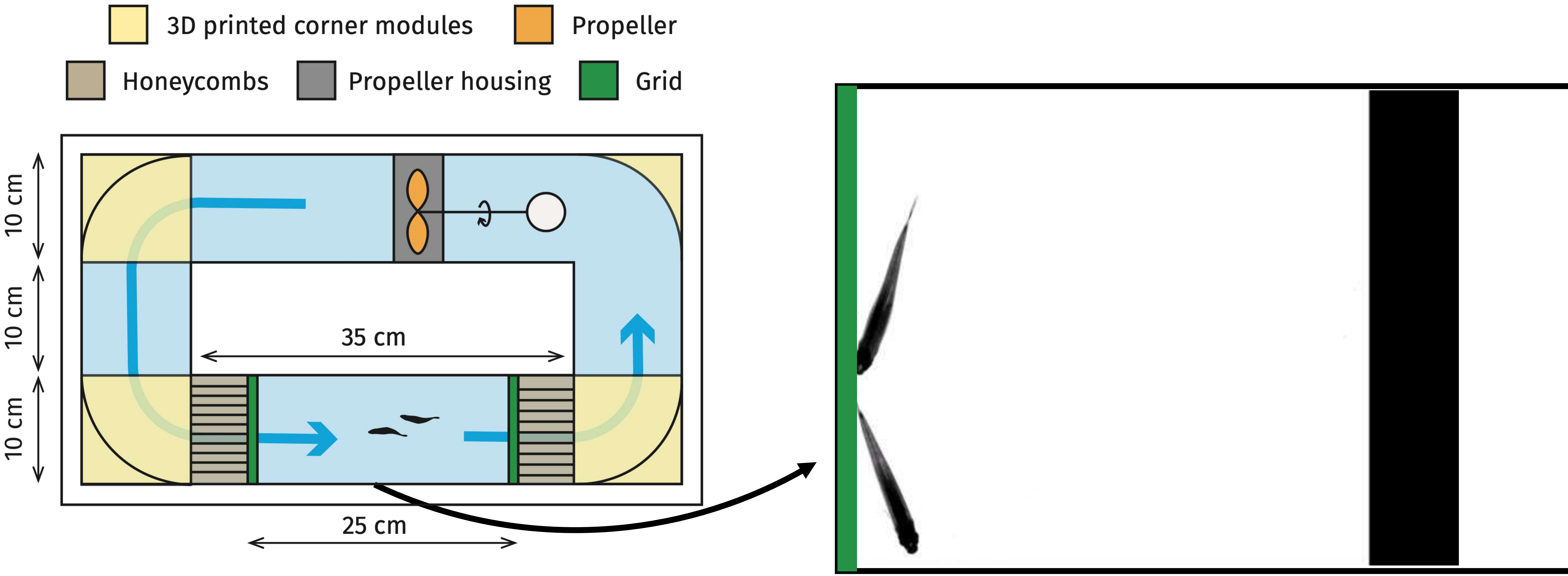
Pitcher *1976*, Filella *et al. 2018*

Is there a hydrodynamic advantage of swimming in schools?

Fish swimming against the tidal flood current (Boyardville Port, Ile d’Oléron)

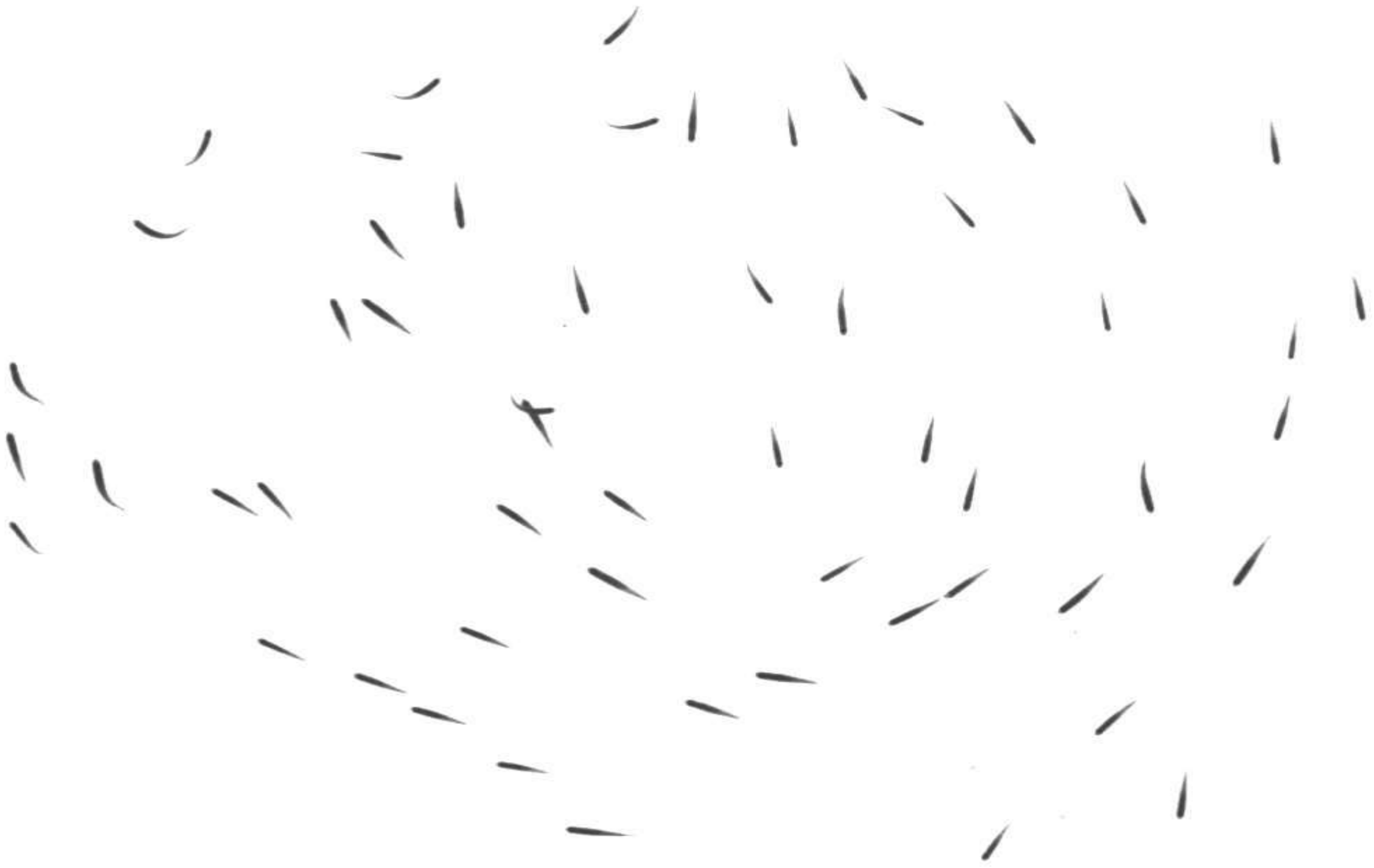
Two kinds of model experiment…

1. Swimming against the flow



STATION KEEPING IN THE LABORATORY FRAME

2. The free swimming arena



Collective motion and interactions

IN SCHOOLS OF RED NOSE TETRAFISH (HEMIGRAMMUS RHODOSTOMUS)

A model organism

Red nose tetrafish

3.5 - 4 cm

Approach

Field experiments — complex, difficult to interpret, low reproducibility

Theory — needs experimental validation

This work: Controlled lab experiments on live animals

How do **perturbations** of the environment influence **collective motion** ?

Outline

Part 1 **The minimal fish school**

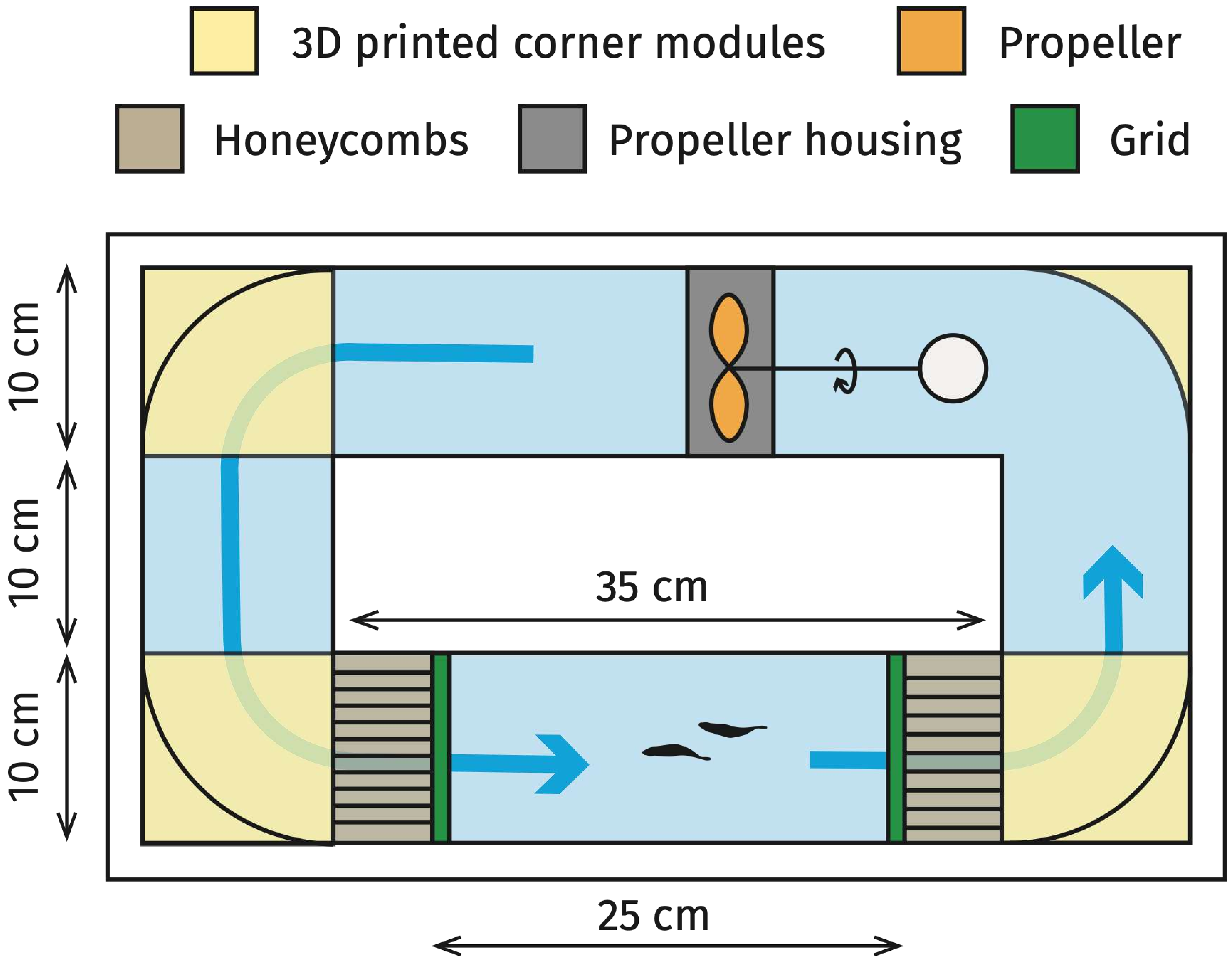
Part 2 **Illuminance-tuned collective motion**

Part 3 **Confinement-driven state transitions**

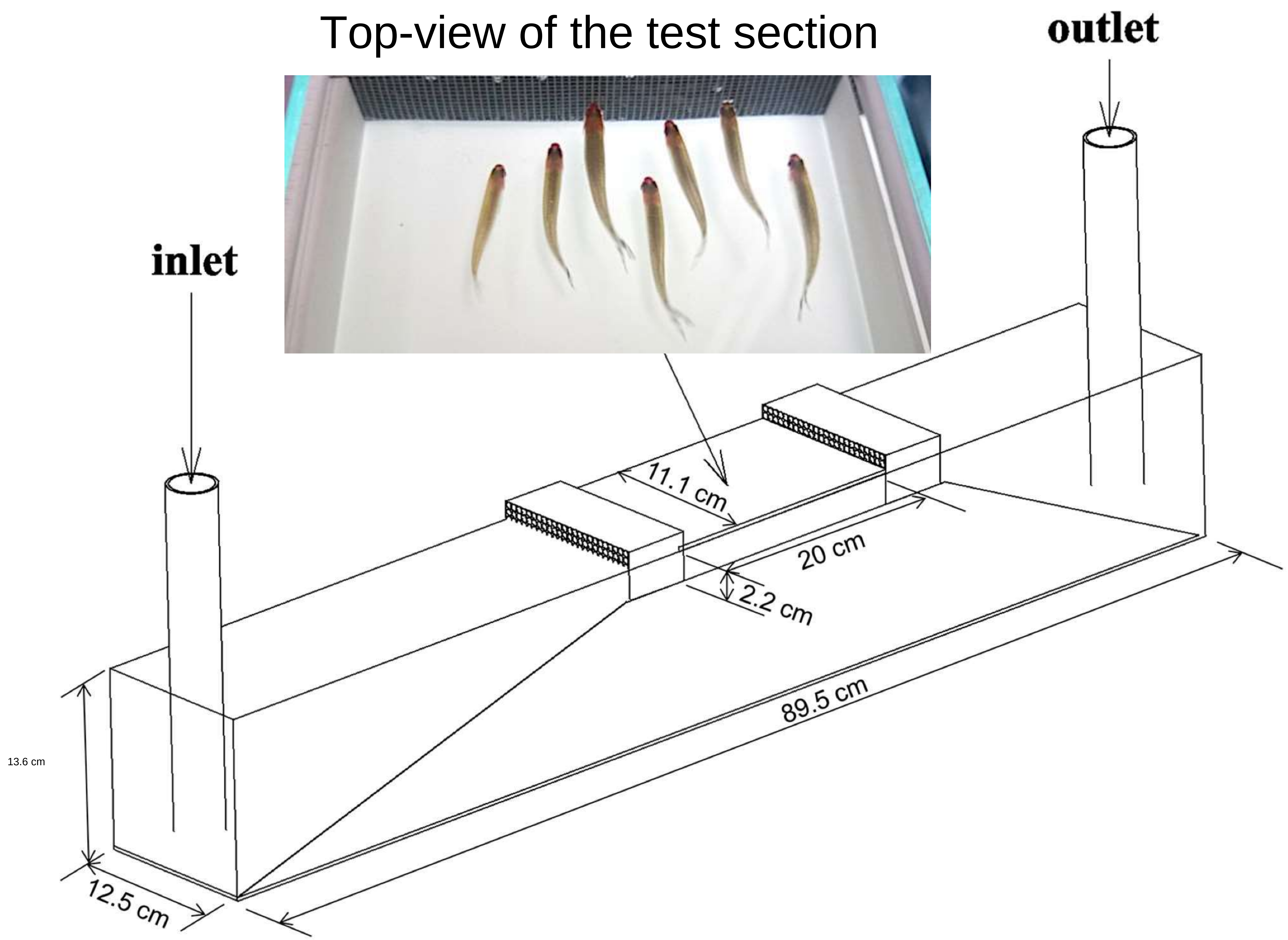
Conclusions and perspectives

The minimal fish school

The swimming channel experiment



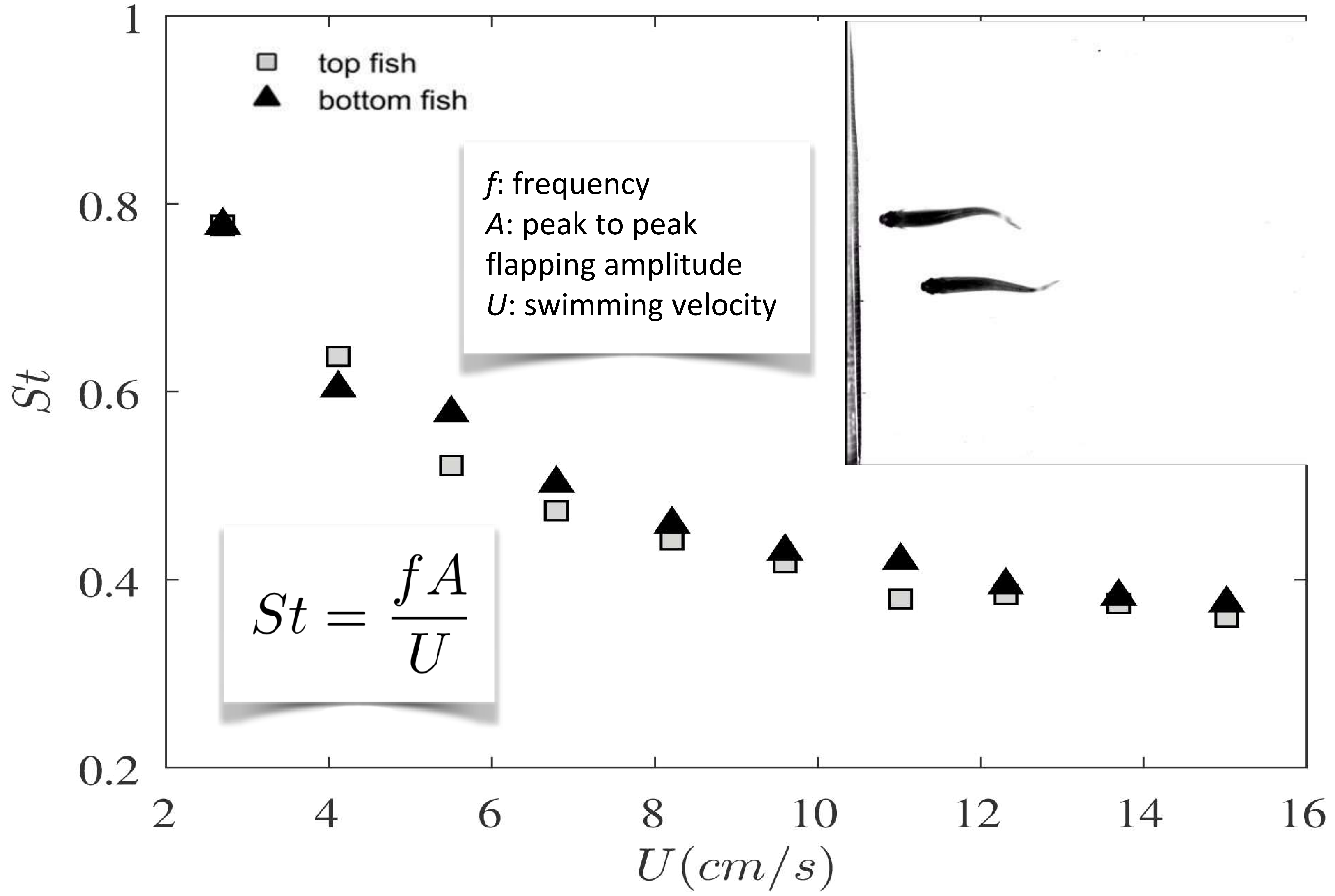
The swimming channel experiment (the old one)



A closed loop water channel with a shallow test section

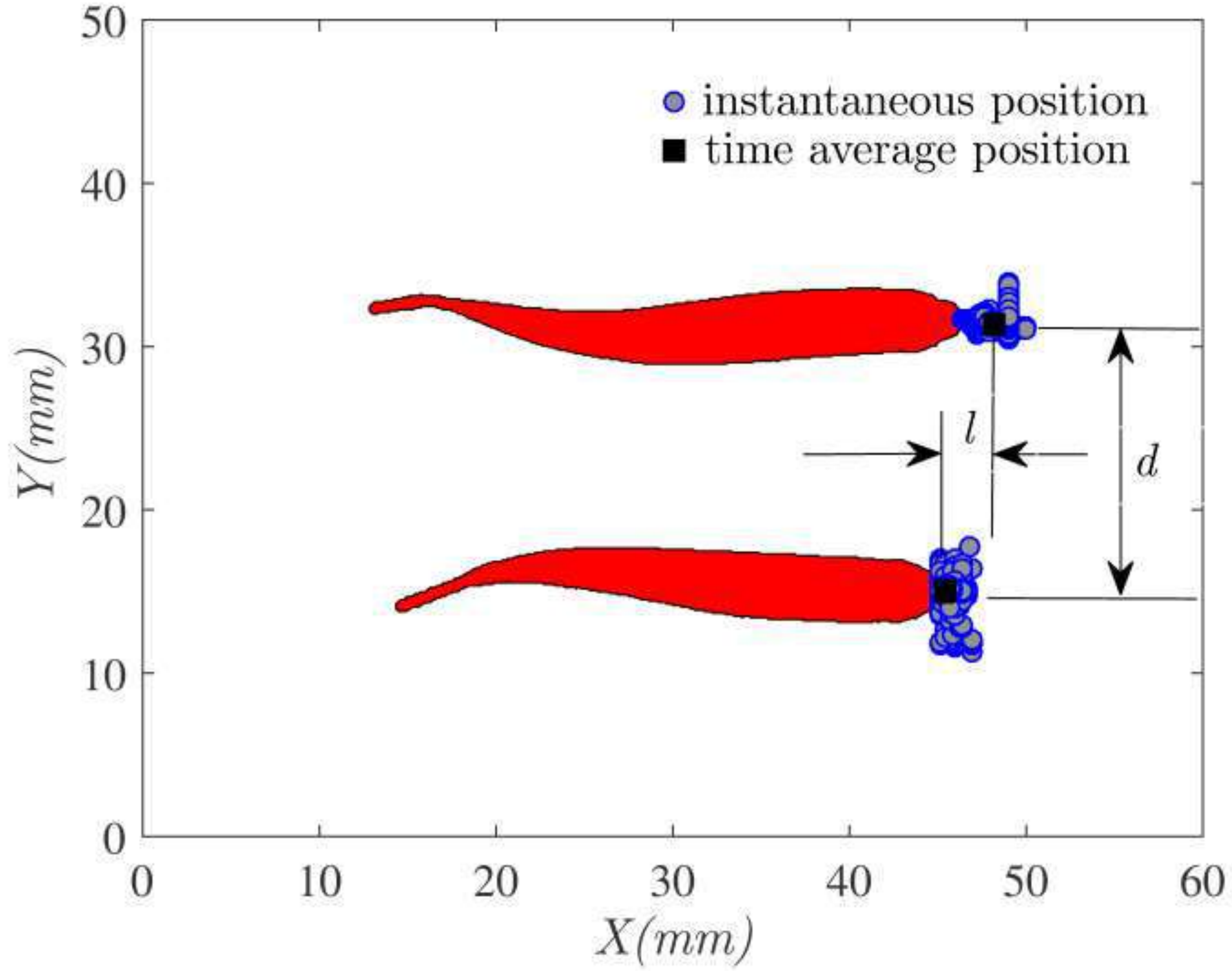
Intesaaf Ashraf (circa 2017)

Swimming kinematics: Strouhal number



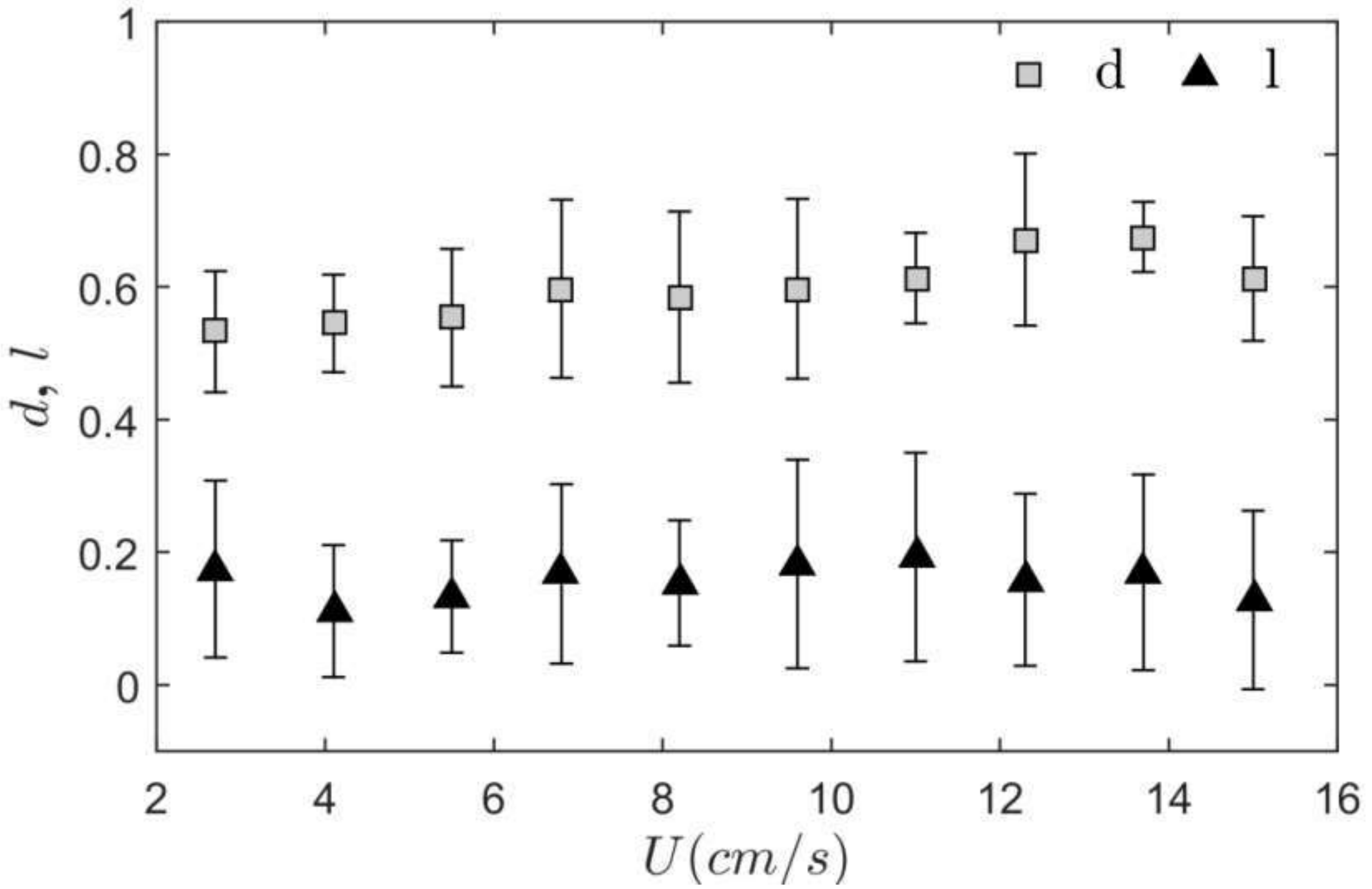
As the swimming velocity increases the Strouhal number tends to lower values, in the range of those corresponding to efficient swimming

A robust pattern!

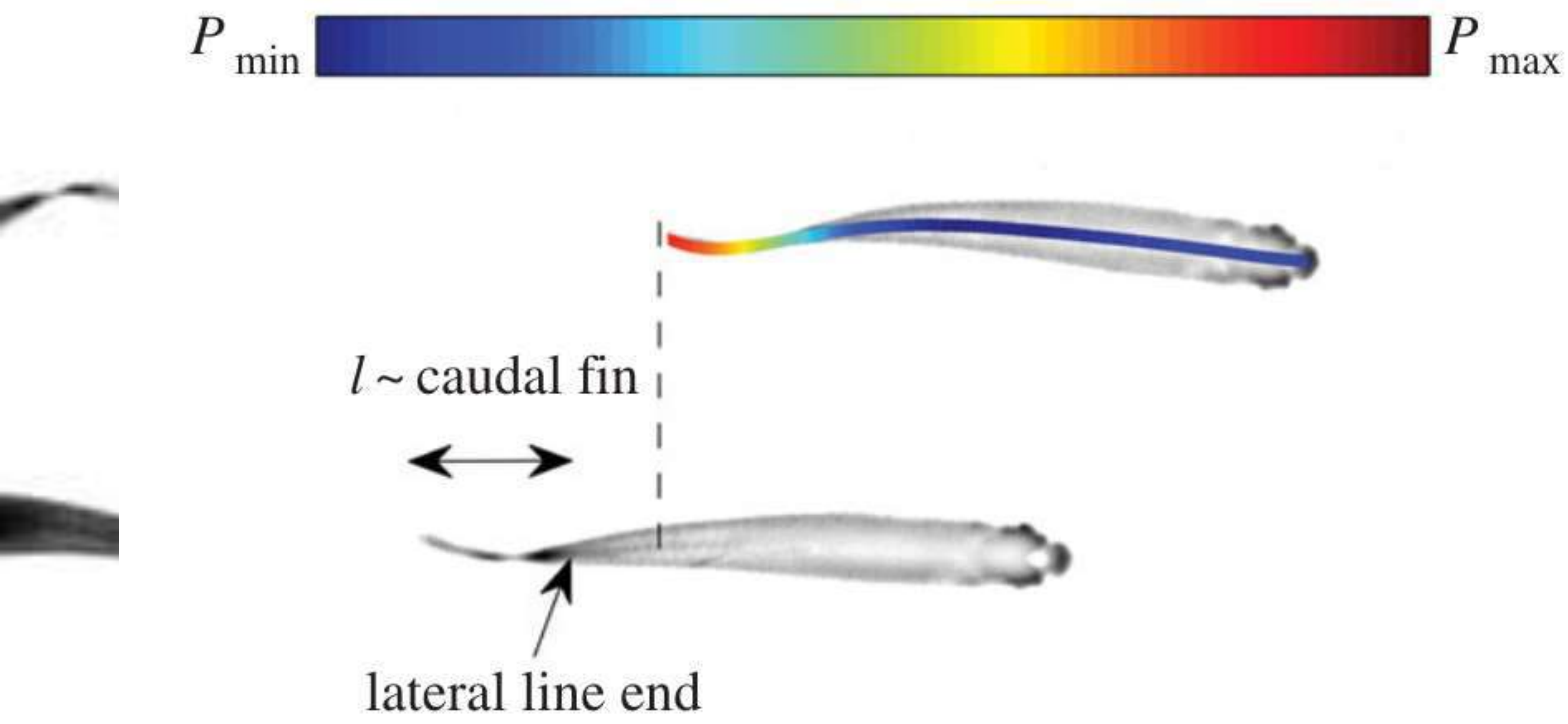


vision?

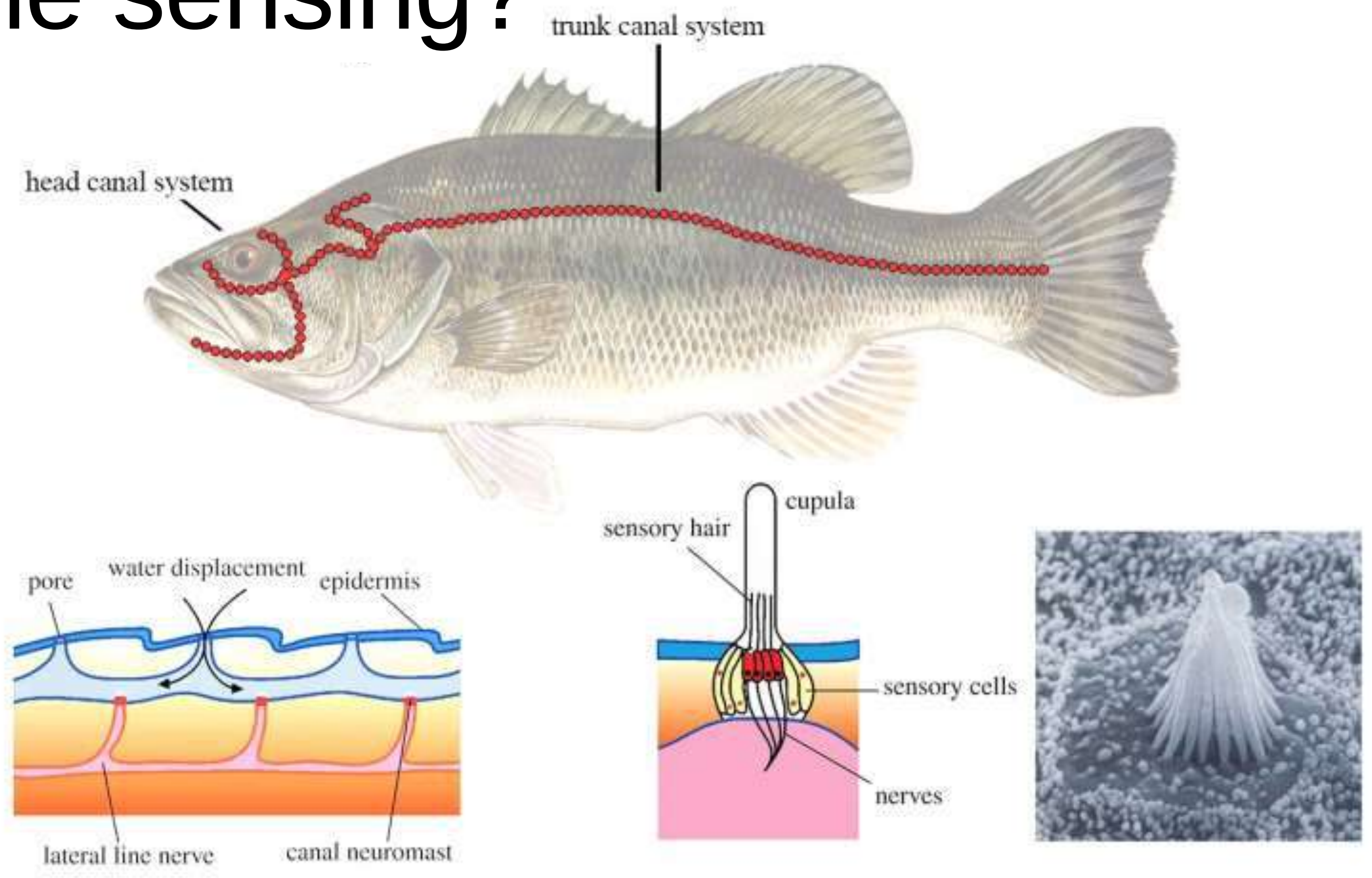
hydrodynamics?



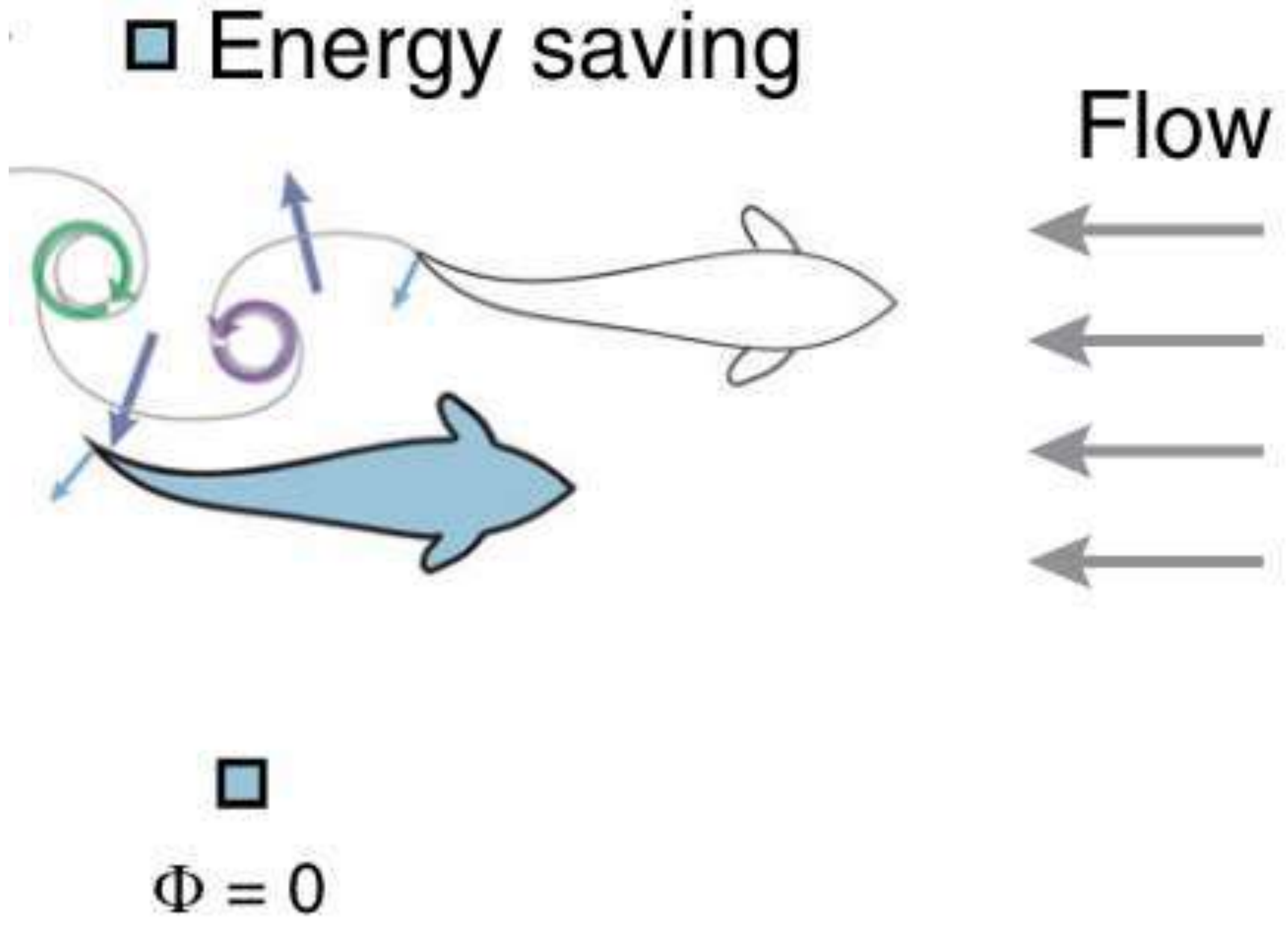
Maybe vision first, and then hydrodynamics…



Lateral line sensing?

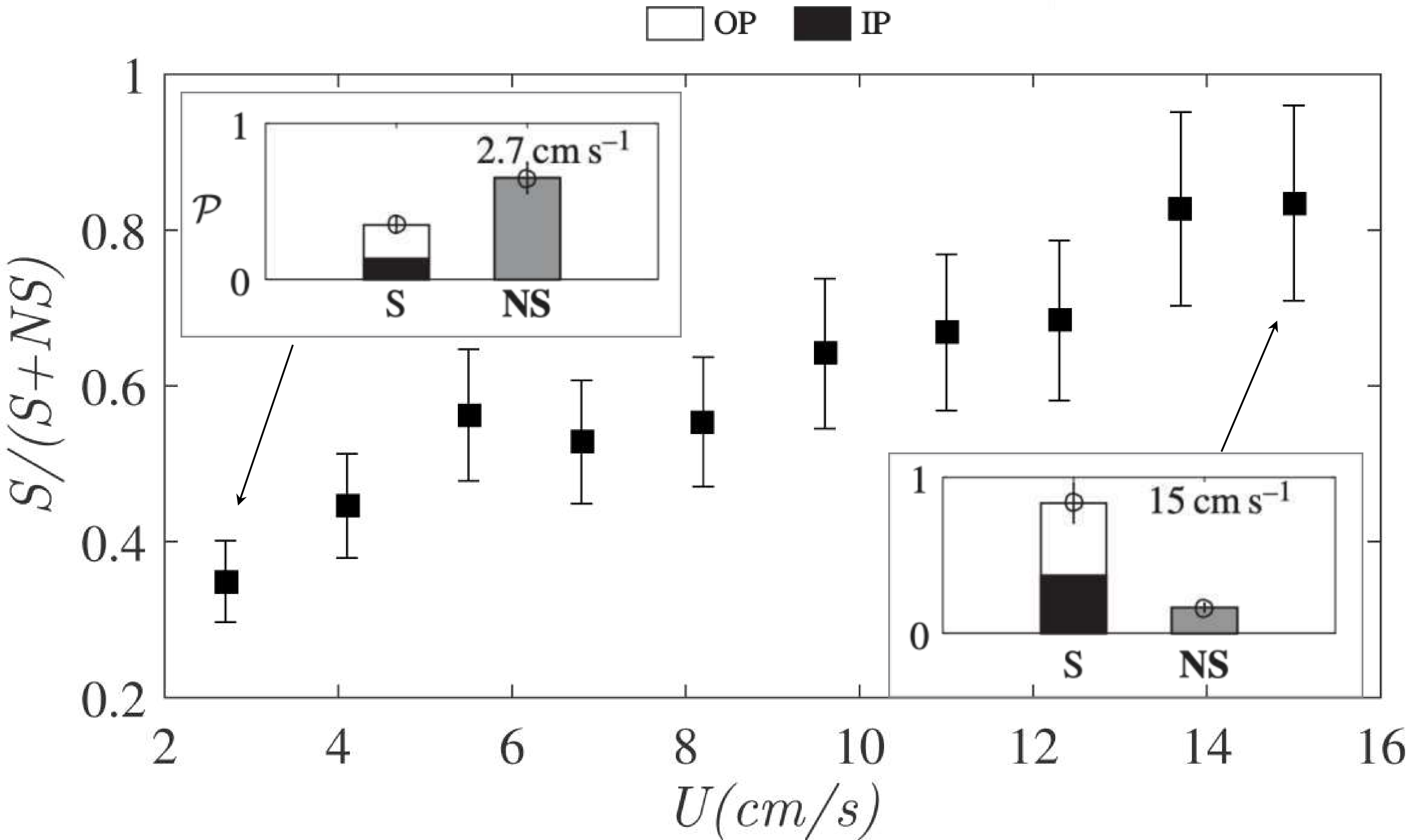


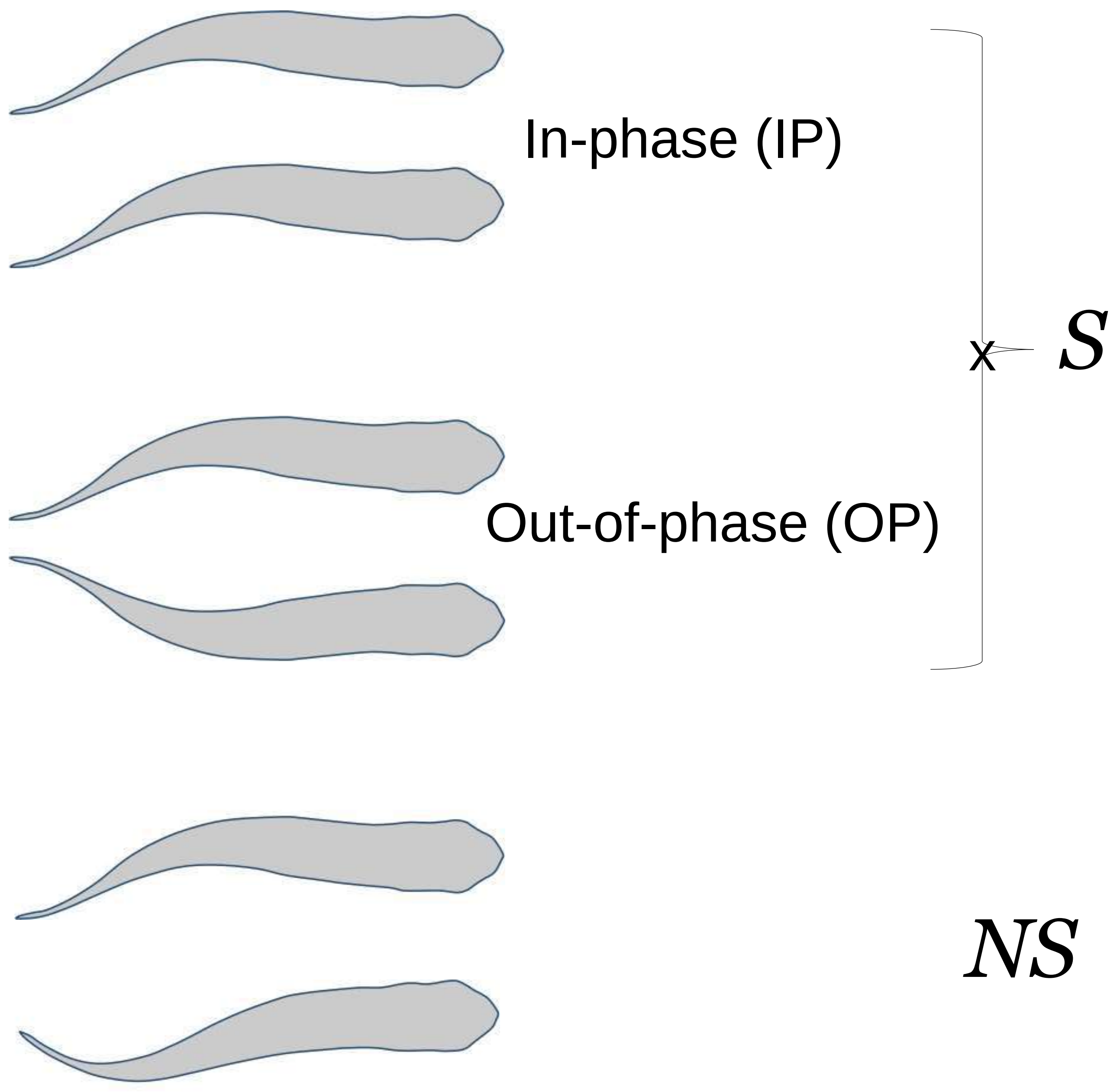
…or a passive mechanism?



Vortex phase matching
Li et al. *Nature Comms.* 2020

Synchronised swimming

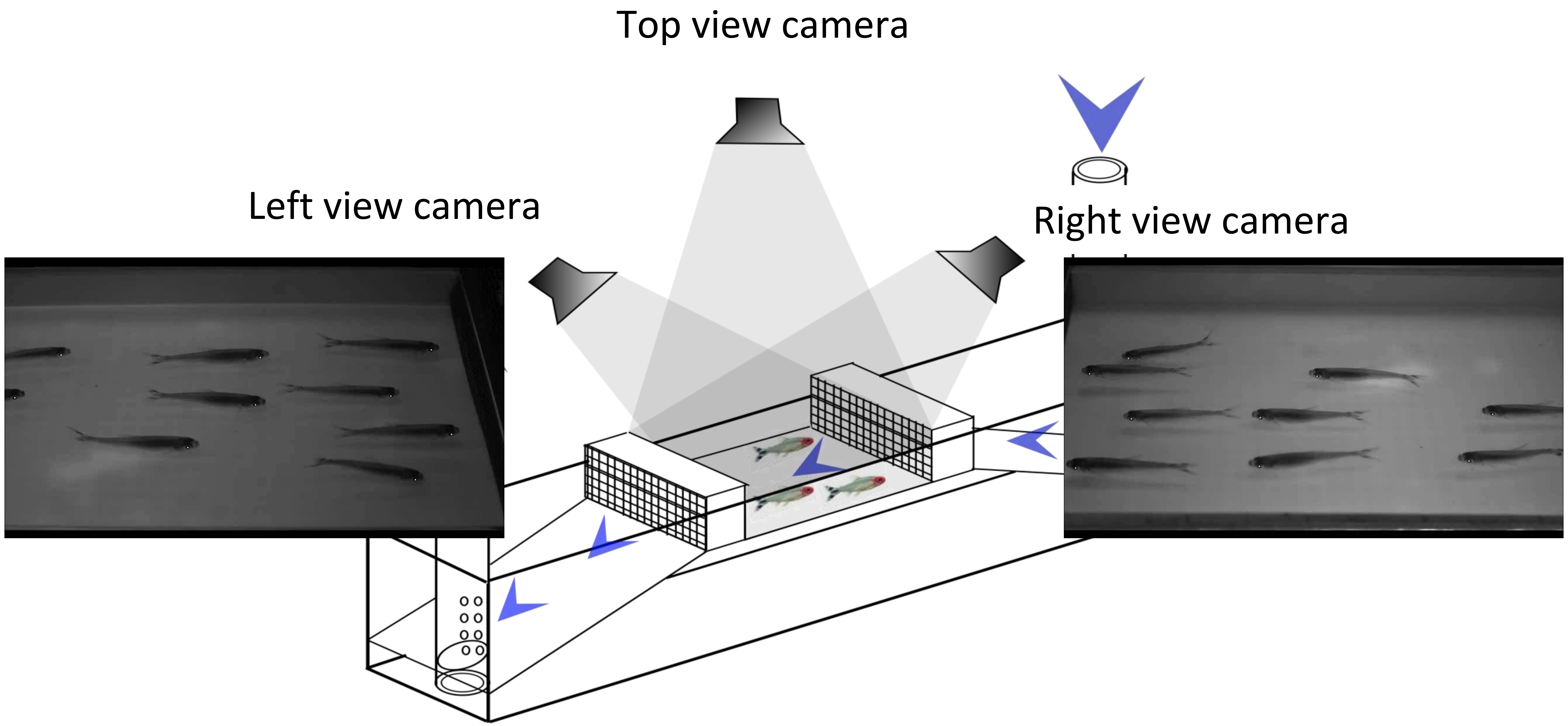




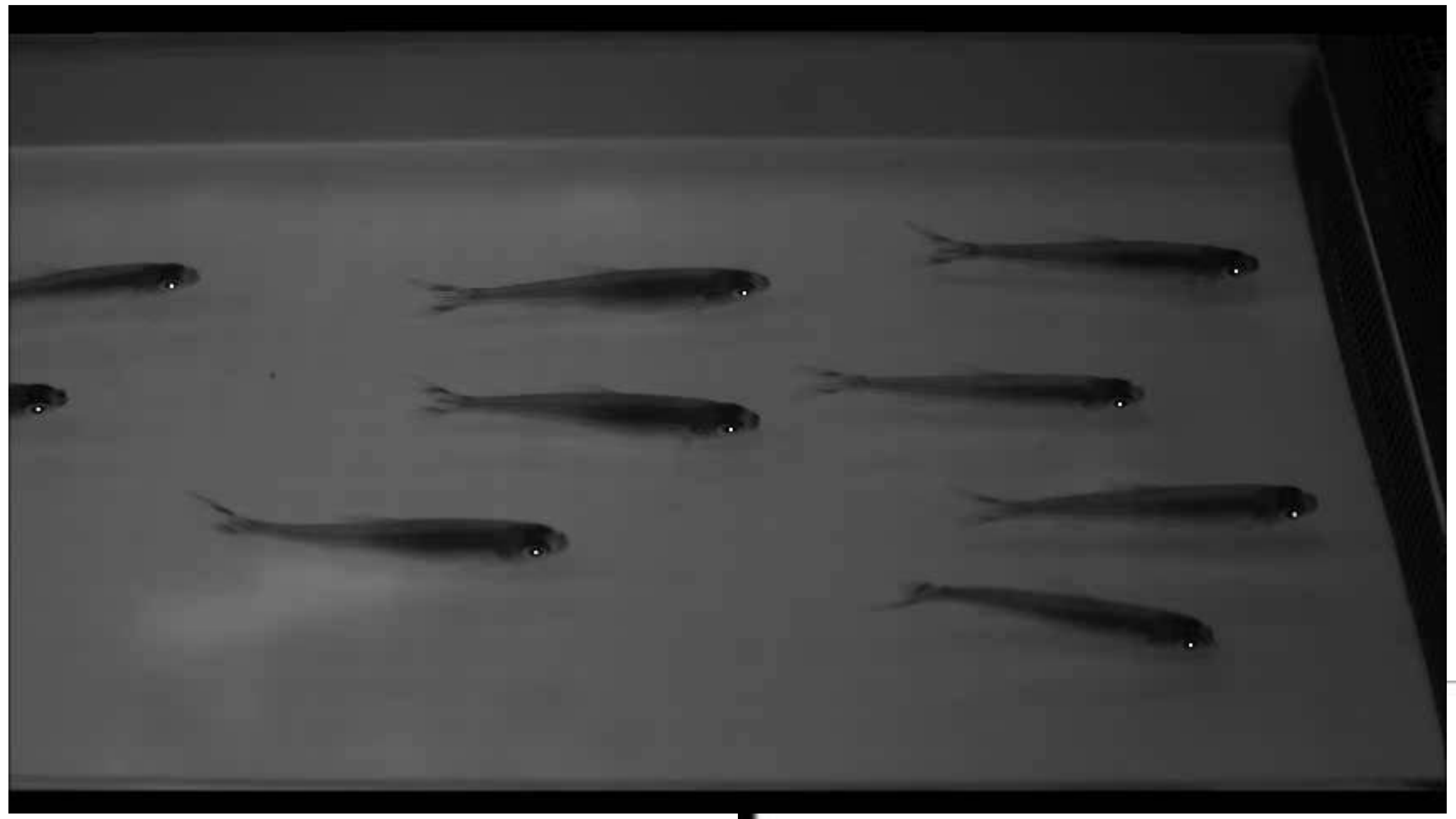
In the experiment, fish tend to synchronize at higher speed.

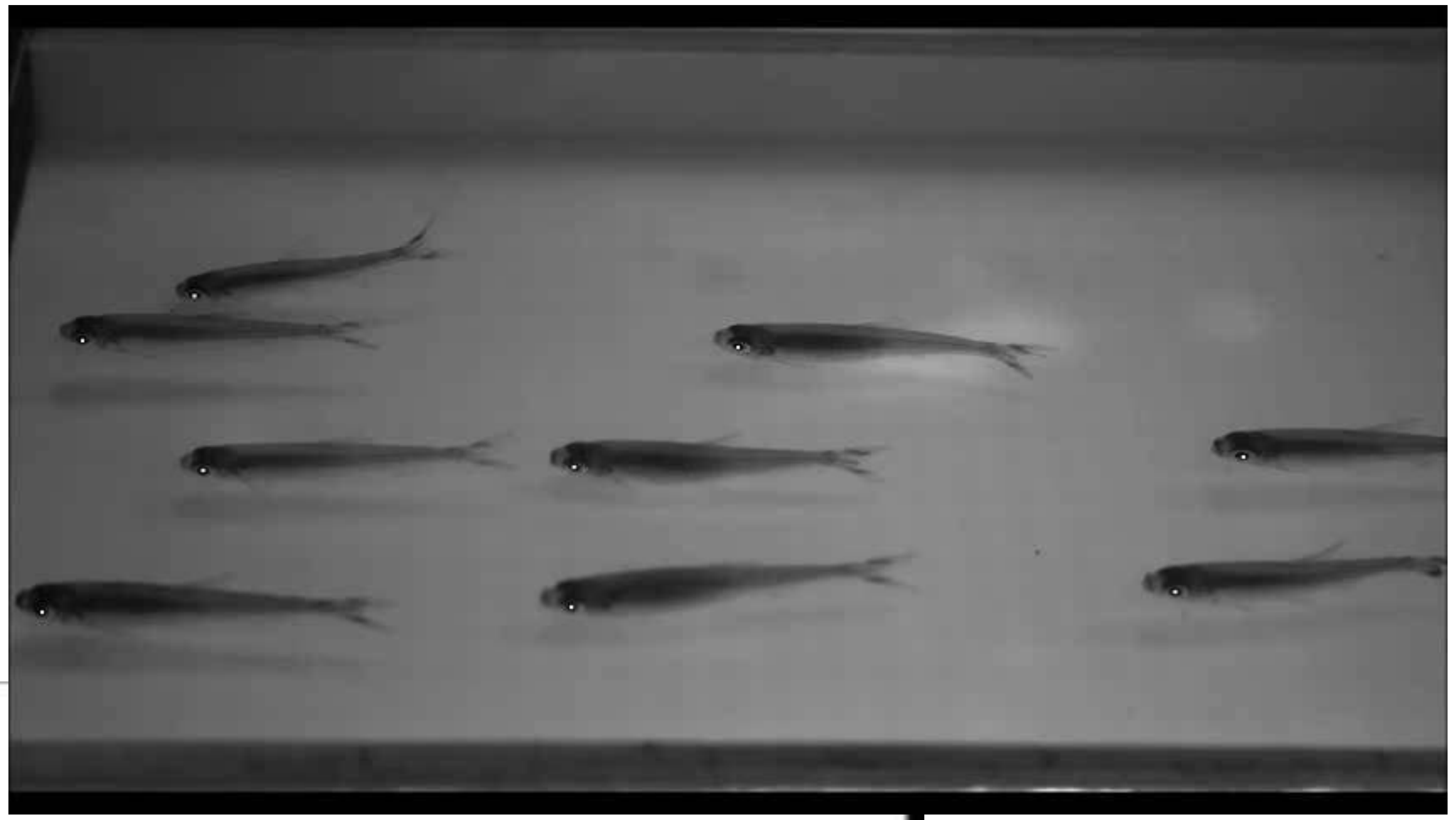
Schools with more fish

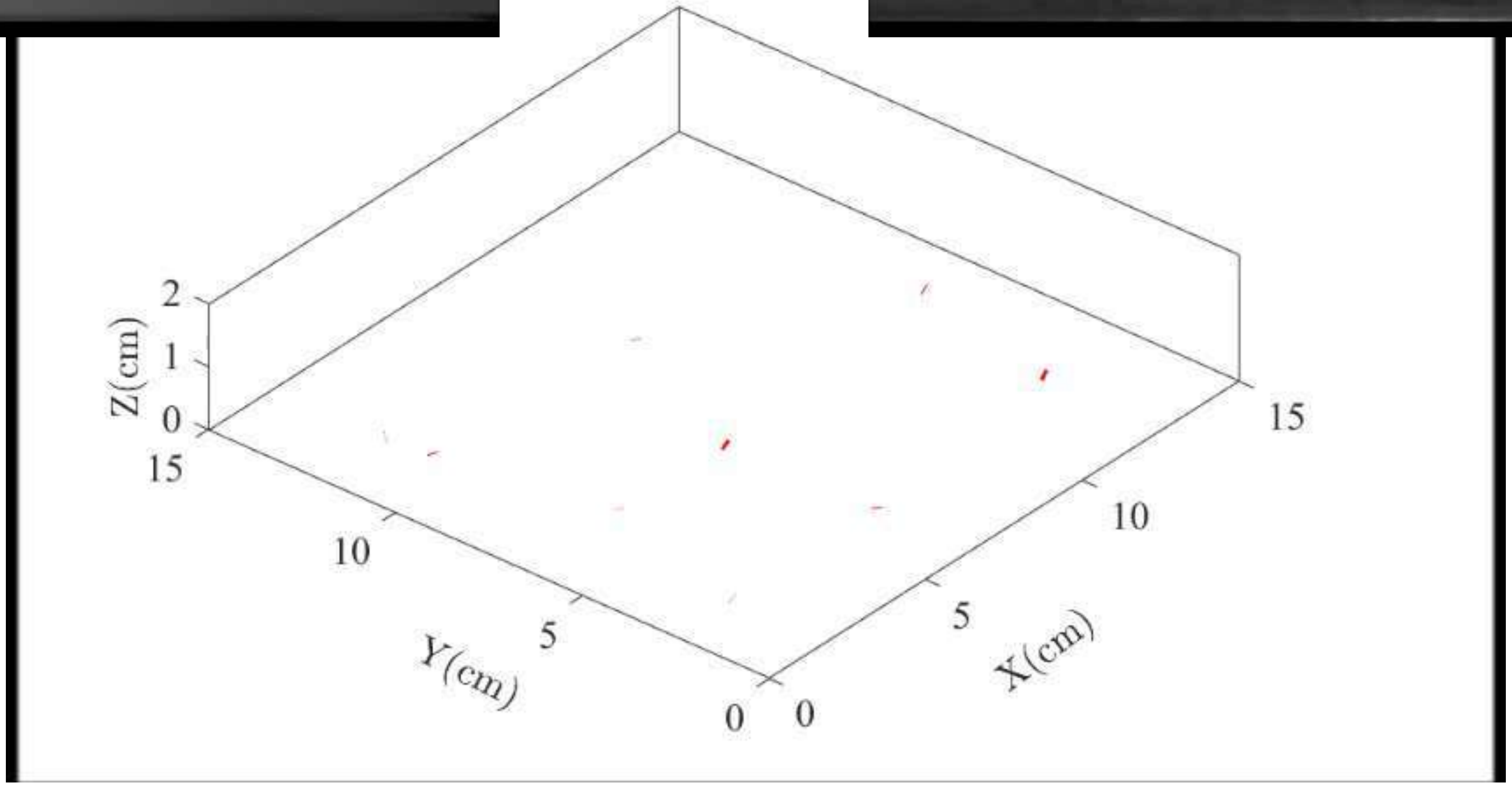
- Need to track the position in 3D
- 3D trajectories of each fish are recovered using a stereoscopic camera system and the Direct Linear Transformation method (DLT) (see Hedrick *Bioinsp. Biomim.* 2008).



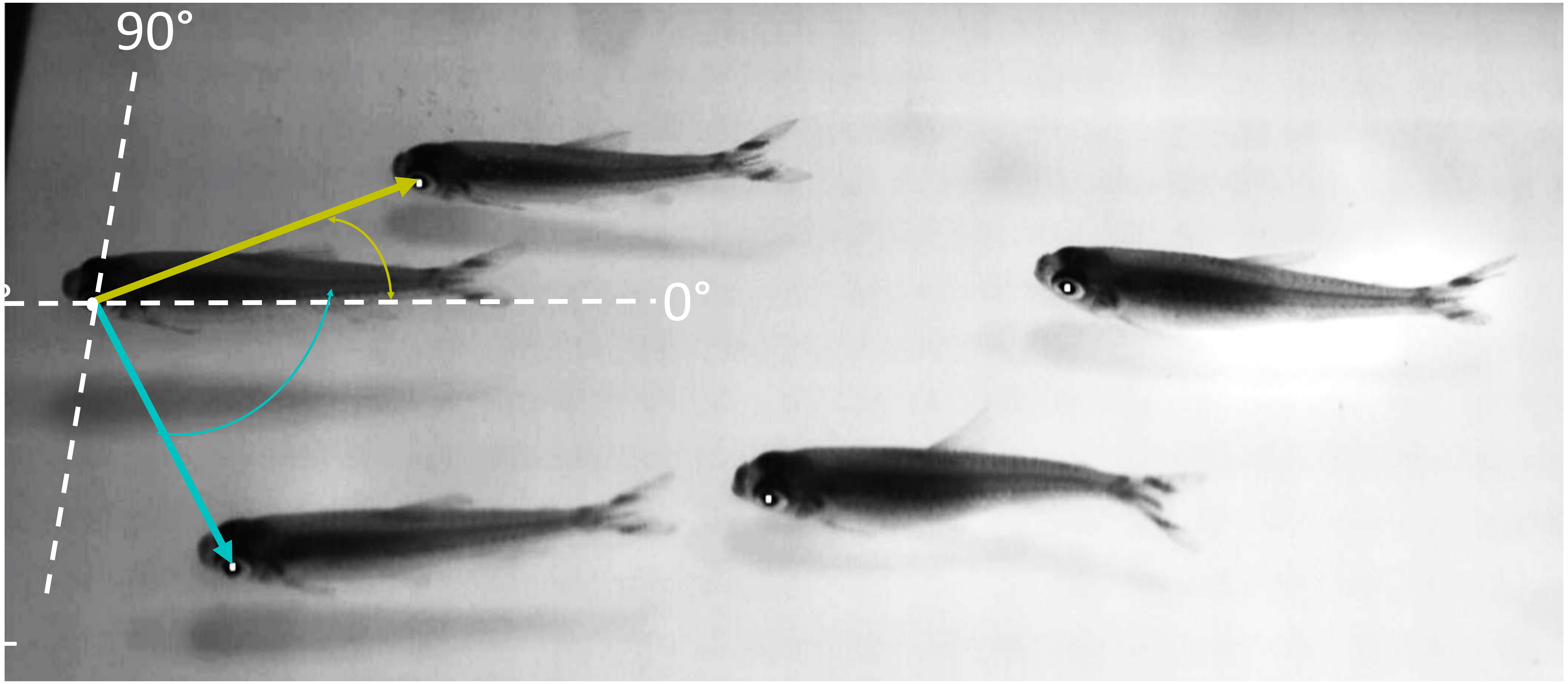
3D Trajectory Recovering



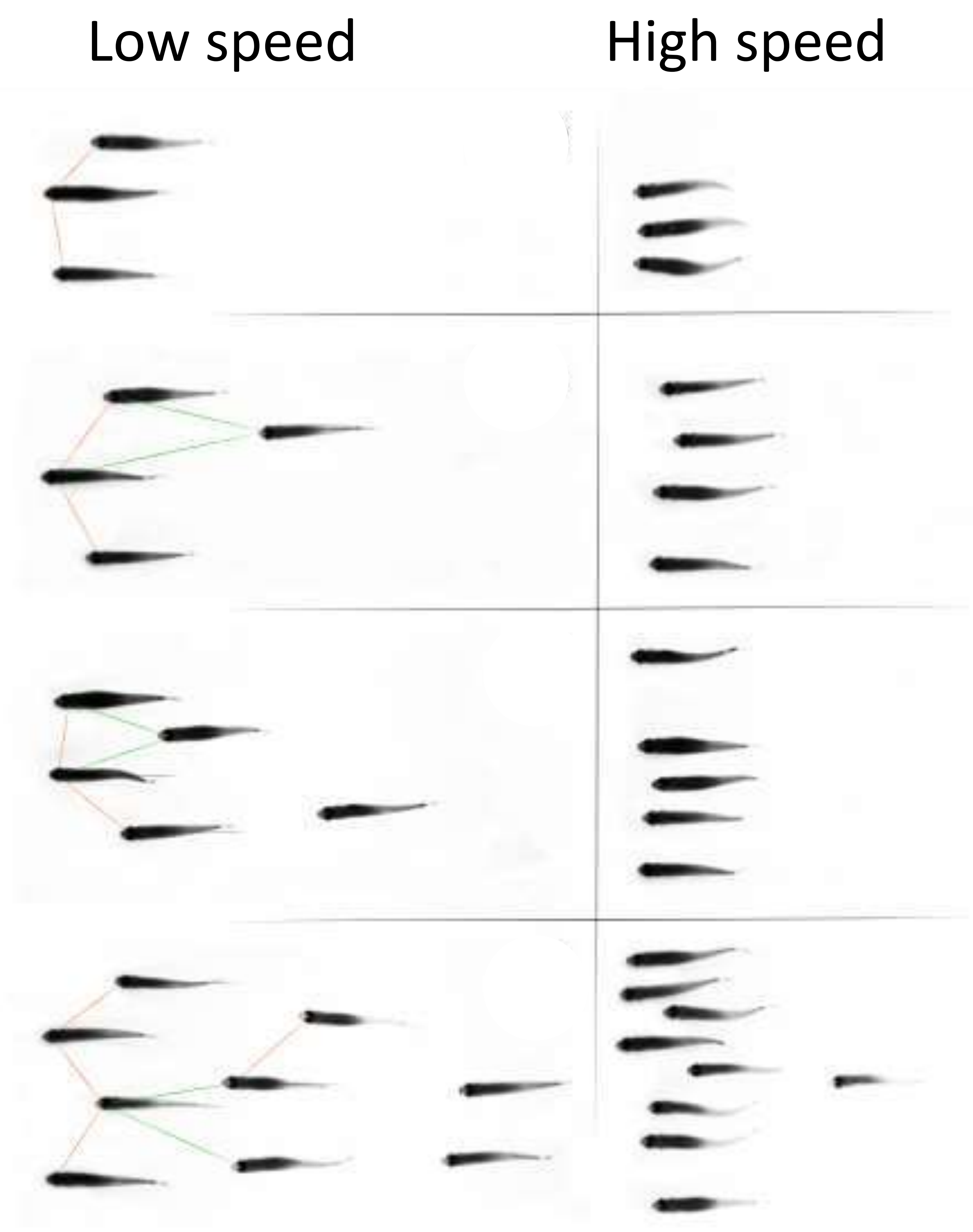


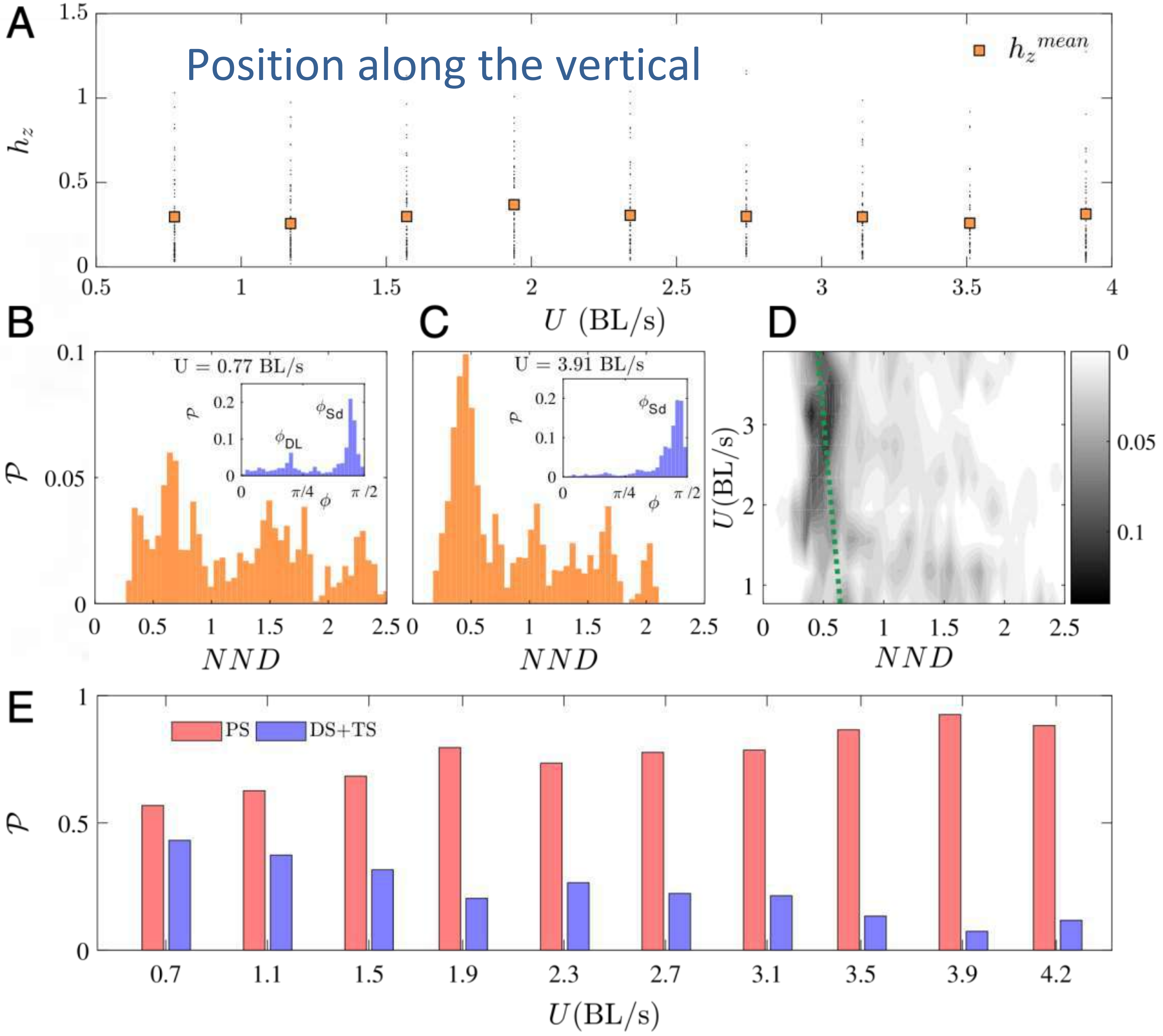


Nearest neighbours distances (NND) and angles



Schooling Patterns

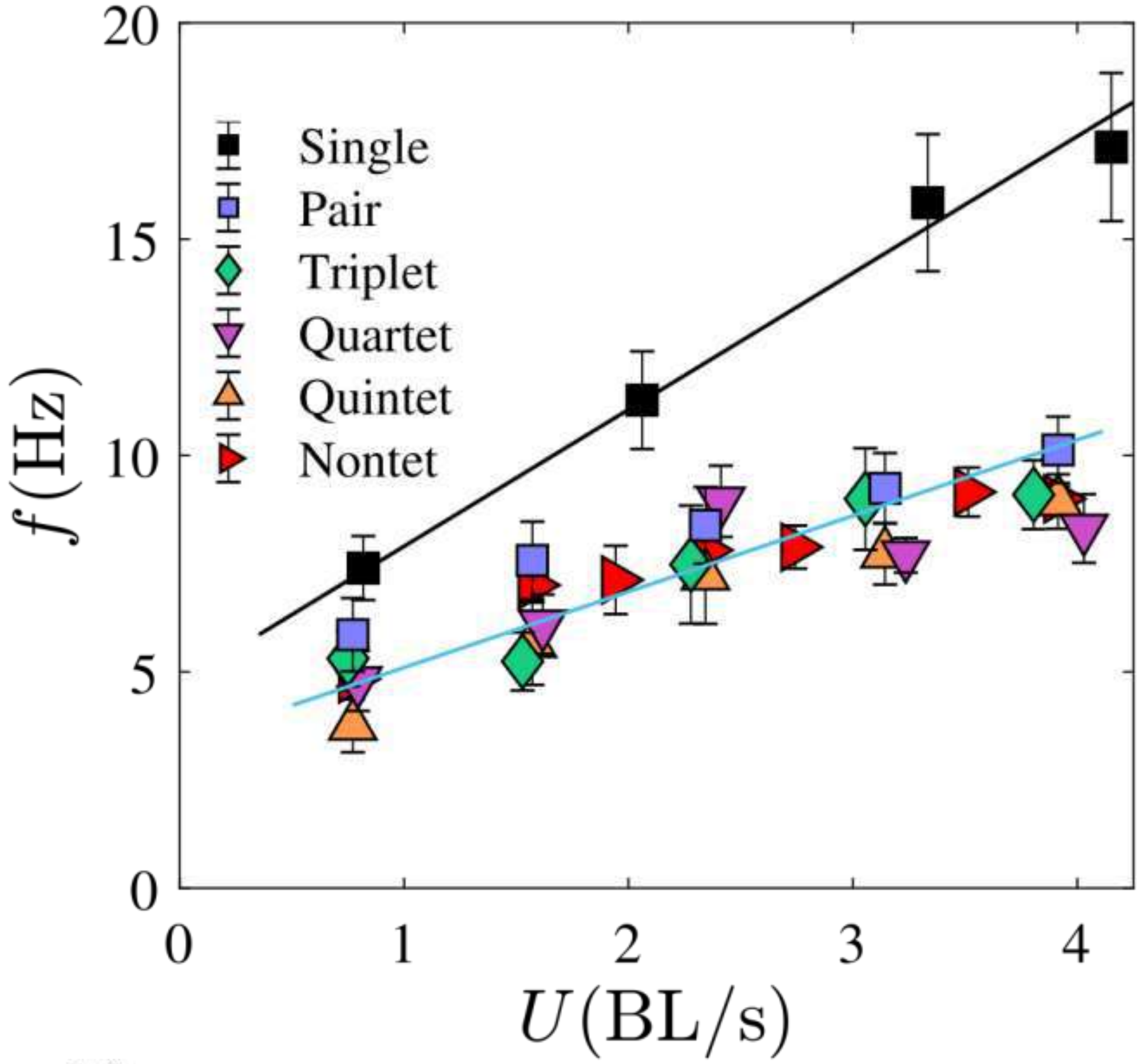


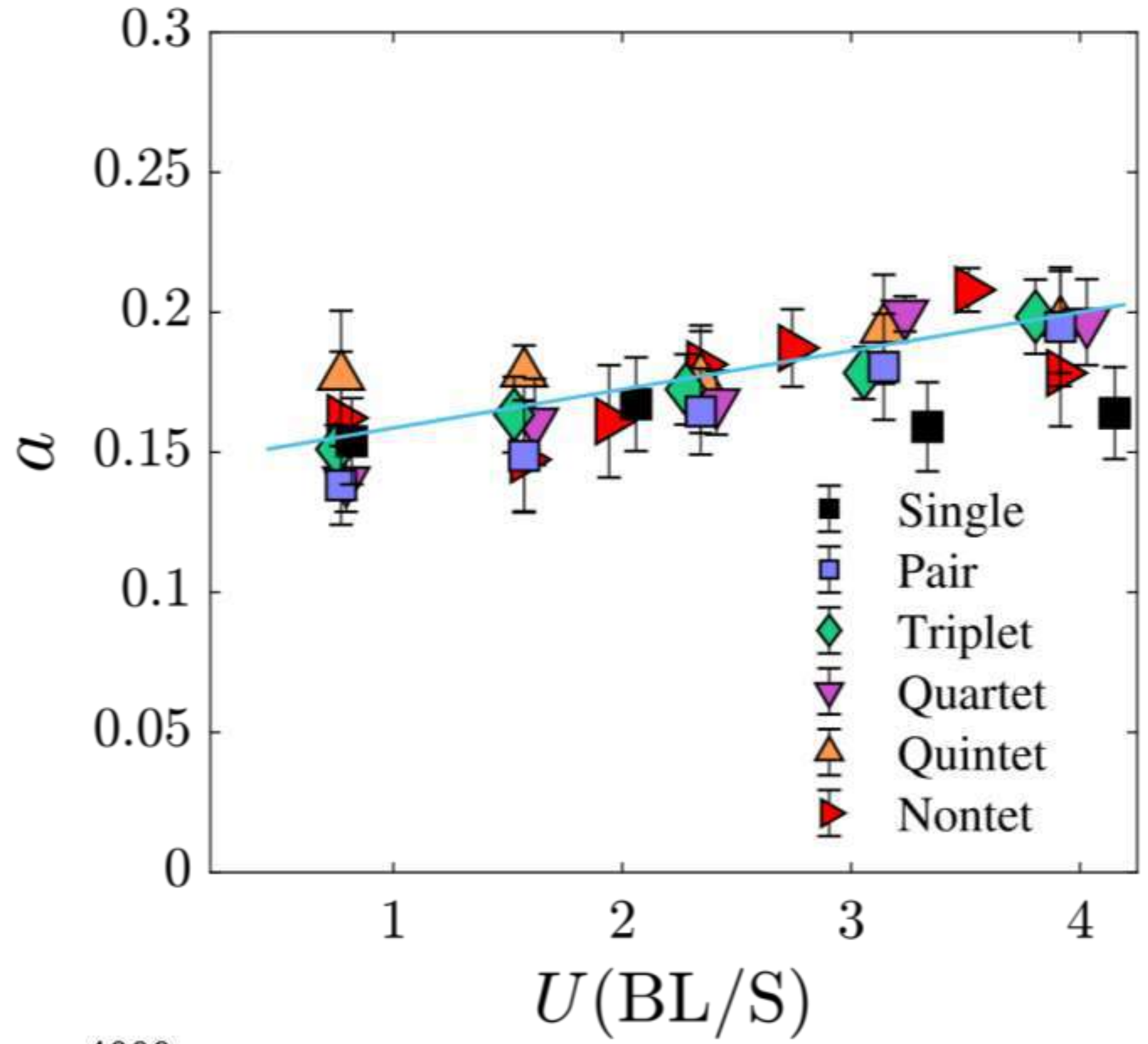


statistics over 200 runs

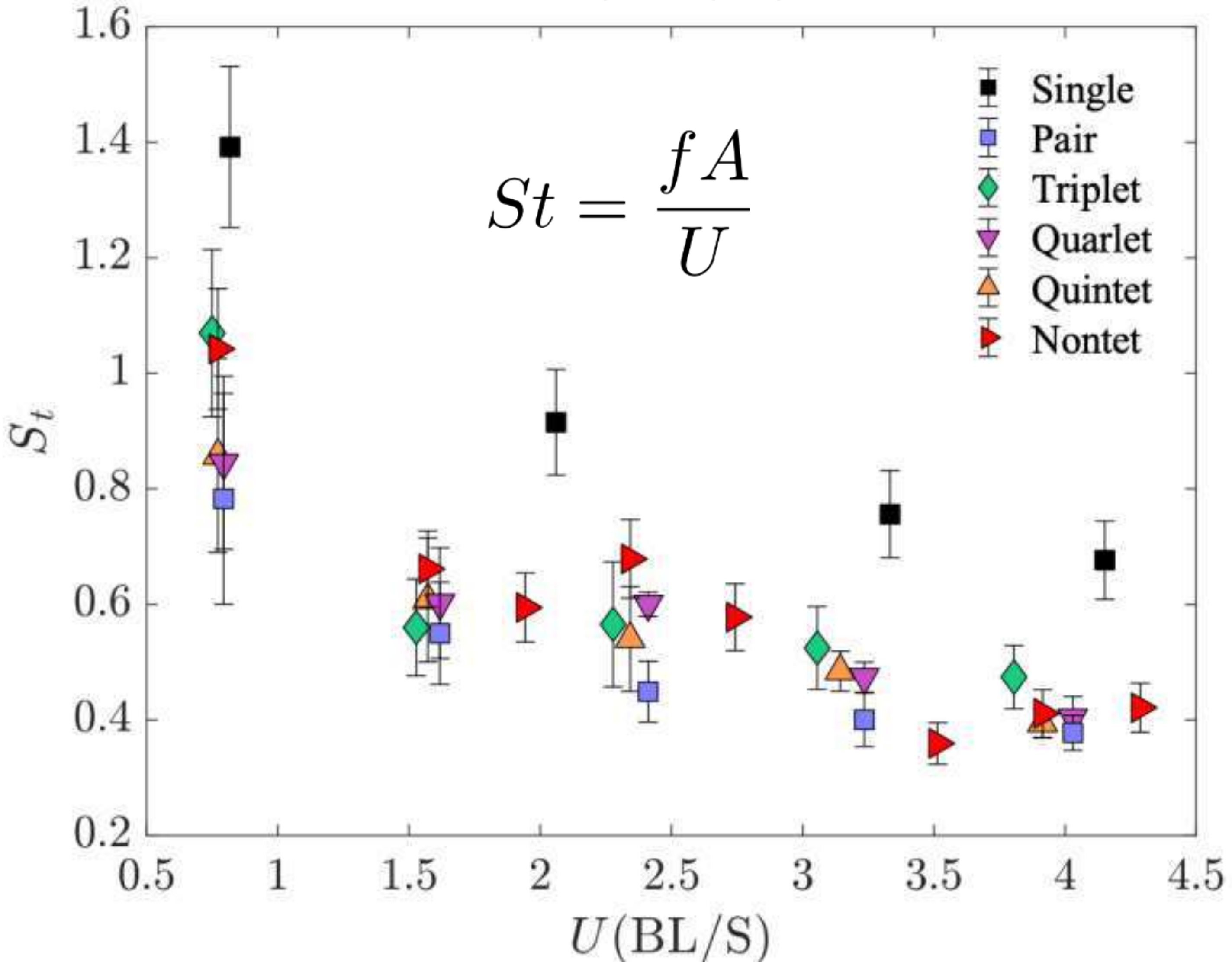
Global Swimming Performance

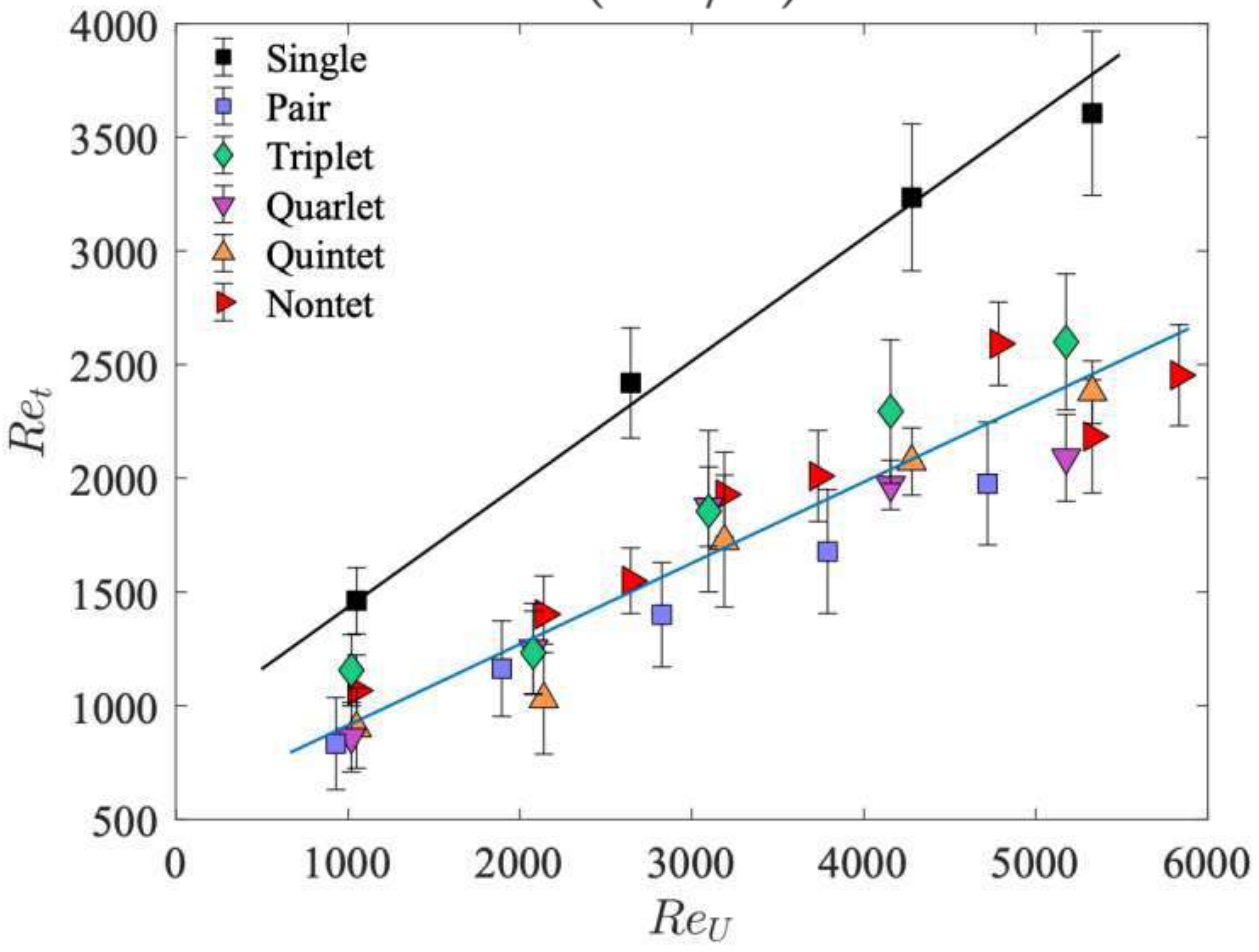
tail beat frequency





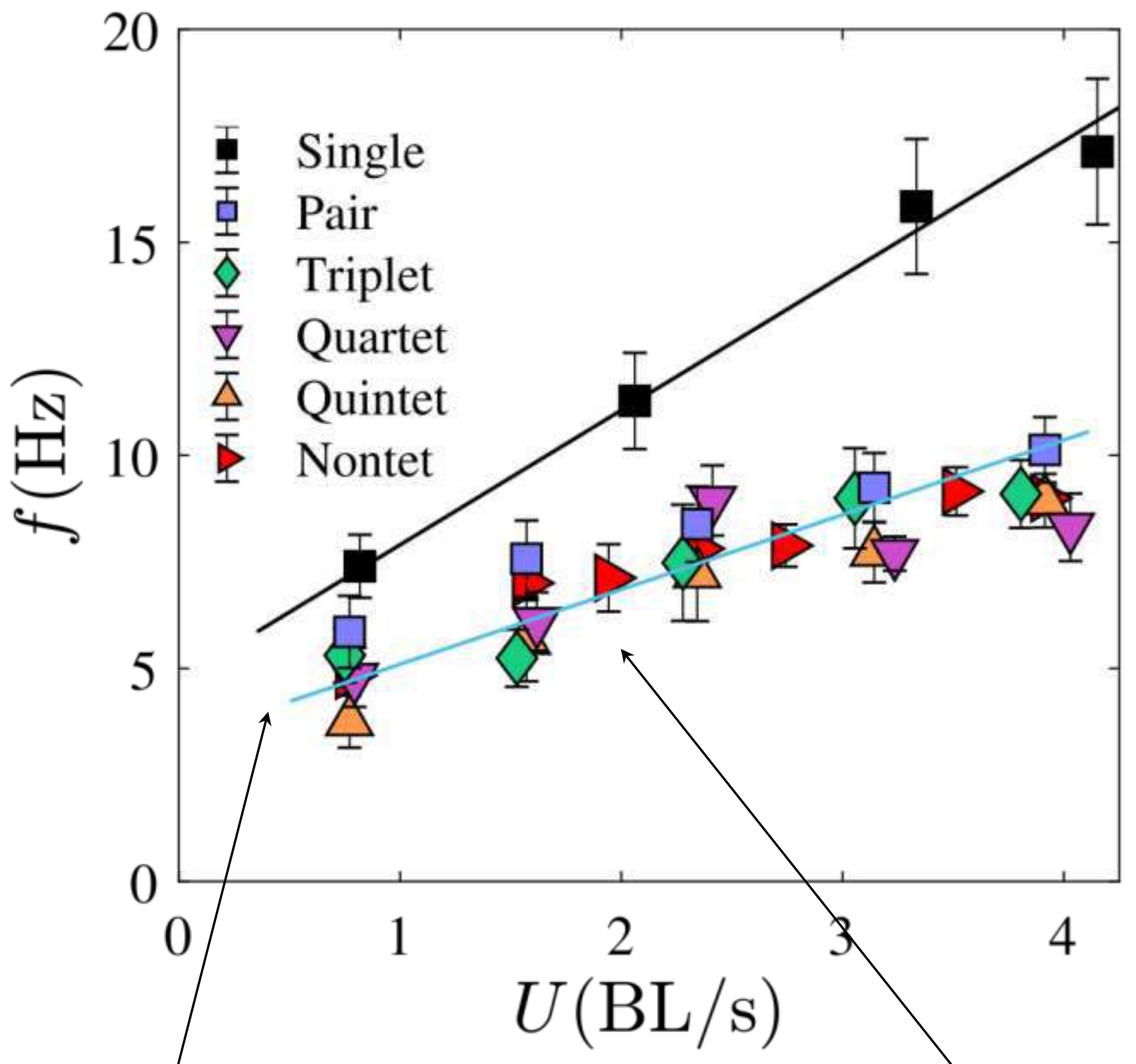
tail beat amplitude

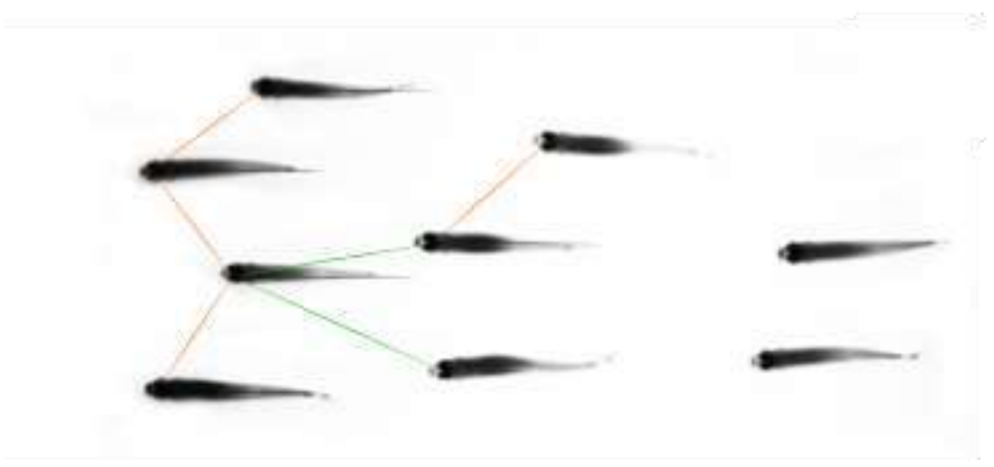


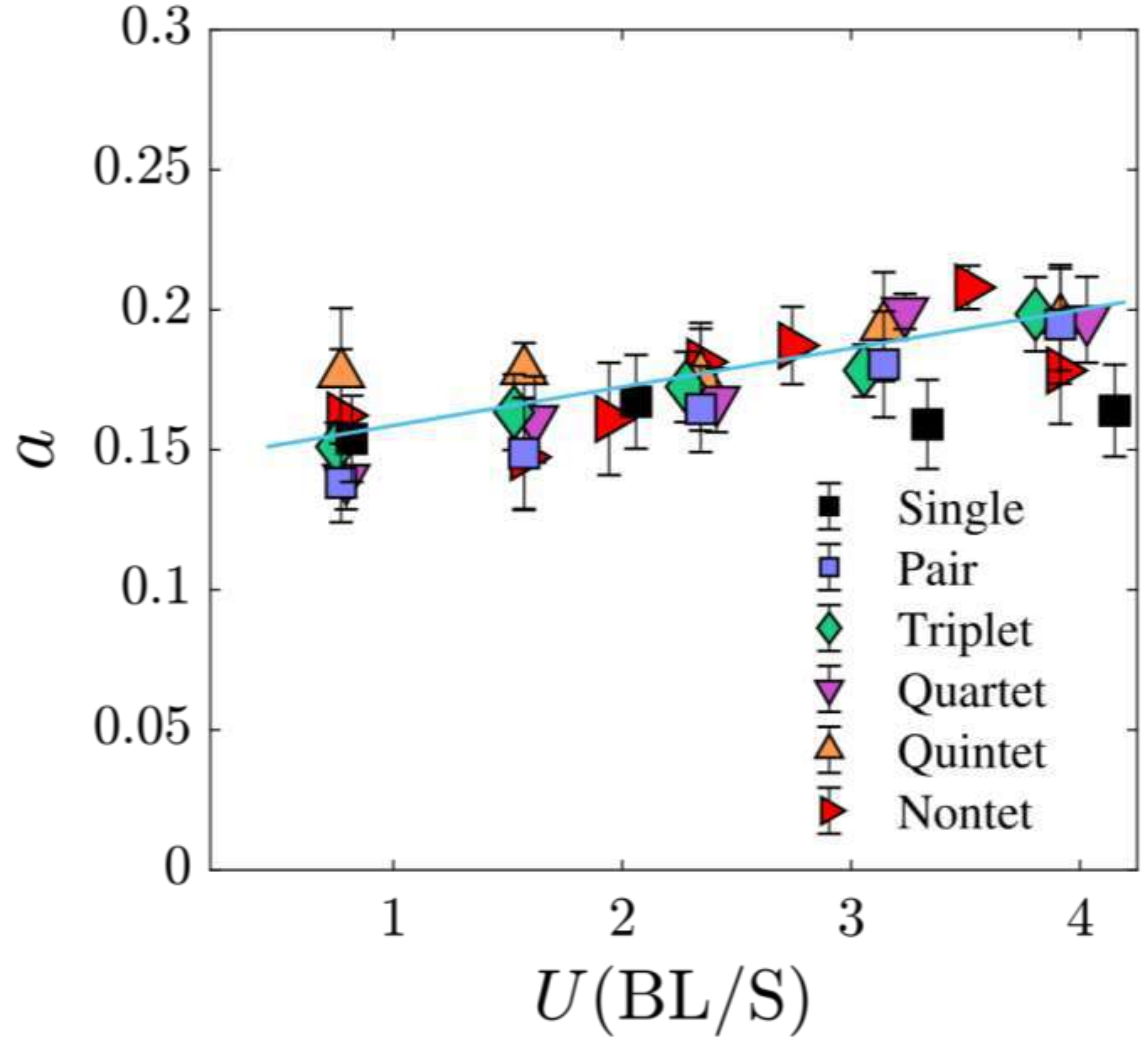


Global Swimming Performance

tail beat frequency



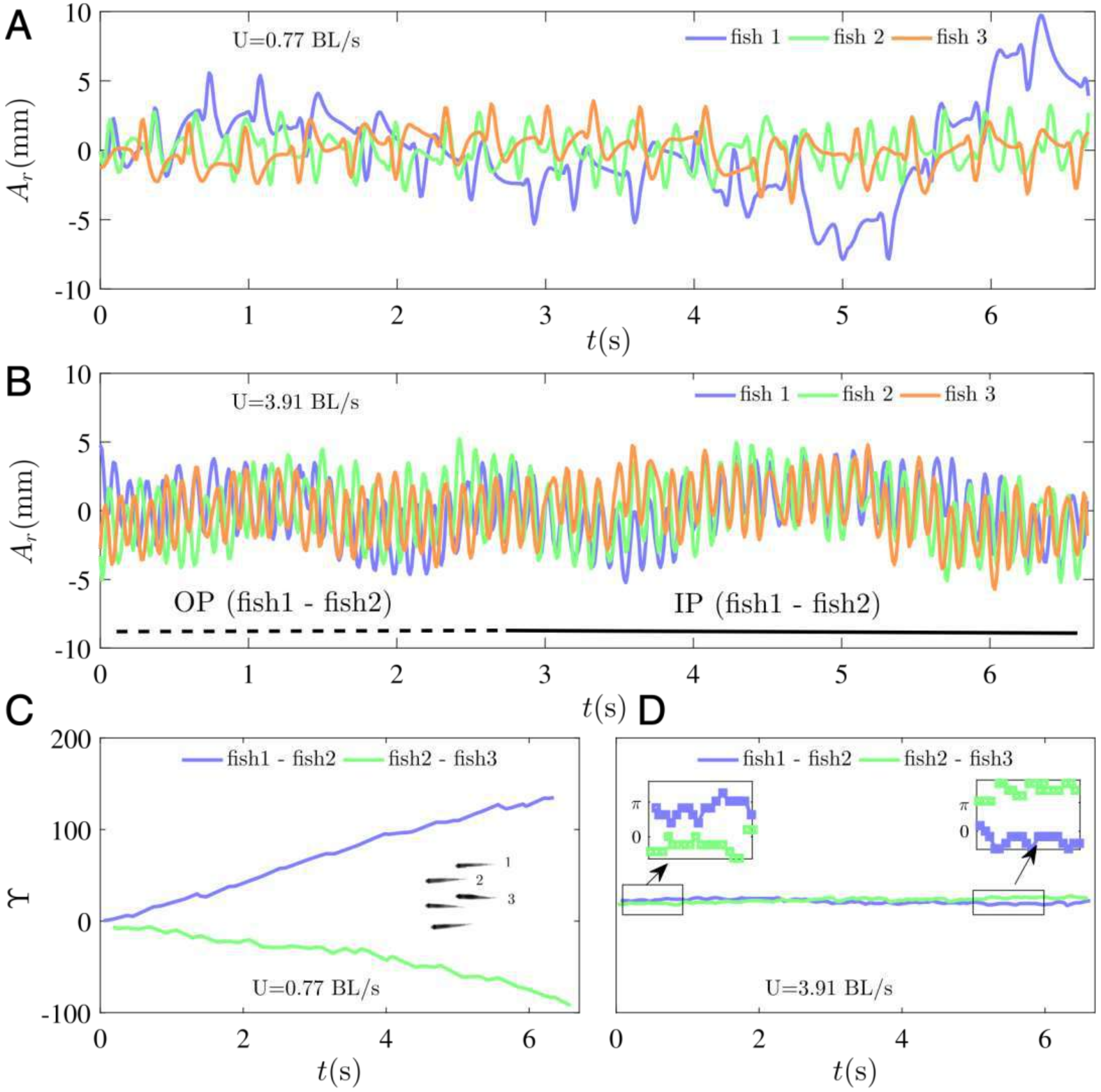




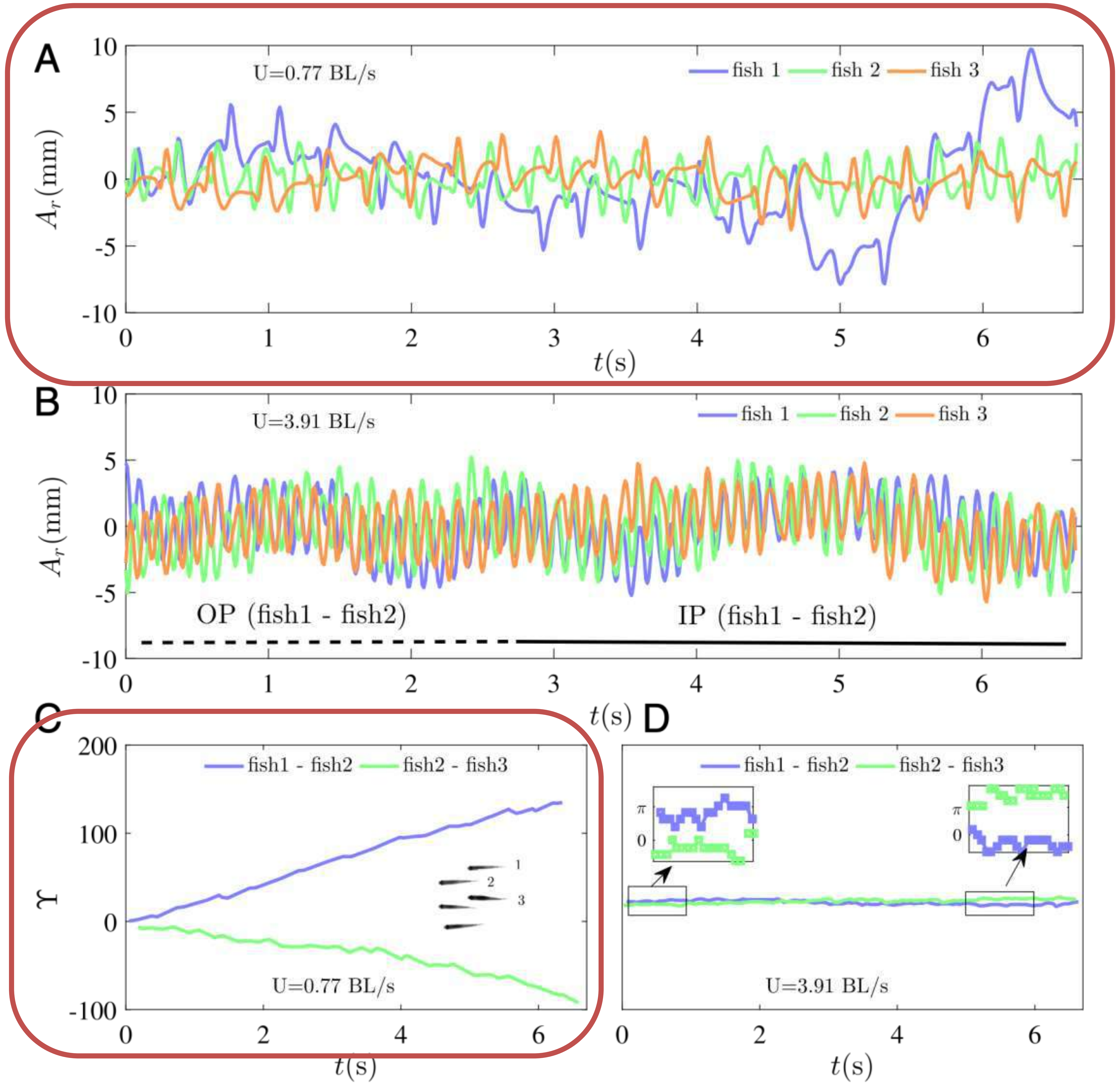
tail beat amplitude

- Performance is always better for fish swimming within a school
- This gain increases with swimming speed, giving an advantage to the side by side configuration vs. the diamond-like pattern

Synchronized States



Synchronized States

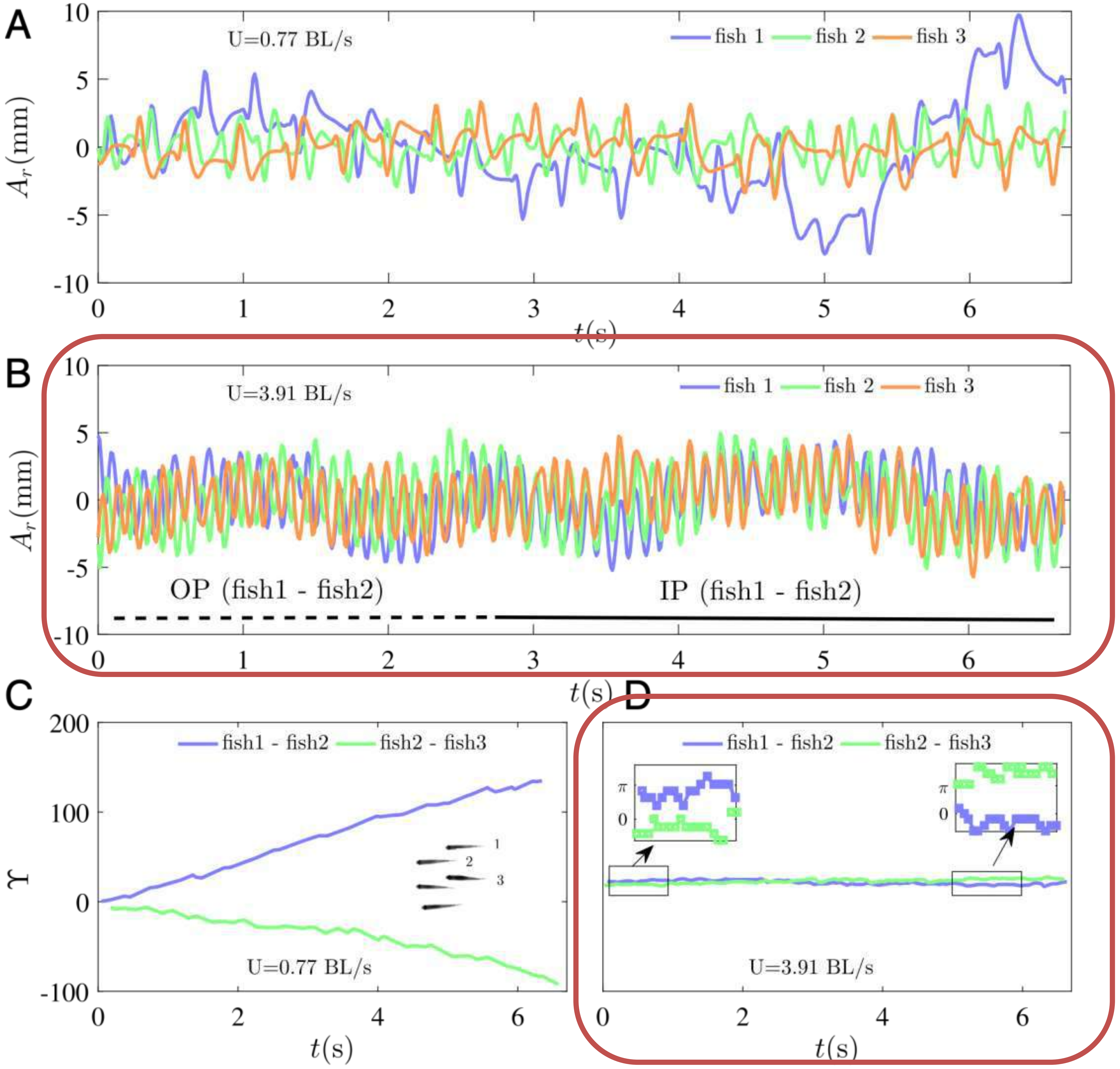


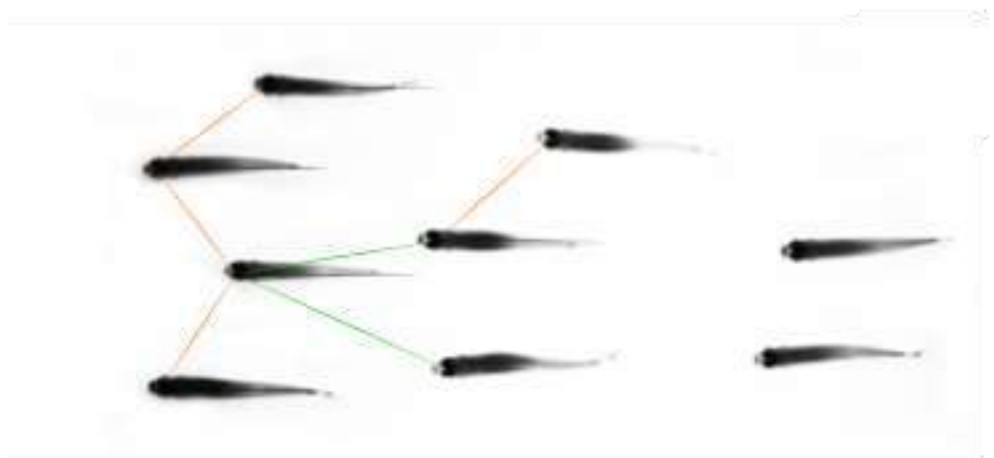
- Fish in the diamond-like pattern are independent

Synchronized States

DIAMOND-SHAPED PATTERN AT $U \approx 0.8$ BL/s

Synchronized States





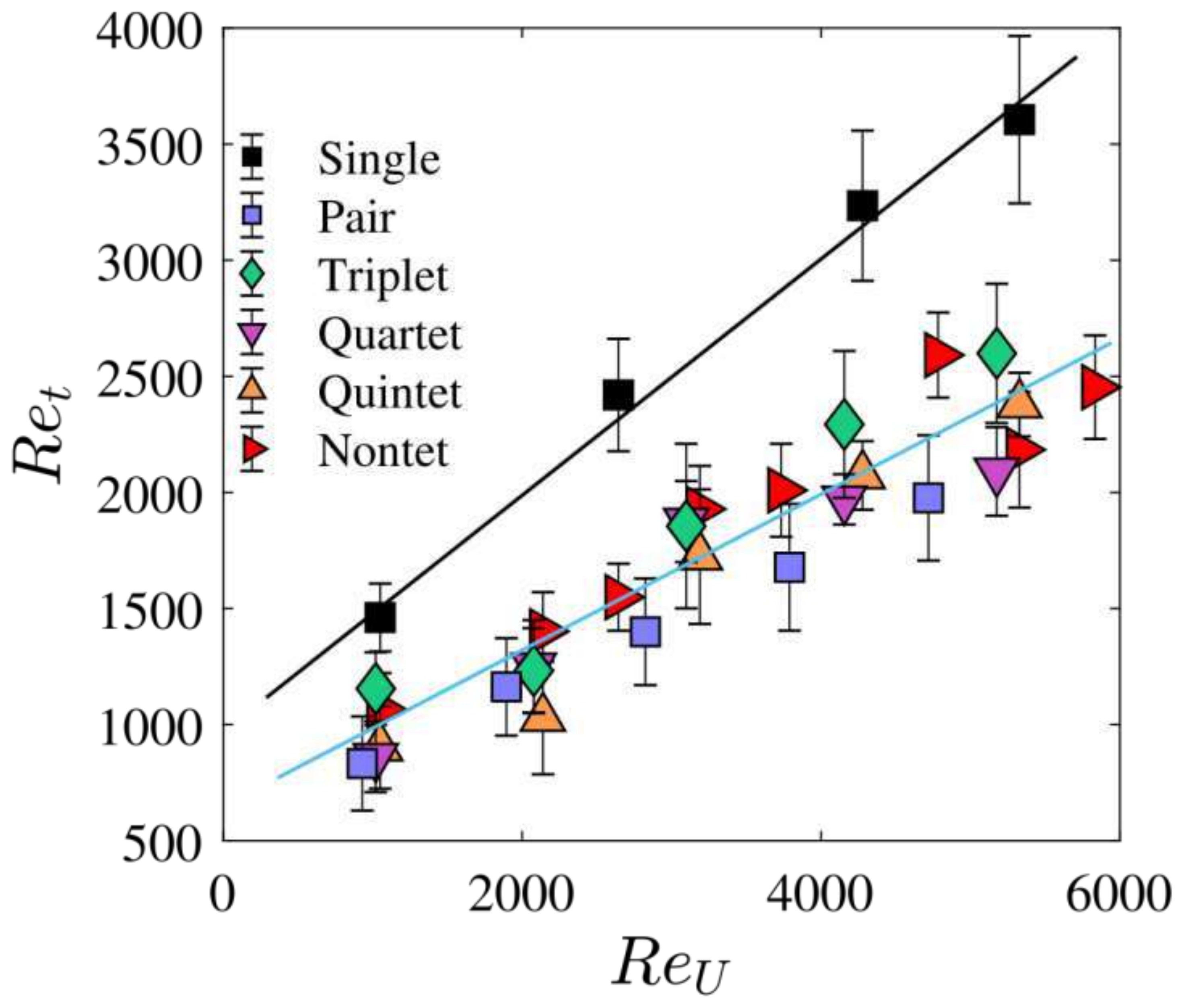
- Fish in side-by-side configuration (high swimming speed) are synchronized with their two nearest neighbors

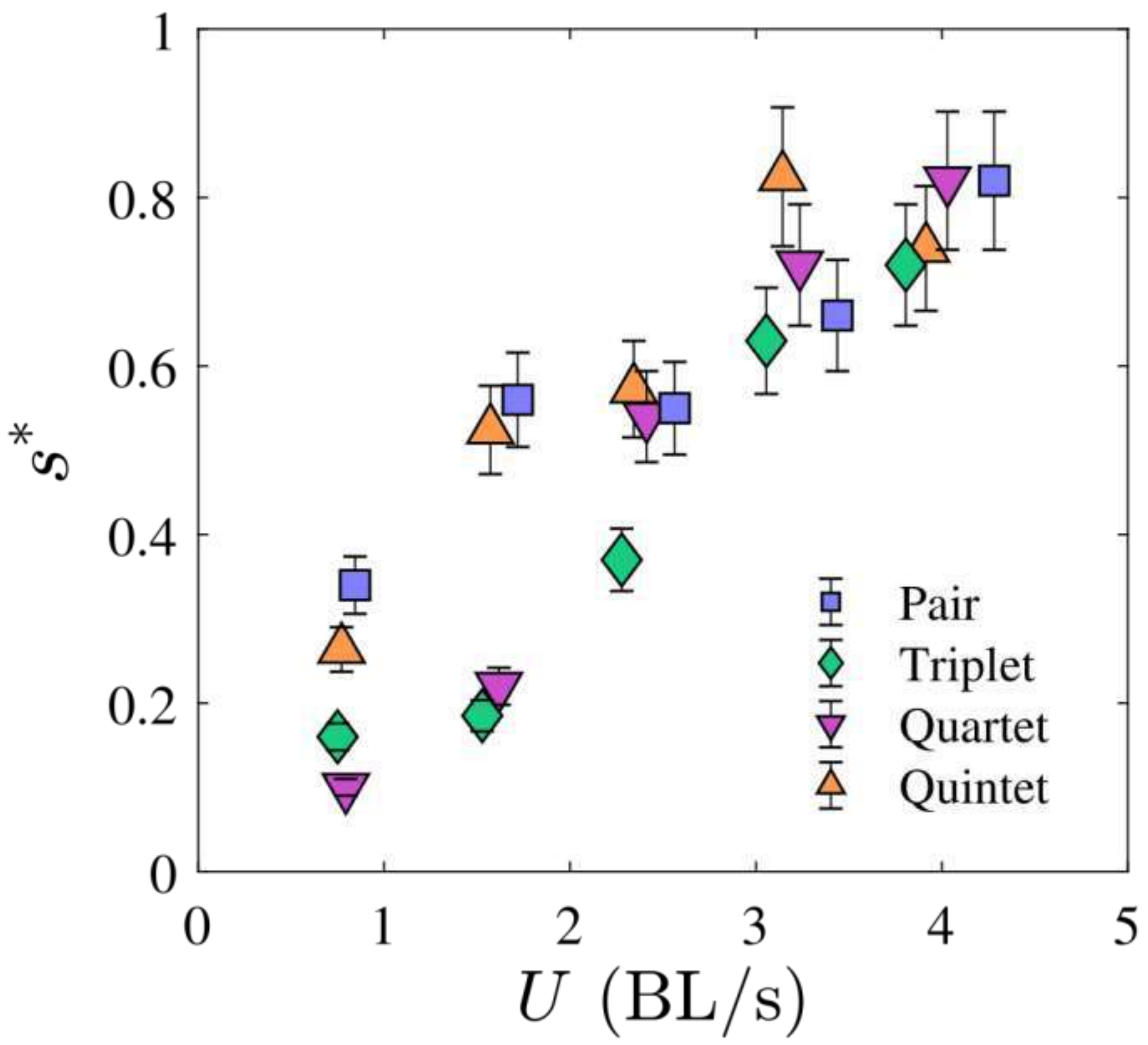
Synchronized States

SIDE-BY-SIDE (PHALANX) PATTERN AT $U \approx 4$ BL/s

Summary

- Low swimming speed fish schools are characterized by a spread-out diamond-like pattern and independent kinematics with no strong difference compared to single fish
- High swimming velocities correspond to highly synchronized swimming in a phalanx pattern
- The rate of synchronization seems to be correlated with the global efficiency of the school





INTERFACE
rsif.royalsocietypublishing.org

Synchronization and collective swimming patterns in fish (*Hemigrammus bleheri*)

I. Ashraf[1], R. Godoy-Diana[1], J. Halloy[2], B. Collignon[2] and B. Thiria[1]

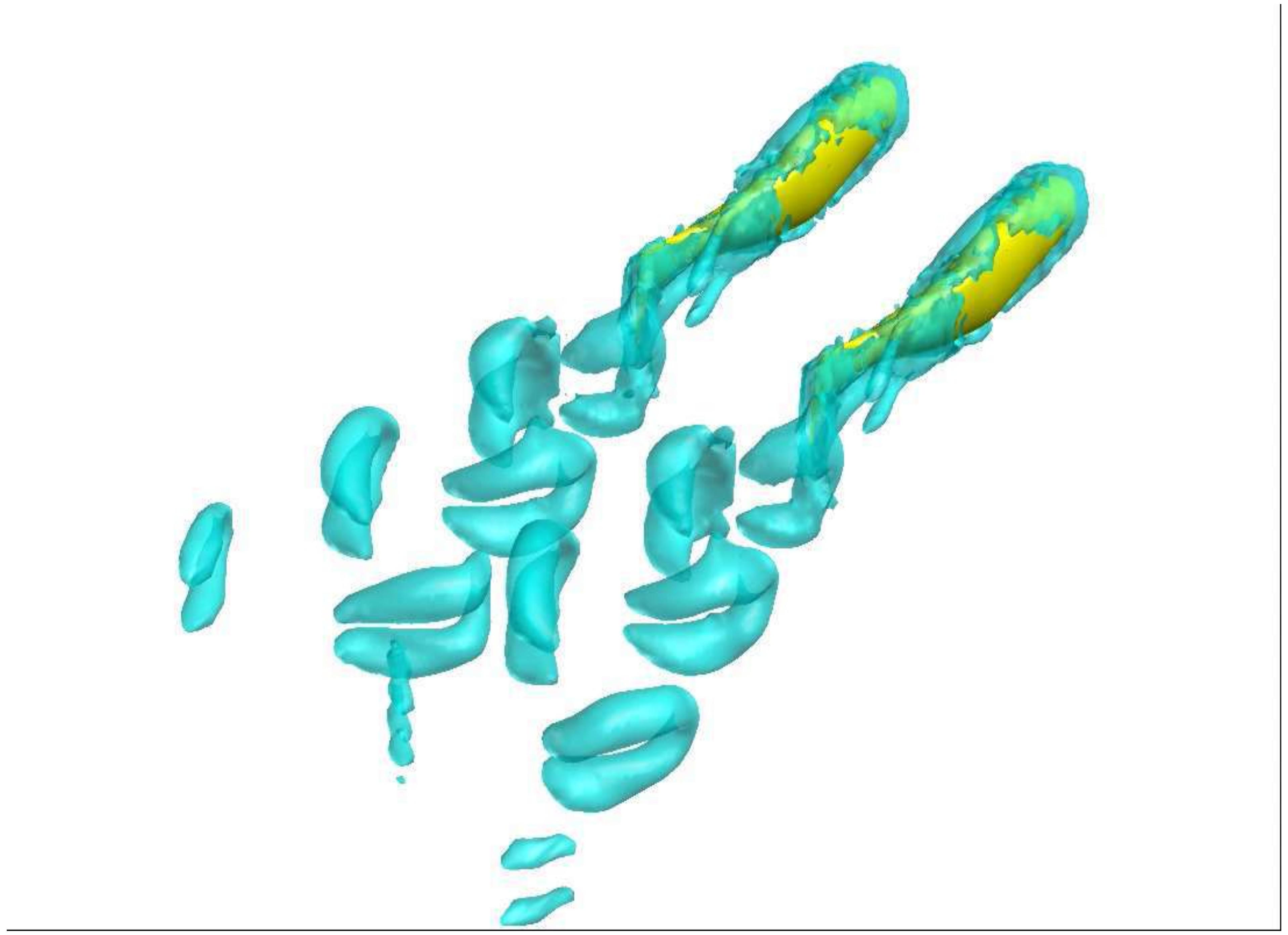
PNAS

Simple phalanx pattern leads to energy saving in cohesive fish schooling

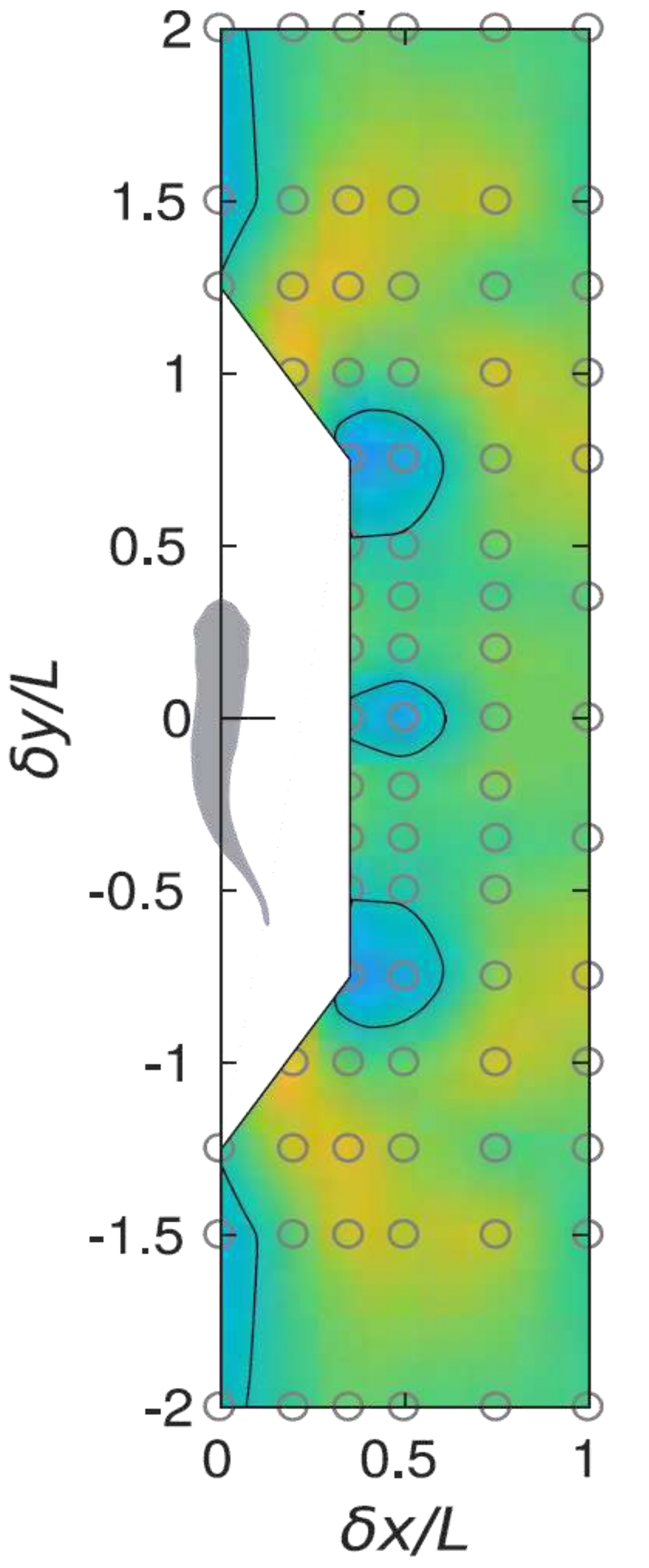
Ashraf et al. PNAS | **September 5, 2017** | vol. 114 | no. 36 | **9599–9604**

How can we examine the underlying fluid dynamic mechanisms?

Option 1: Numerical simulations



cost of transport for the two fish system



cold color = energy saving
hot color = energy waste

PLOS ONE **14**(8): e0215265, 2019

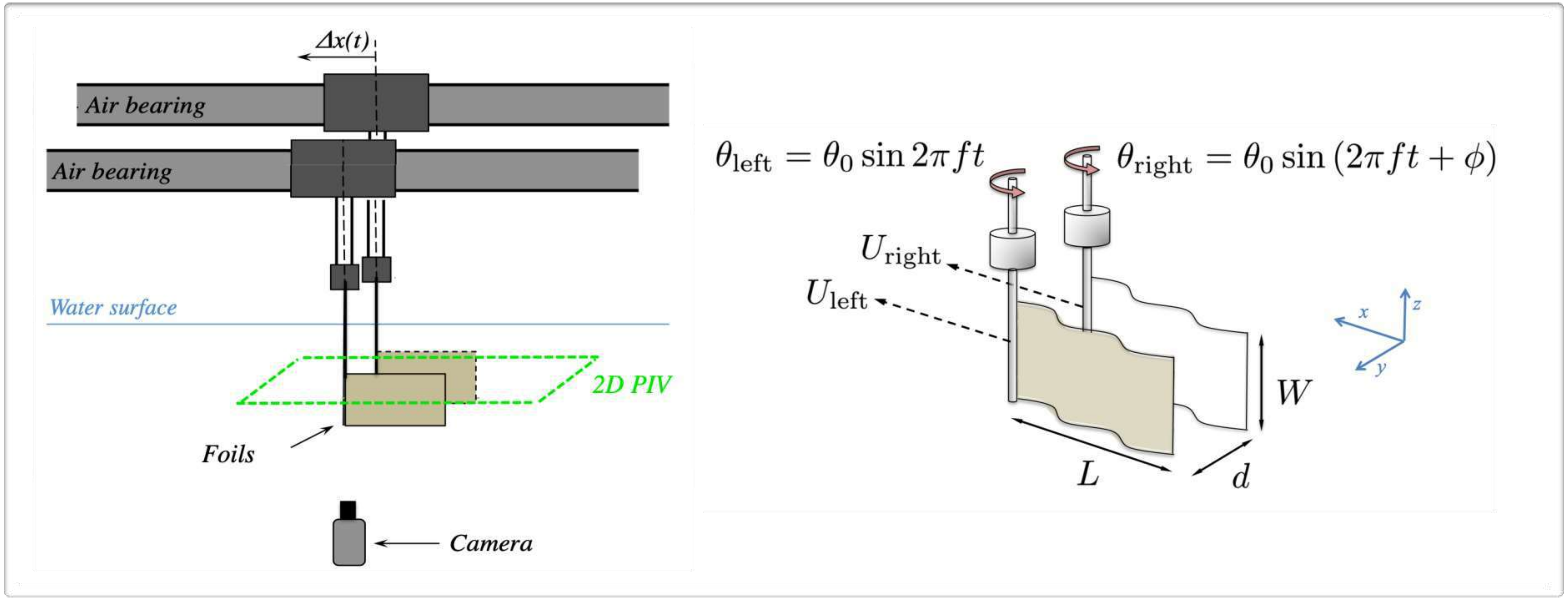
RESEARCH ARTICLE

On the energetics and stability of a minimal fish school

Gen Li[1]*, Dmitry Kolomenskiy[1]*, Hao Liu[2], Benjamin Thiria[3], Ramiro Godoy-Diana[3]

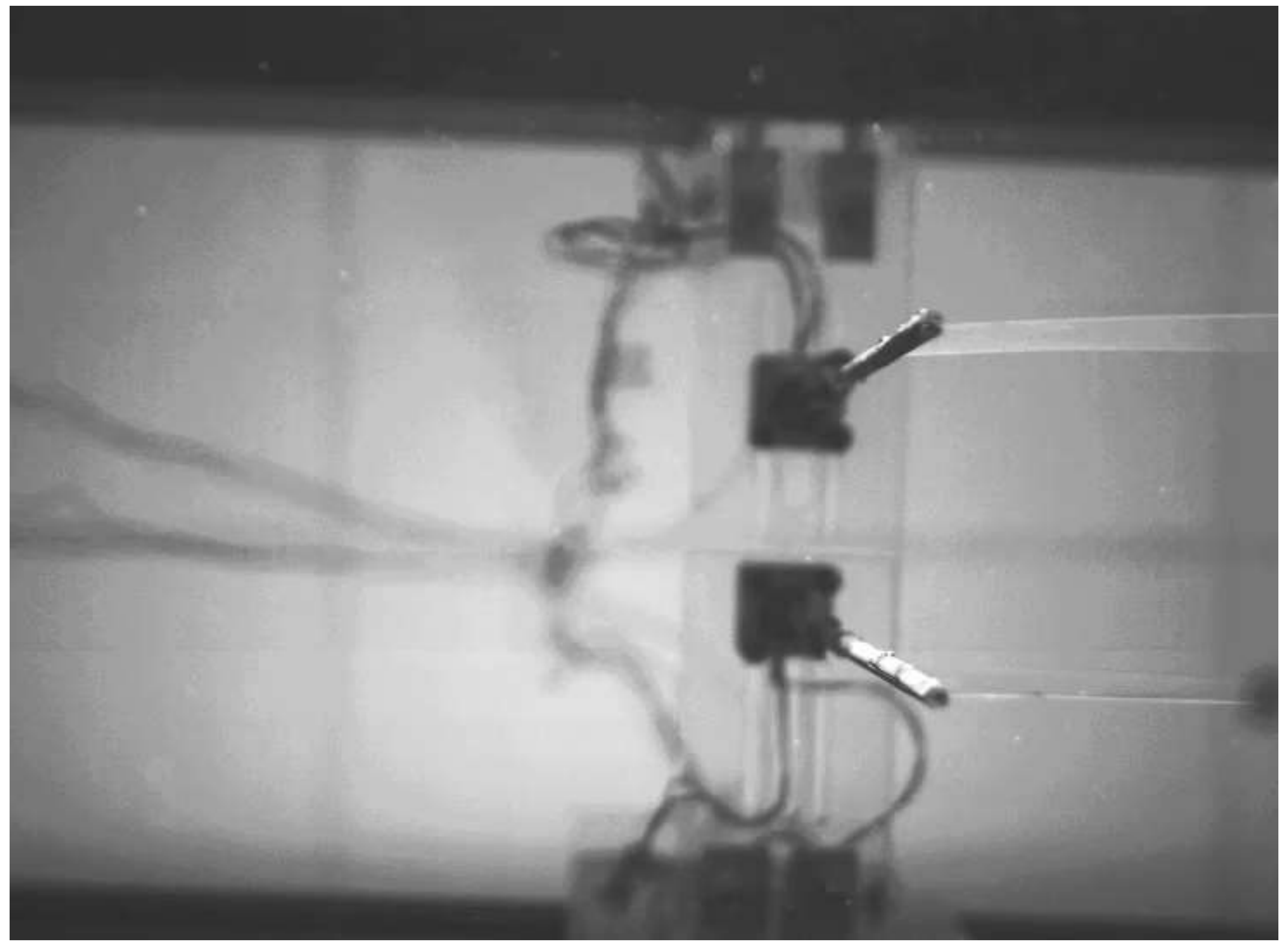
How can we examine the underlying fluid dynamic mechanisms?

Option 2: A model experiment

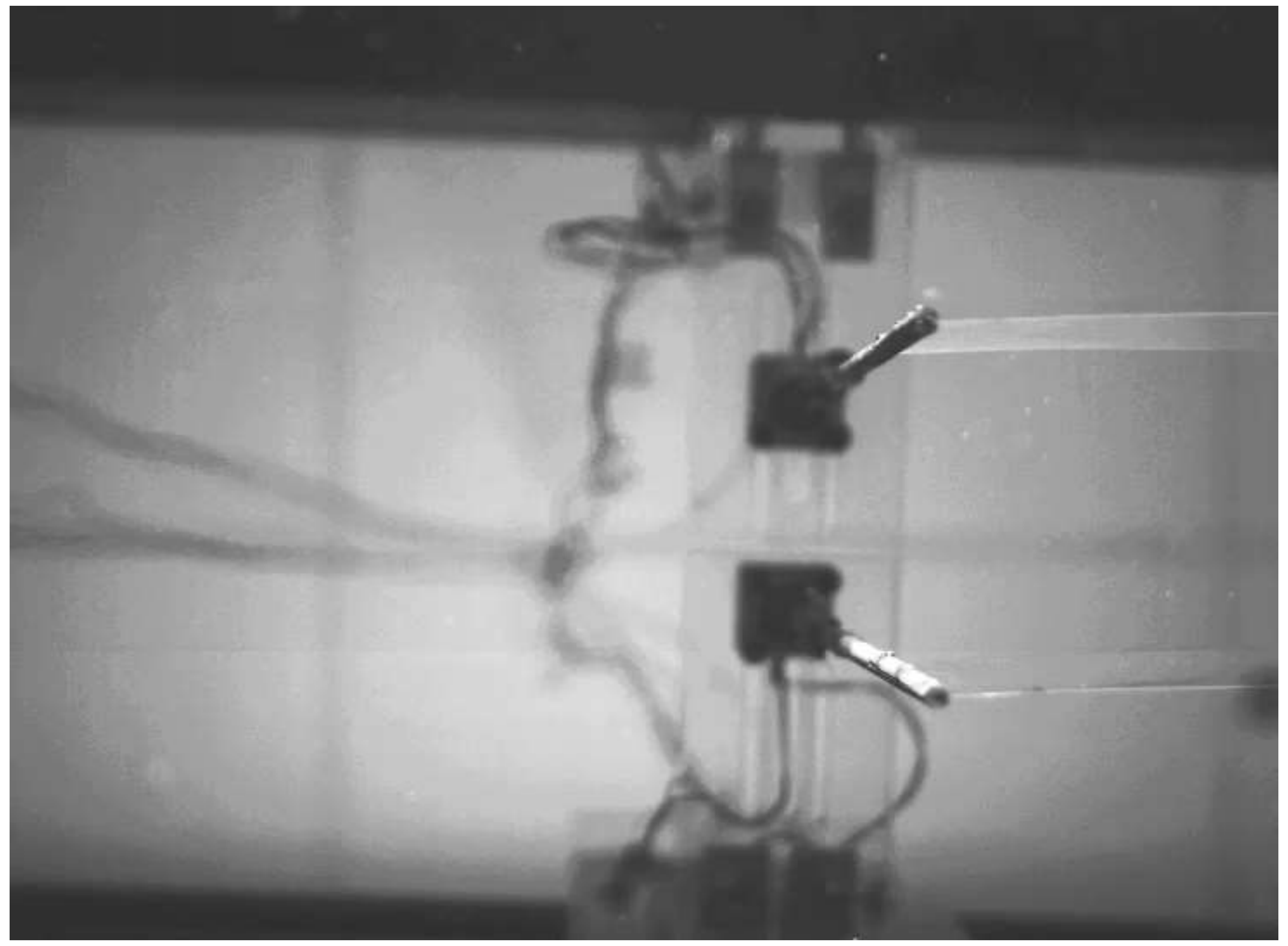


Two independent foils swimming side-by-side

Two independent foils swimming side-by-side

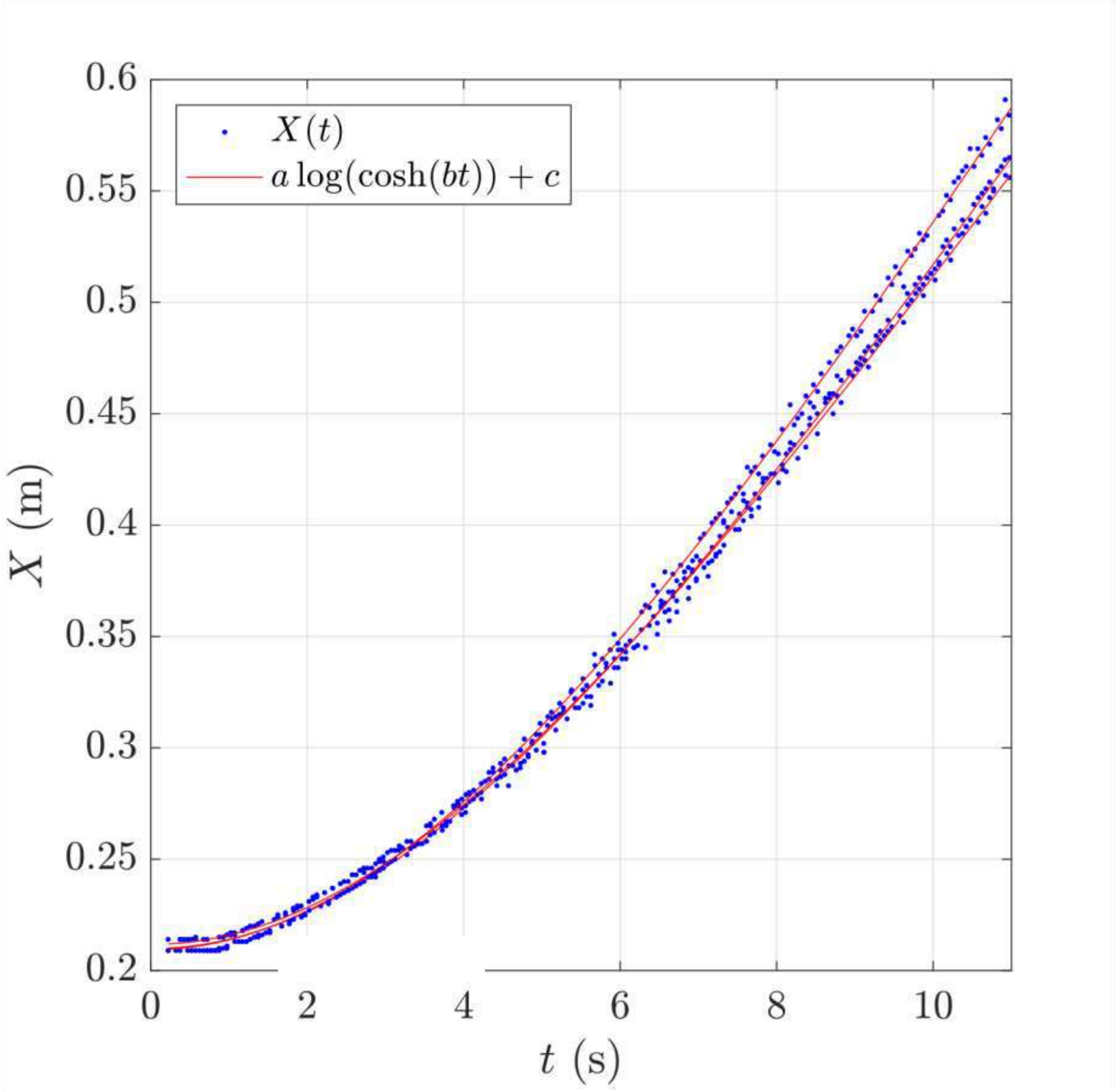


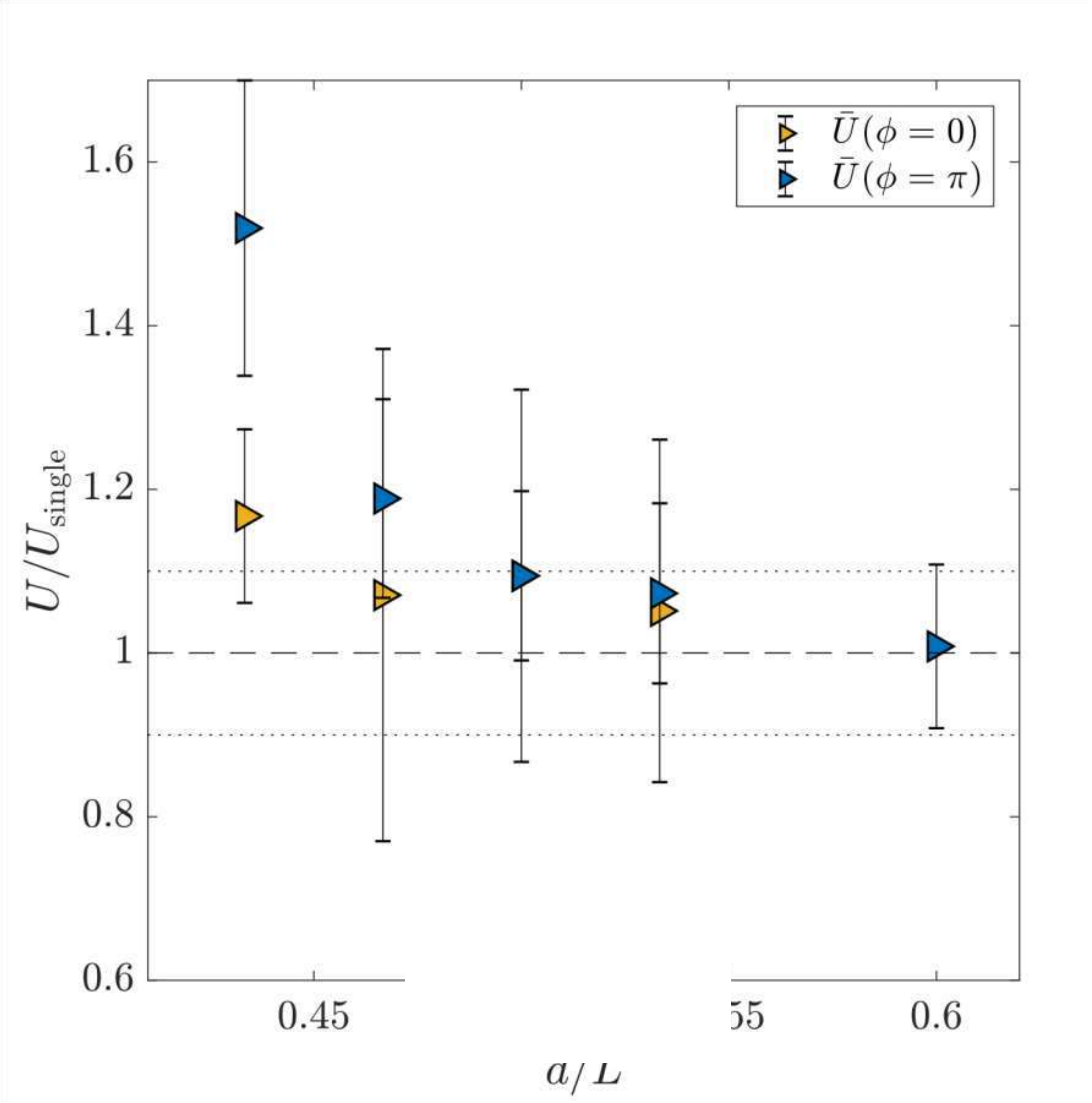
In-phase (IP)



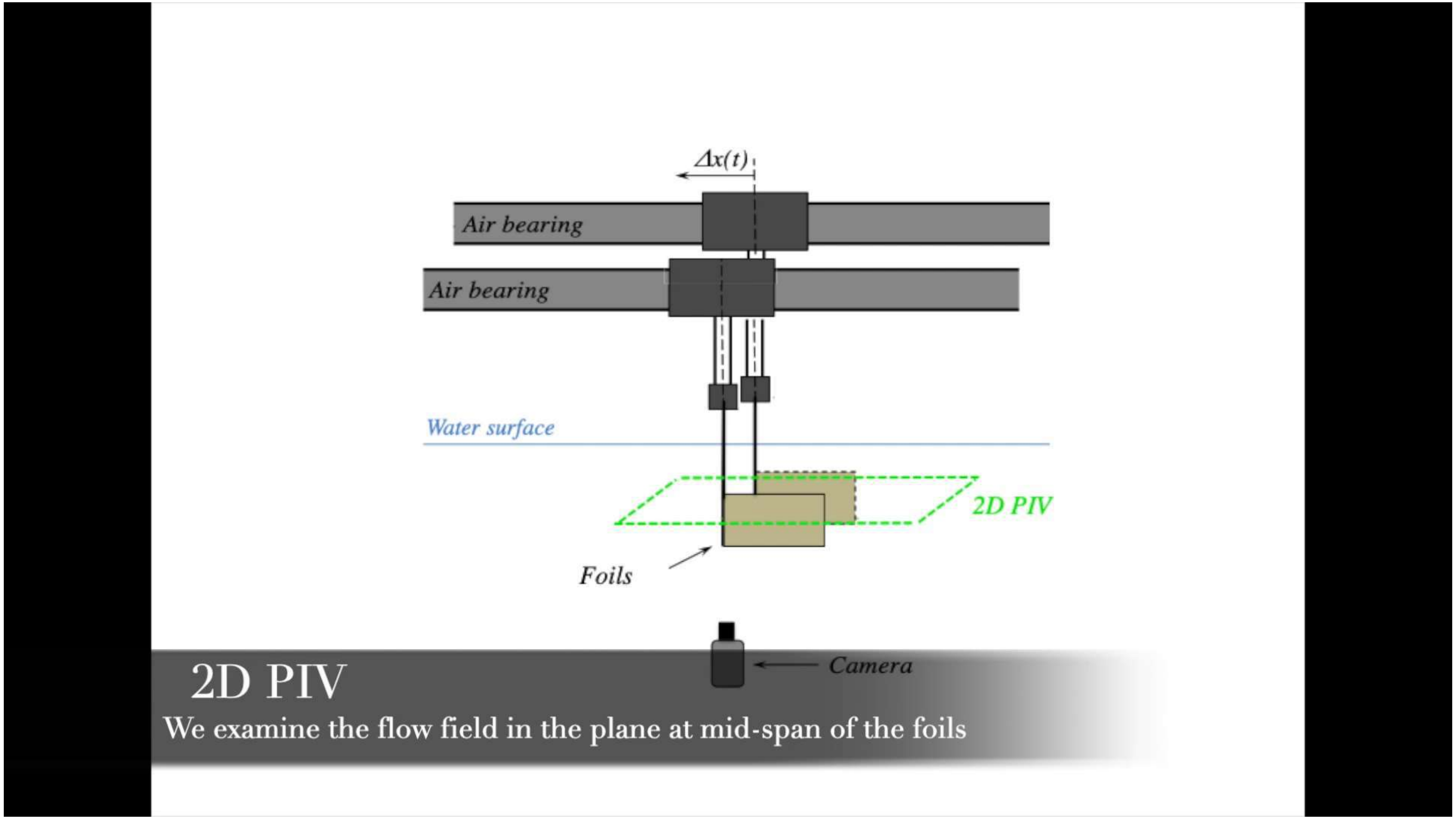
Out-of-phase (OP)

Self-propelled swimming velocity

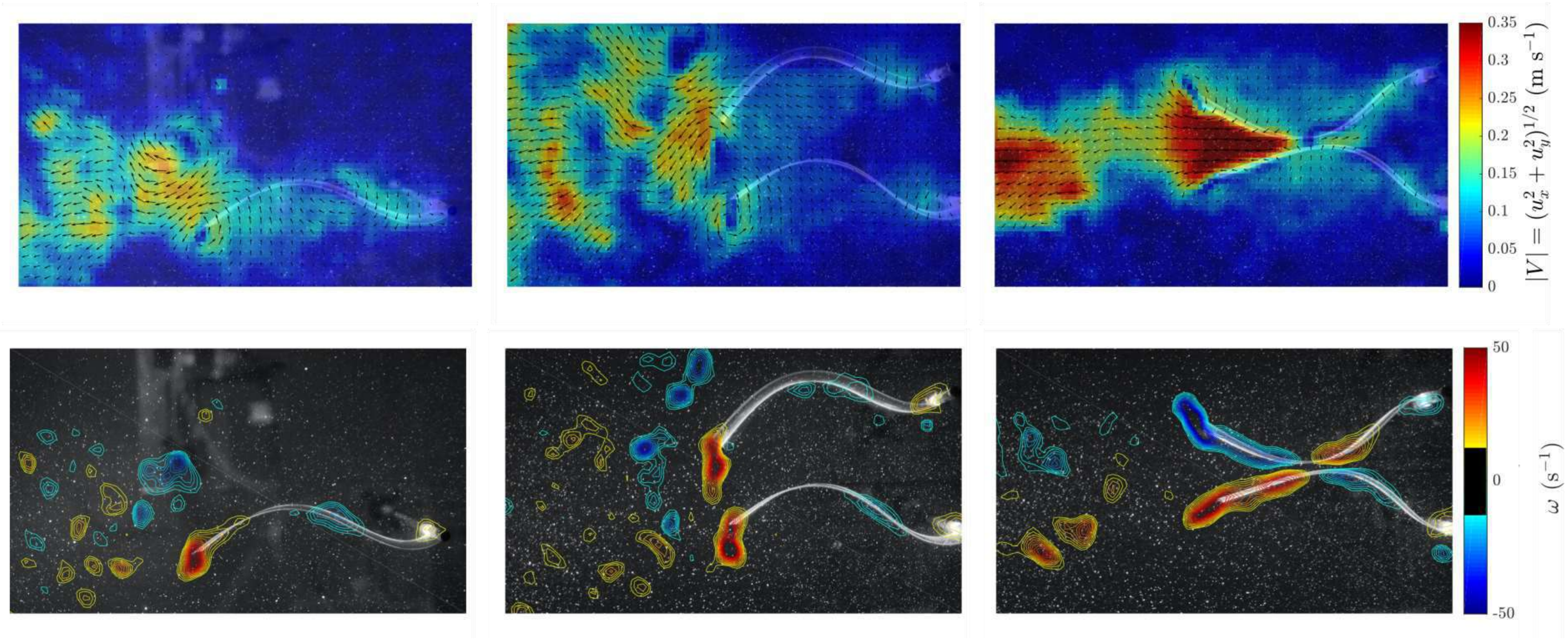




Particle Image Velocimetry (PIV)



Particle Image Velocimetry (PIV)

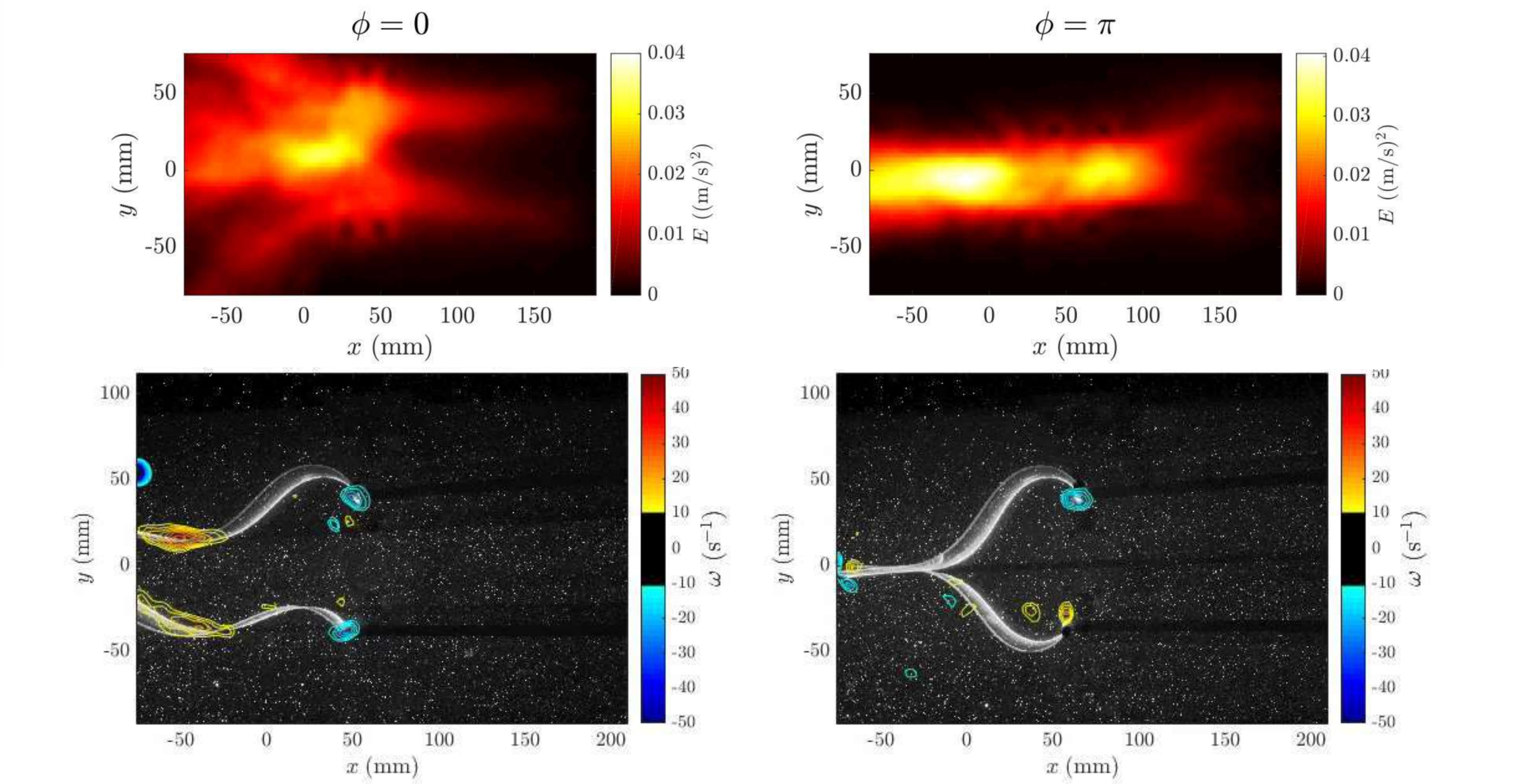


Single swimmer

In-phase (IP)

Out-of-phase (OP)

Time average of the kinetic energy



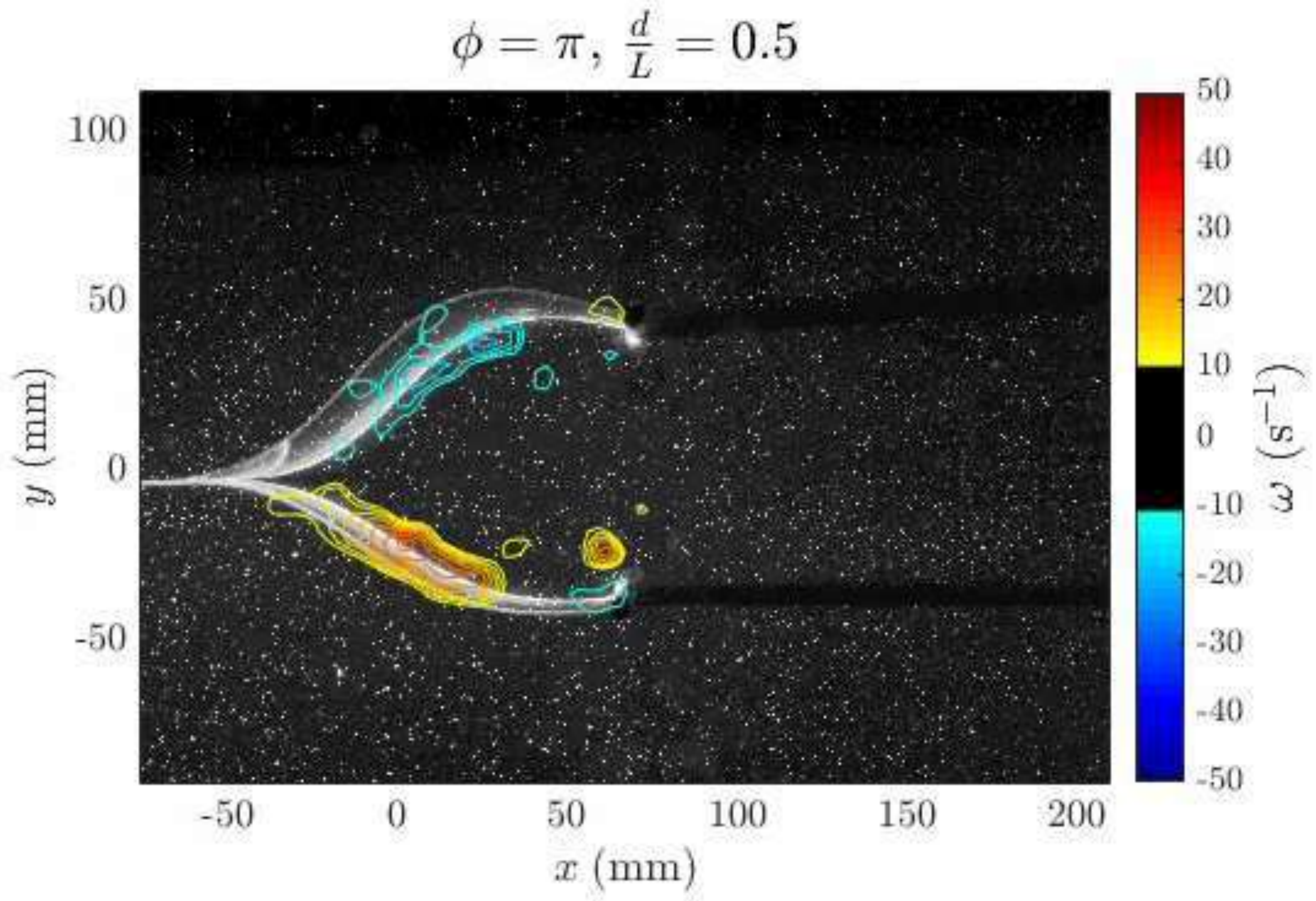
Out-of-phase: the symmetric vortex shedding recalls the propulsive mechanisms found in nature in axisymmetric animals such as squid or jellyfish: a coherent jet whose alignement determines the swimming velocity.

In-phase: the average propulsive jet is much more spread laterally, much of the momentum flux directed laterally, so not contributing to the propulsion.

In summary

- The preference of fish for schooling patterns where nearest neighbors are close to each other and their kinematics are synchronized makes sense hydrodynamically even in a two-dimensional physical interpretation.

- The jetting phenomenon observed with the model experiment is in favour of out-of-phase synchronization.



biomimetics

Article

On the Fluid Dynamical Effects of Synchronization in Side-by-Side Swimmers

Ramiro Godoy-Diana *, Jérôme Vacher, Veronica Raspa † and Benjamin Thiria

Biomimetics, **4**(4), 77. (In the Special issue “Fluid Dynamic Interactions in Biological and Bioinspired Propulsion”, Editors K. W. Moored and G. V. Lauder)

Illuminance-tuned collective motion

Baptiste Lafoux

Jeanne Moscatelli

Lafoux, Moscatelli, Godoy-Diana, & Thiria (2023) Commun. Bio.

Sensory mechanisms of schooling

HOW DO FISH SCHOOL ?

Vision

Partridge *et al.* (1980), McKee *et al.* (2021)

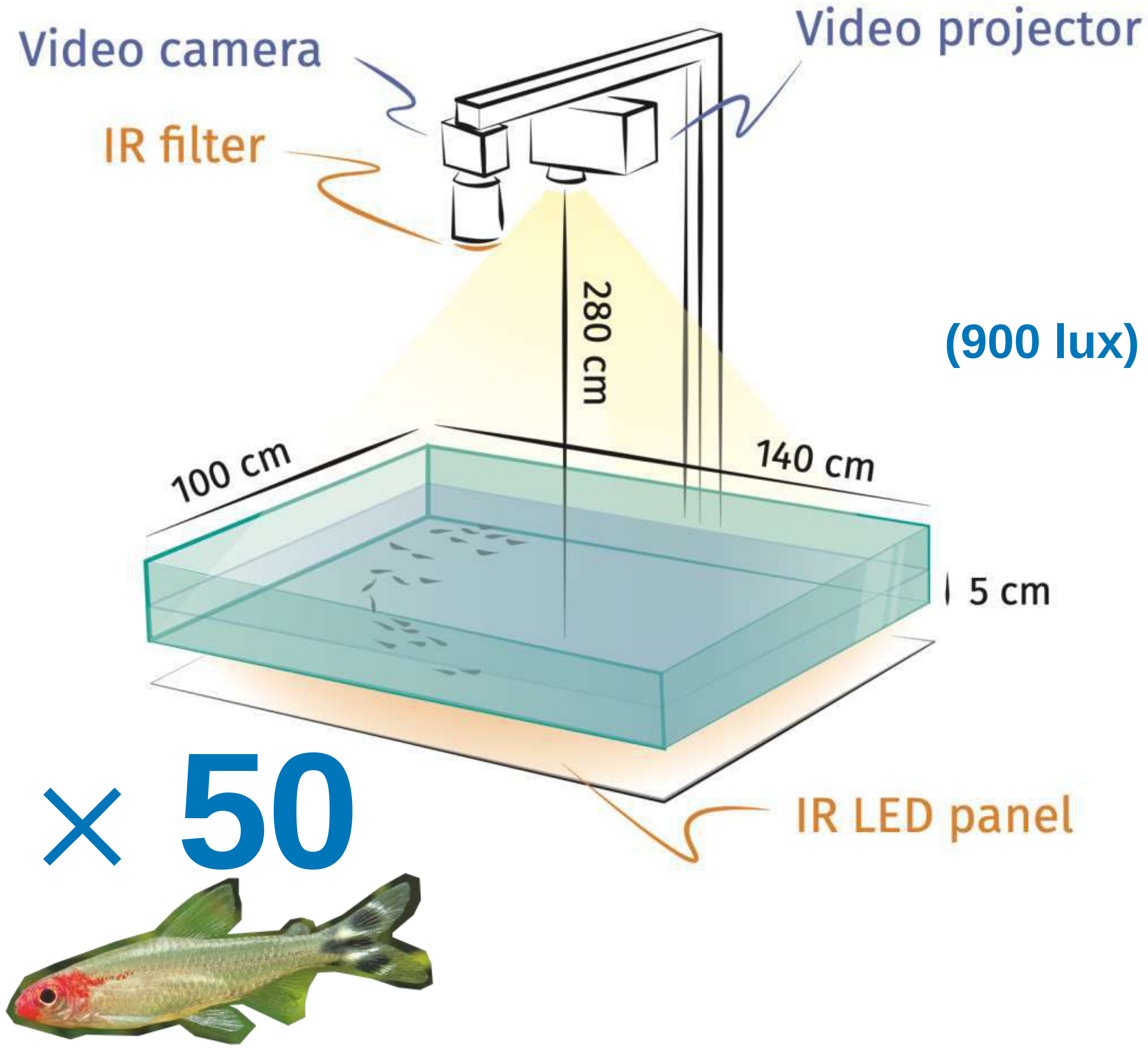
Hydrodynamic sensing

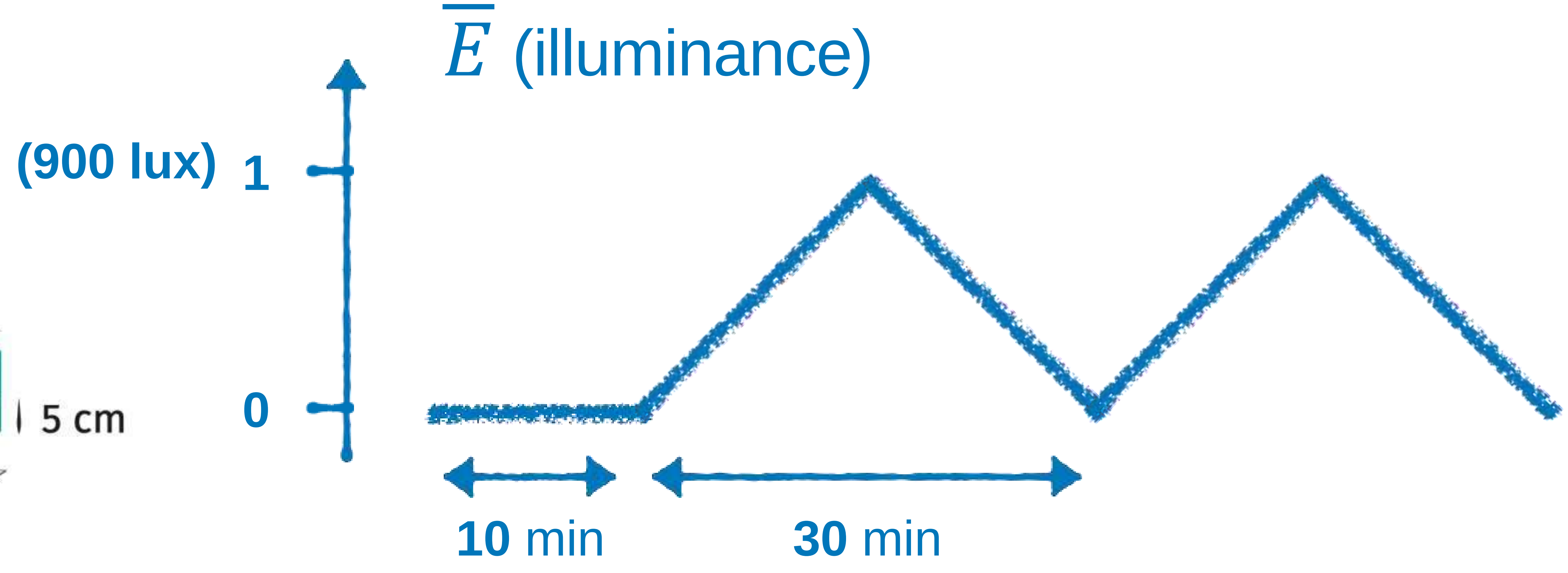
Pitcher (1976), Faucher *et al.* (2010)

also: **Chemo-olfactory, mechanosensory cues, electric signals, …**

What is the influence of **light** on **fish schooling** ?

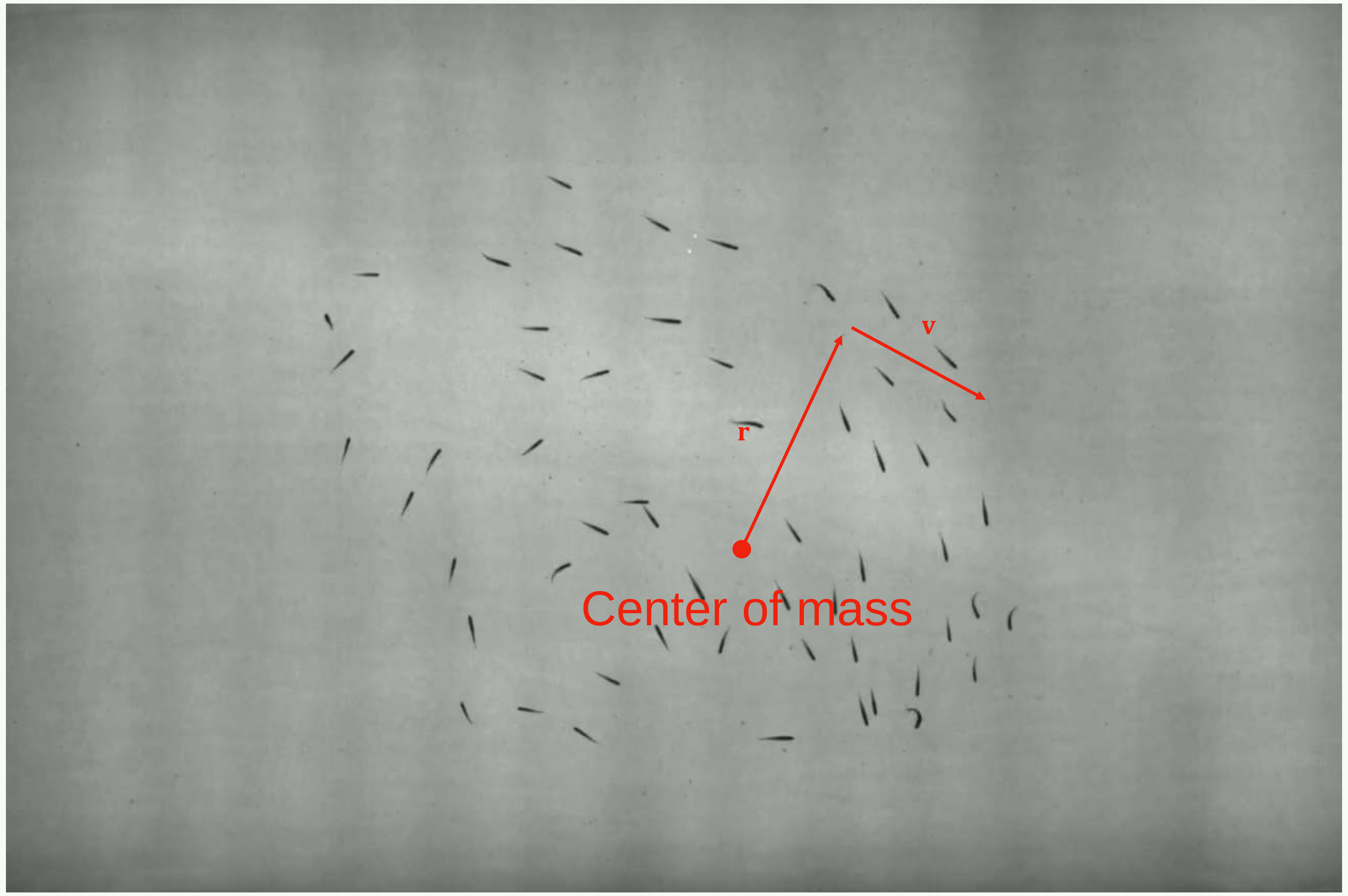
Experimental setup and procedure





Free swimming setup

Measured quantities



FastTrack
Gallois, Candelier (PLoS Comp. Bio., 2019)

- **Trajectories ($\mathbf{x}$, $\mathbf{v}$)**

- **Schooling parameters**

Milling

$$\mathcal{M} = \frac{1}{N}\left|\sum_{\text{fish}} \frac{\mathbf{v}\times\mathbf{r}}{|\mathbf{v}||\mathbf{r}|}\right|$$

Polarization

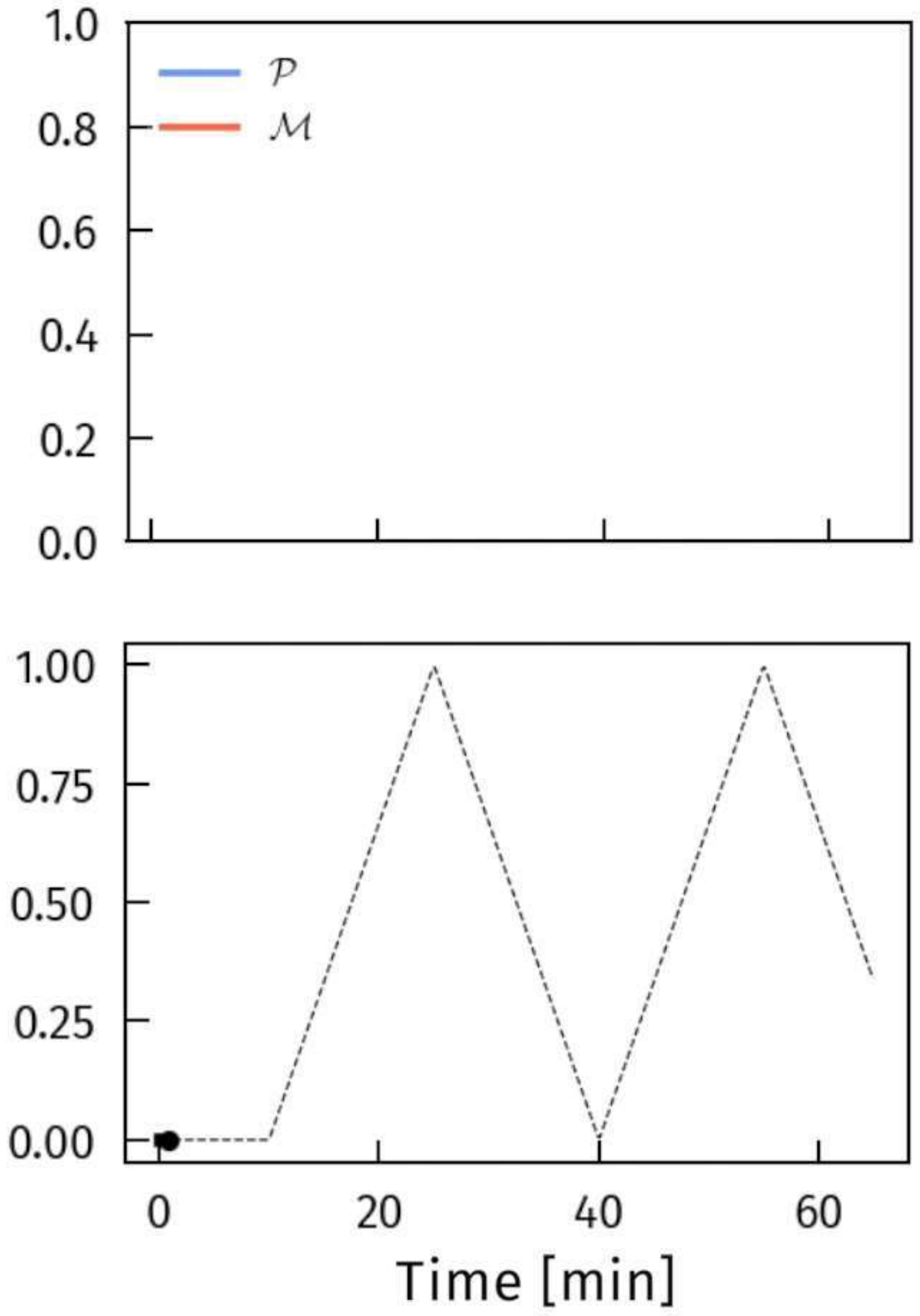
$$\mathcal{P} = \frac{1}{N}\left|\sum_{\text{fish}} \frac{\mathbf{v}}{|\mathbf{v}|}\right|$$

- **Distances**

NN-D (nearest neighbor)

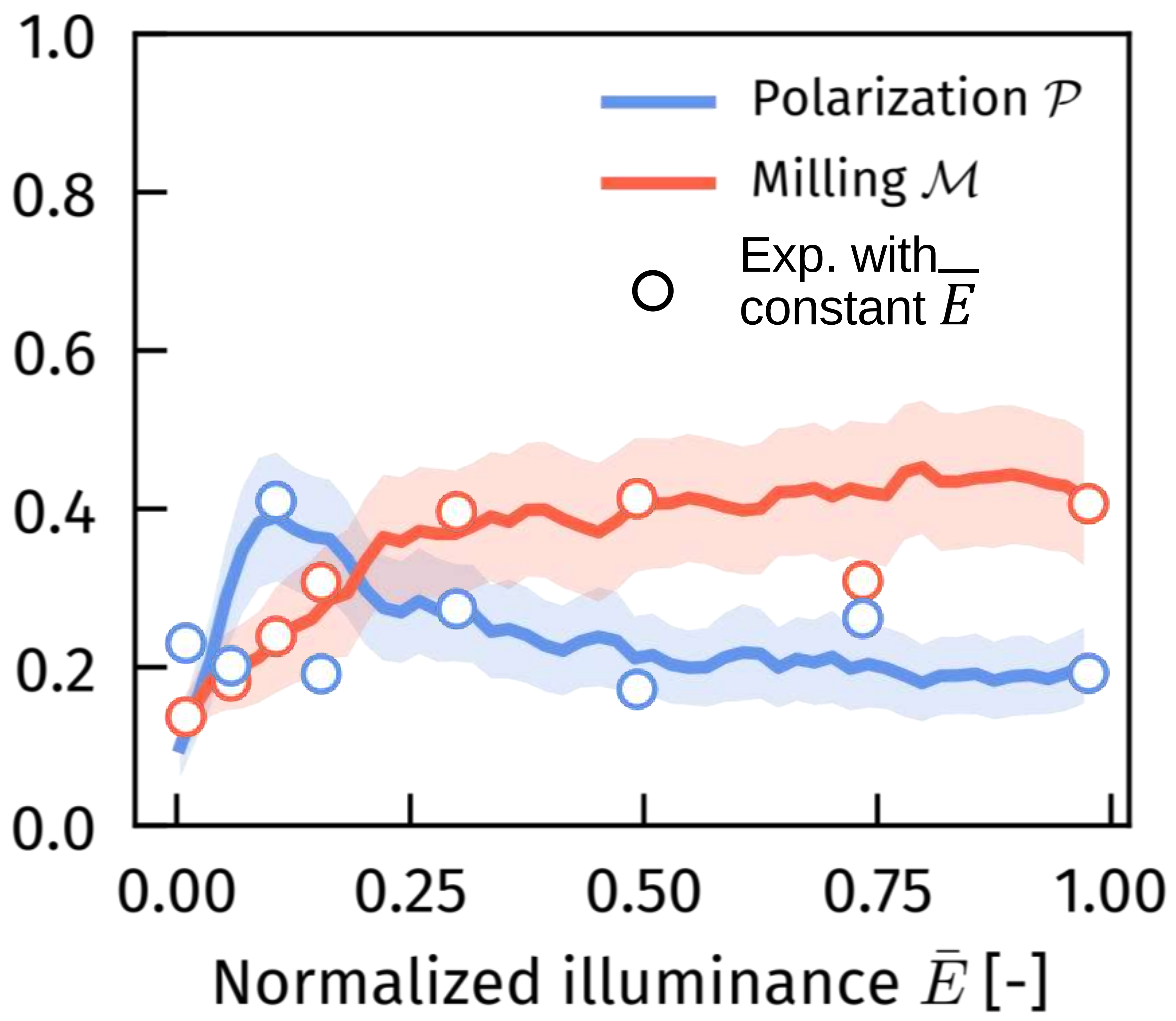
II-D (inter-individual) → average distance

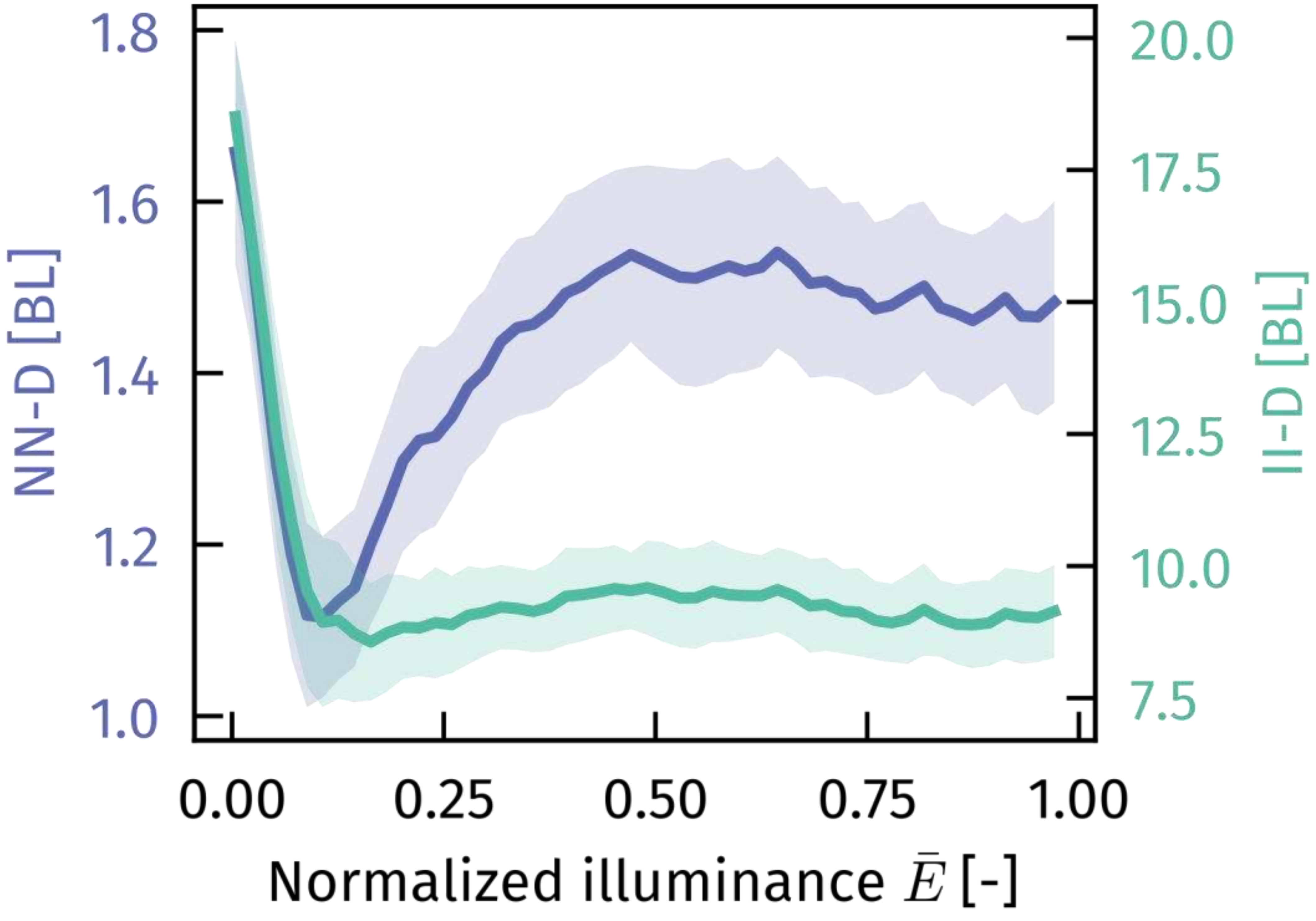
A typical experimental result



Illuminance controls the collective state

AND THE TOPOLOGY OF THE GROUP





Conclusion on illuminance

WHAT DID WE LEARN ?

- lateral line sensing is here insufficient to school
- **order parameters** (= intensity of schooling) scale with **illuminance**
- fish **adapt the topology** of the school as illuminance increases

By gradually altering vision,
we were able to trigger a collective state transition

Perspective

What is the relationship light / vision ?

Perspective — light/vision

NUMERICAL SIMULATIONS - EXTENSION OF THE CUCKER-SMALE MODEL

with
Nastassia Pouradier Duteil (LJLL)

$$\underline{F}_i^{\mathrm{prop}} = \frac{1}{\tau}\left(1 - |\underline{v}_i|^2/v_0^2\right)\underline{v}_i$$

Auto-propulsion

$$\underline{F}_i^{\mathrm{att}} = a \sum_{j \in \mathrm{visible}} \frac{\underline{r}_{ij}}{|\underline{r}_{ij}|} - \frac{R_a^2 \underline{r}_{ij}}{|\underline{r}_{ij}|^3}$$

Attraction - repulsion

$$\underline{F}_i^{\mathrm{ali}} = -J \sum_{j \in \mathrm{visible}} \underline{v}_i - \underline{v}_j$$

Alignment

What could be modified by light

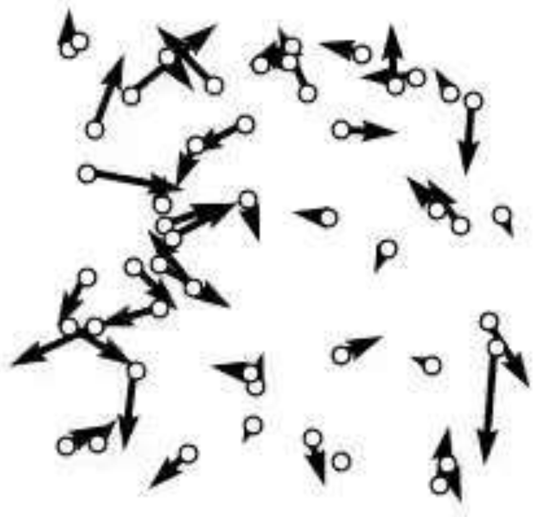
- interaction range
- interaction angle
- topological interaction distance

Niwa (J. Theor. Biol., 1994)

Perspective — light/vision

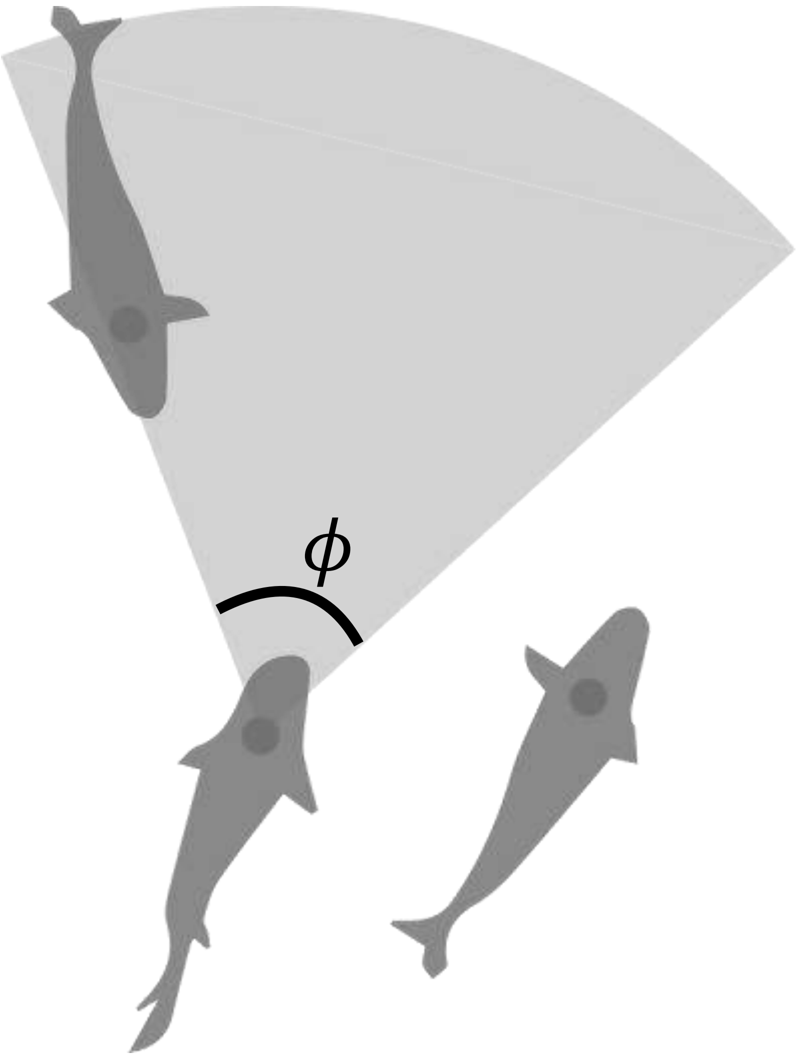
NUMERICAL SIMULATIONS — N = 50 AGENTS

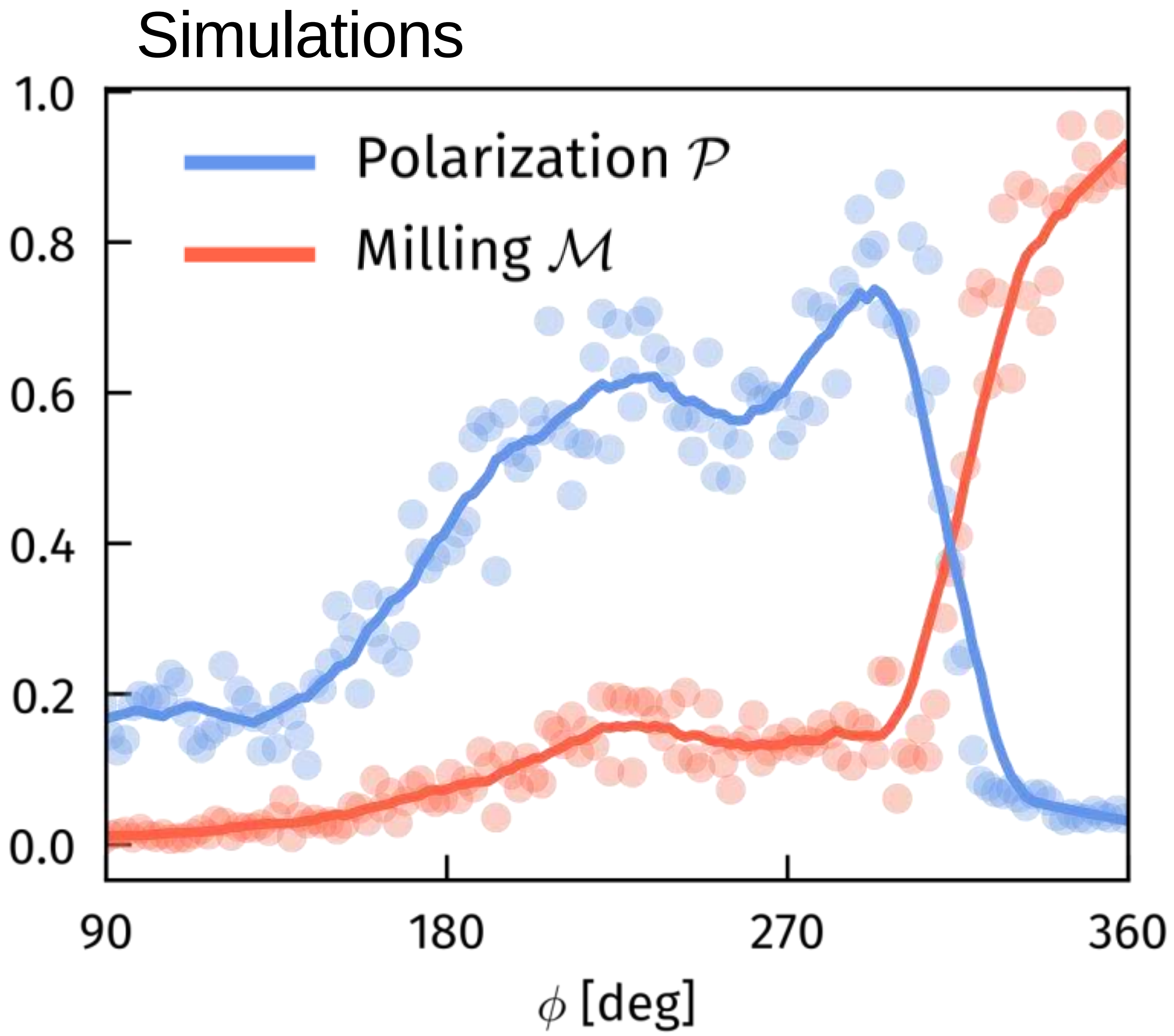
$\tau = 0.02 | J = 0.05$



$\tau = 1 | J = 0.05$

$\tau = 1 | J = 0.3$





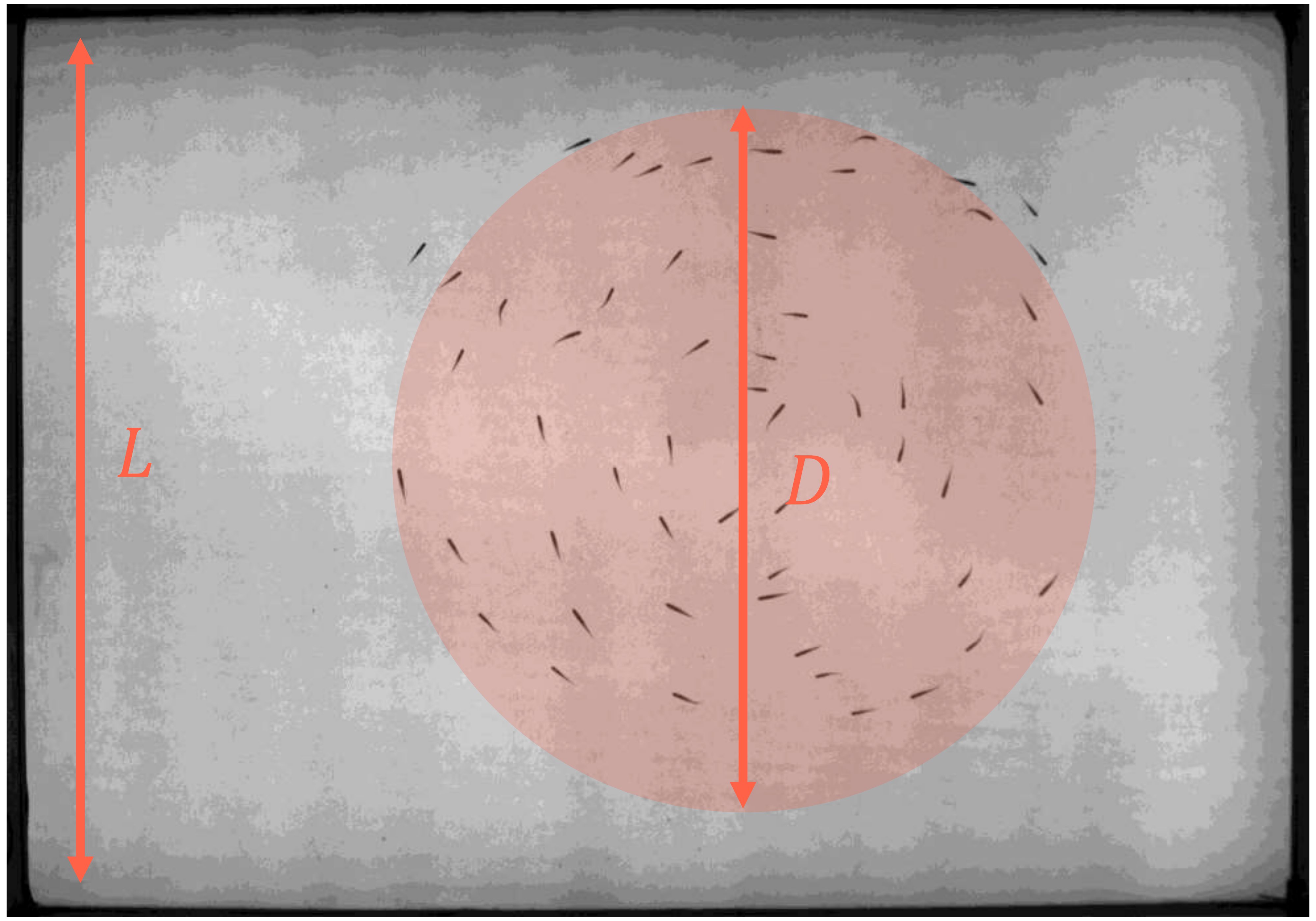
Confinement-driven state transitions

Baptiste Lafoux

Paul Bernard

Lafoux, Bernard, Thiria, & Godoy-Diana (2023) *Under review*

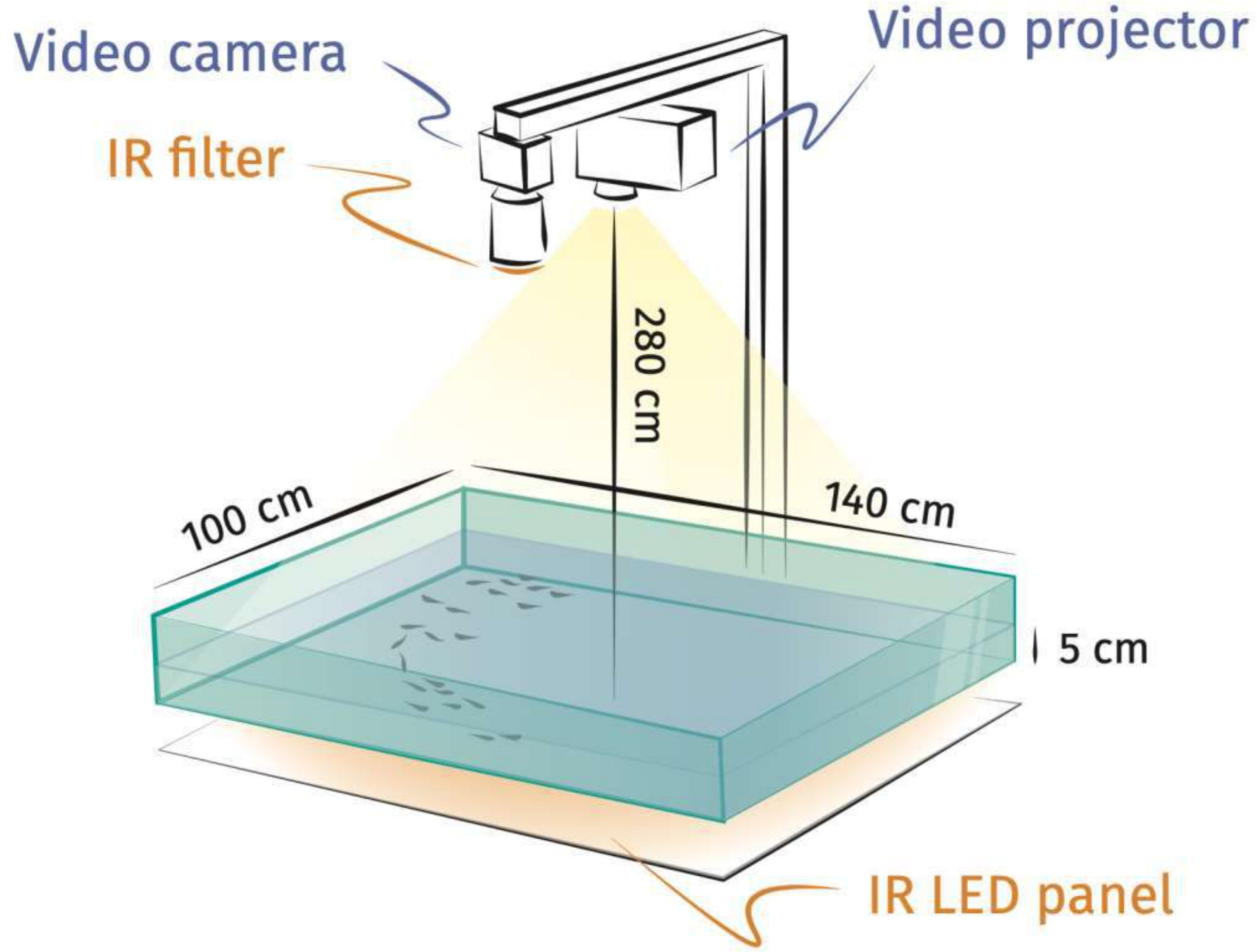
Confinement



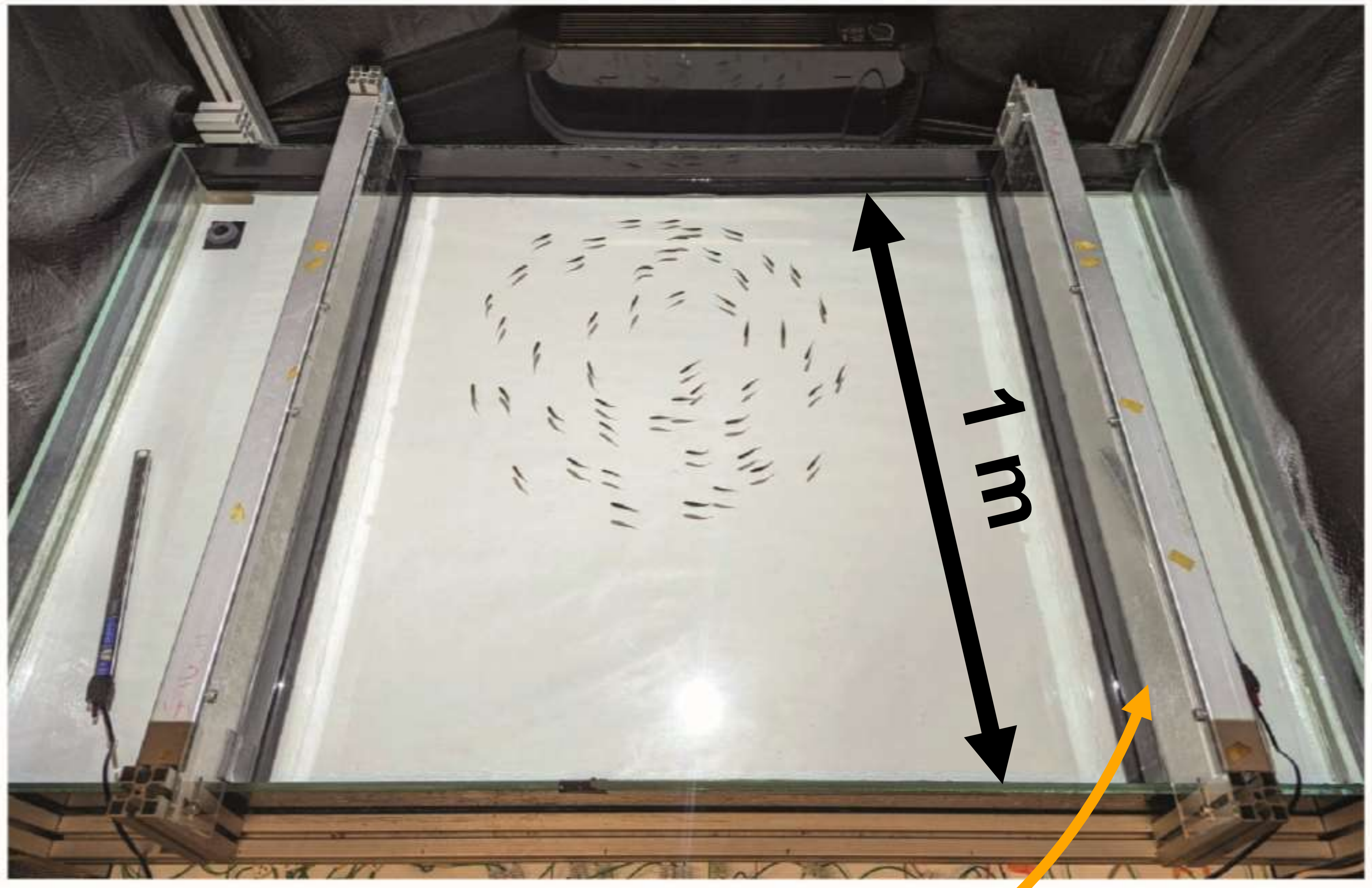
$D \approx L$

What is the influence of **confinement** on **collective state transition** ?

Experimental setup



$\times$ **10-70**



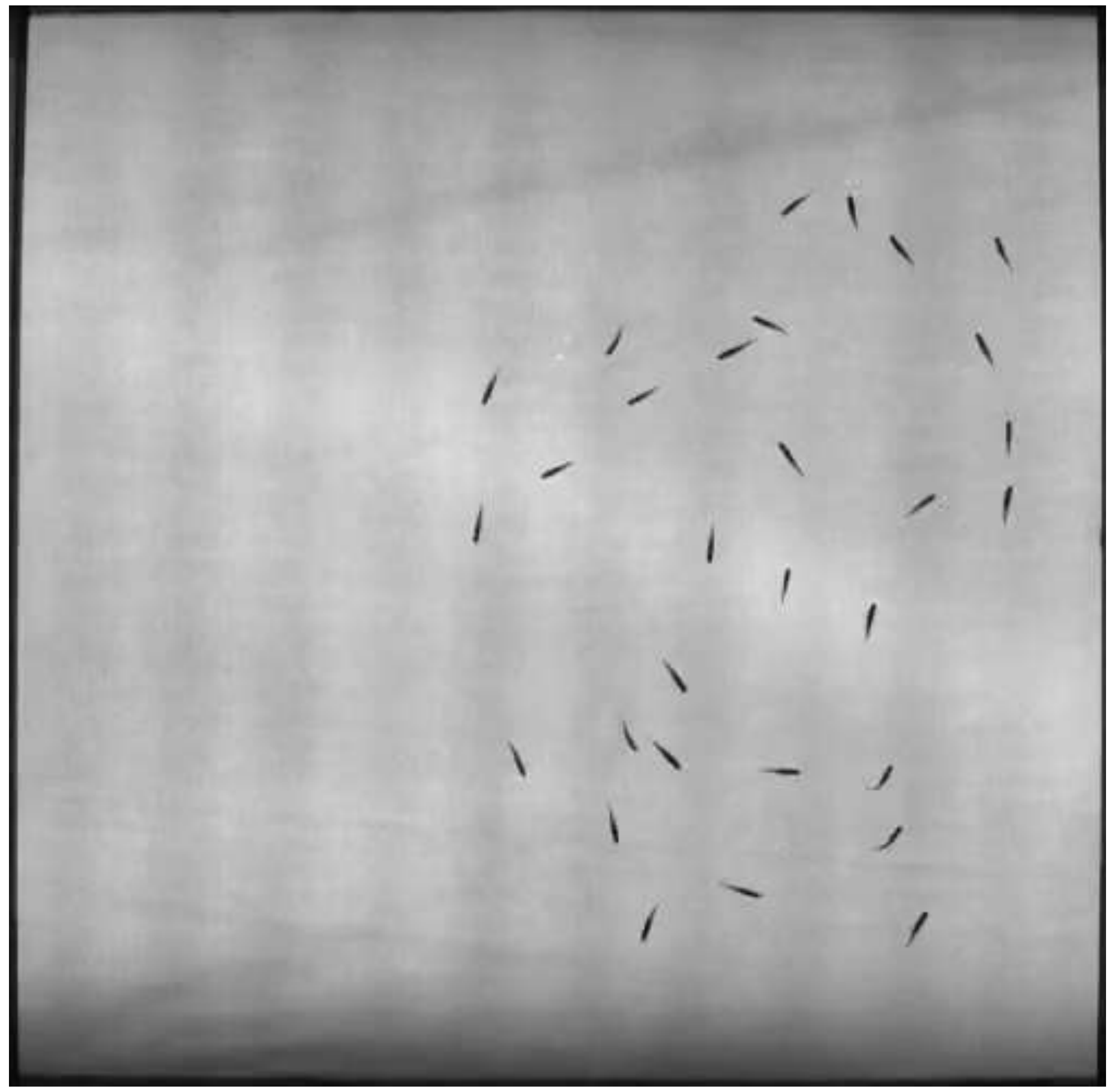
Movable partition wall

S = [0.25, 0.5, 1] m^2

A typical result — bistable state

▶▶ ×10

N = 30 fish
S = 1 m^2

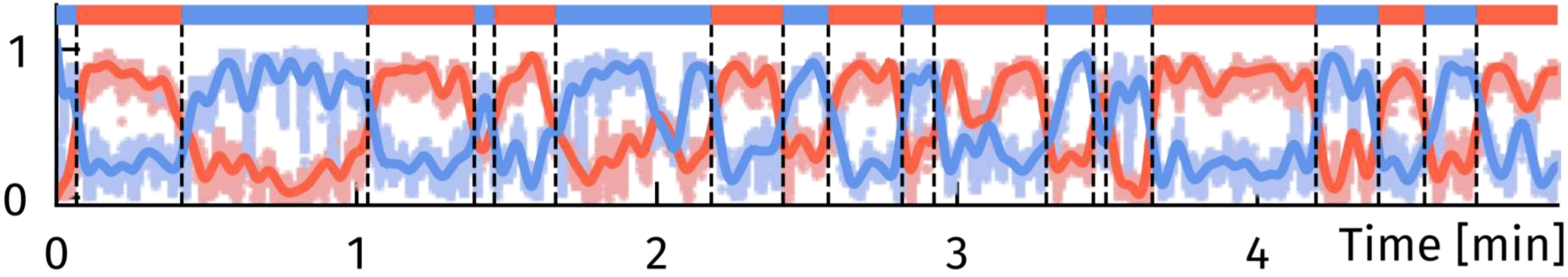


Experimental conditions

- 15 min free-swimming
- High illuminance

$|\mathcal{M}| > 0.5$

$\mathcal{P} > 0.5$

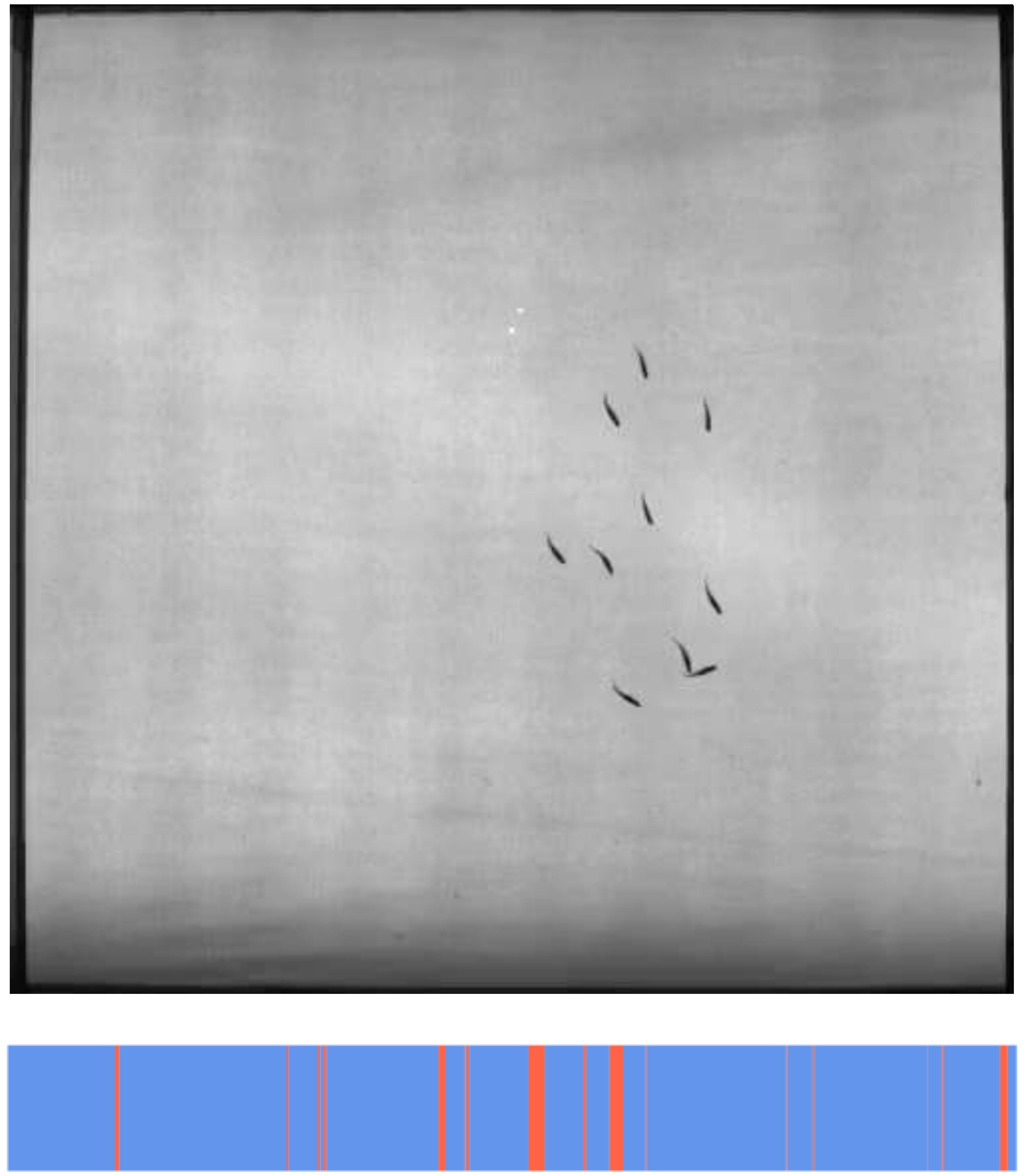


Role of the school size N

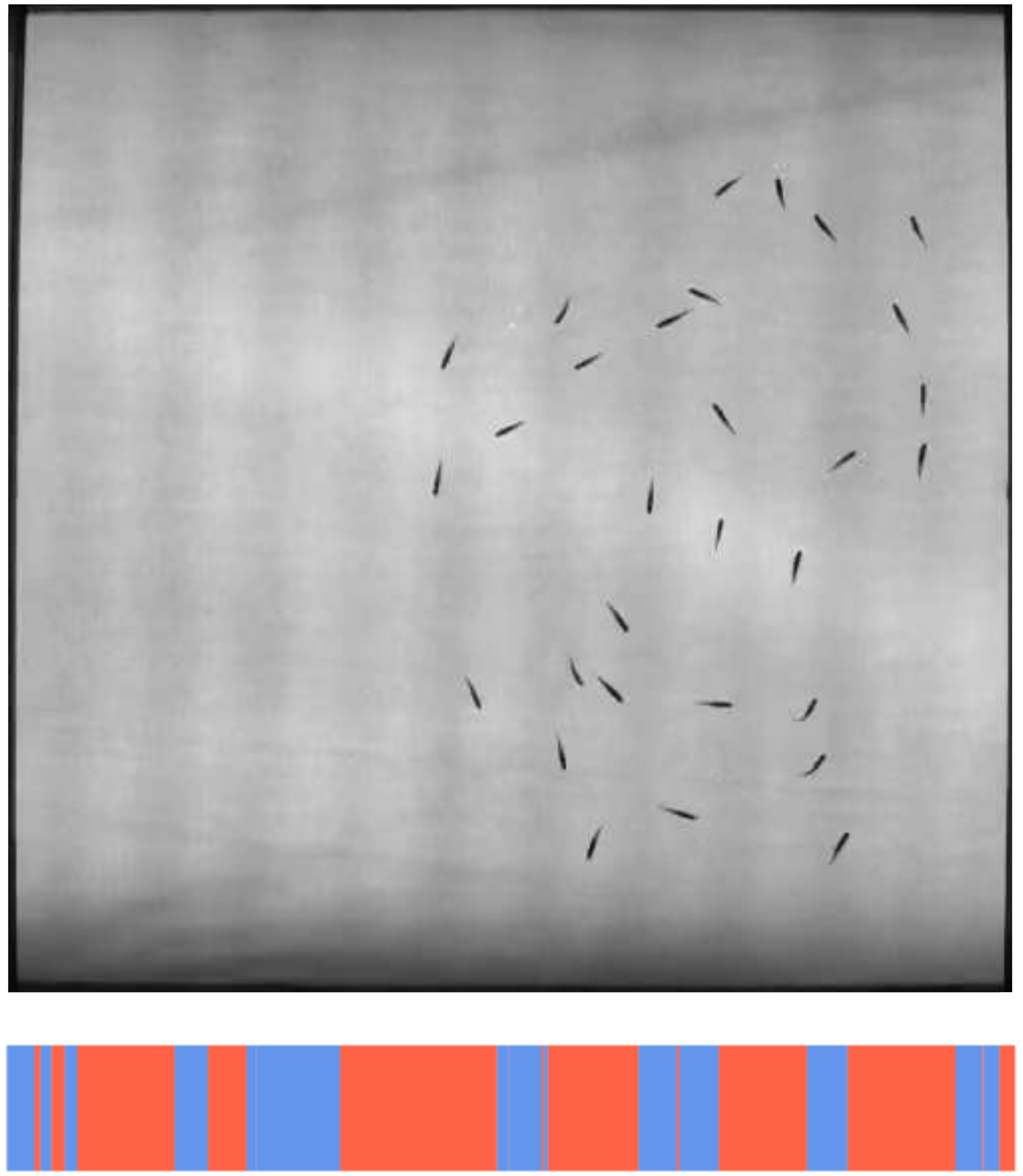
▶▶ ×10

S = 1 m^2

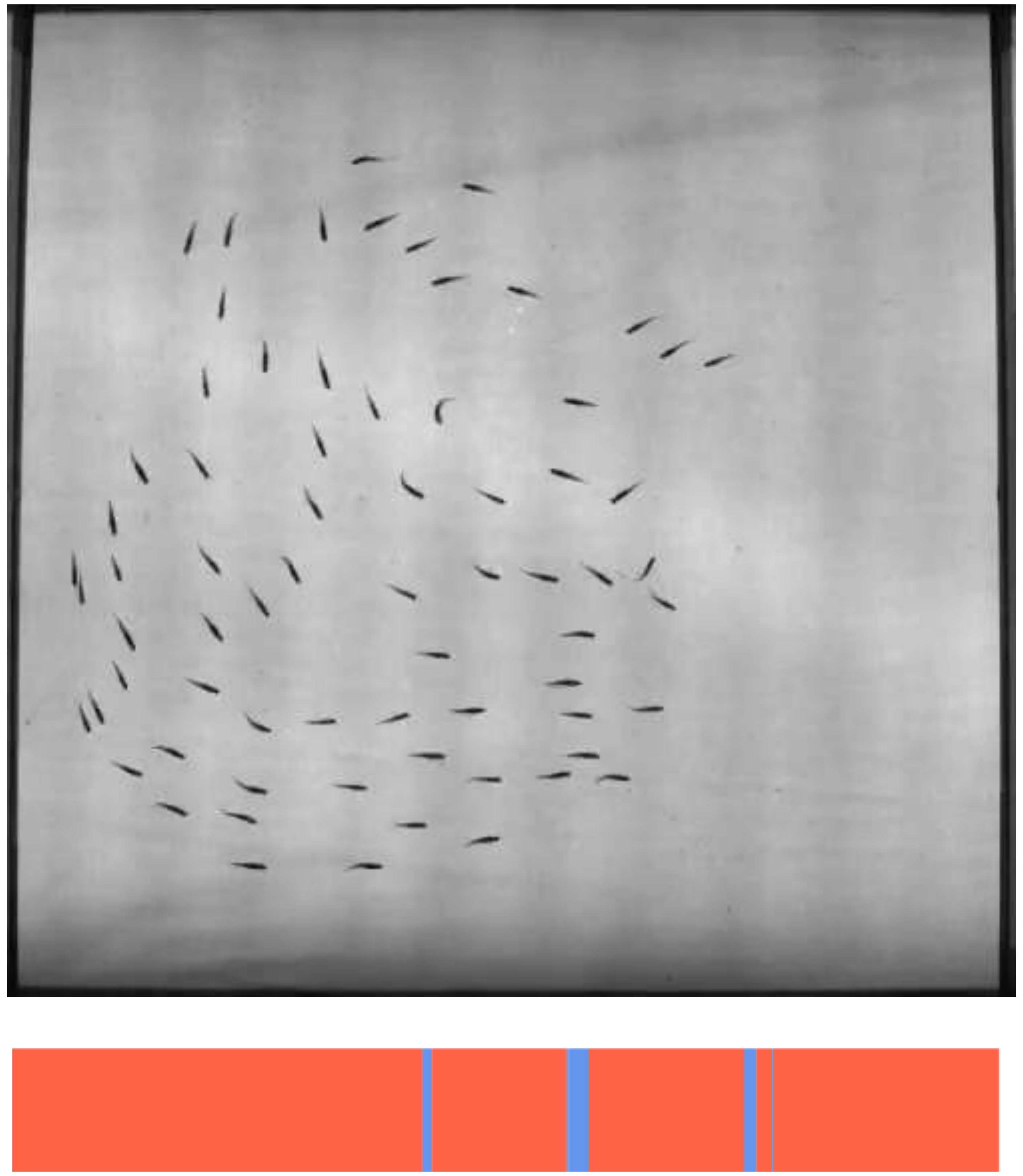
N = 10



N = 30



N = 70



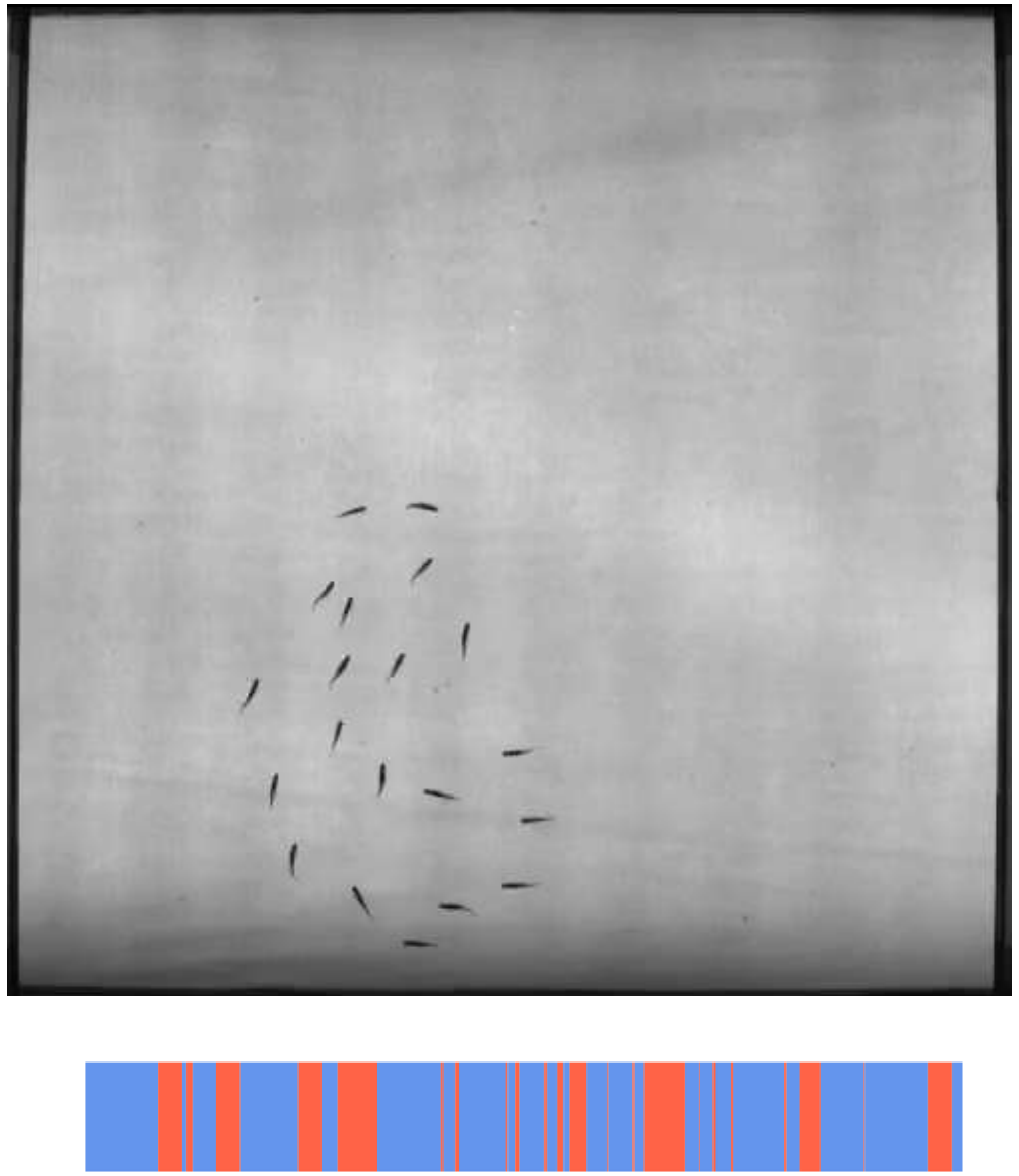
Polarized state   Milling state

Role of the swimming area S

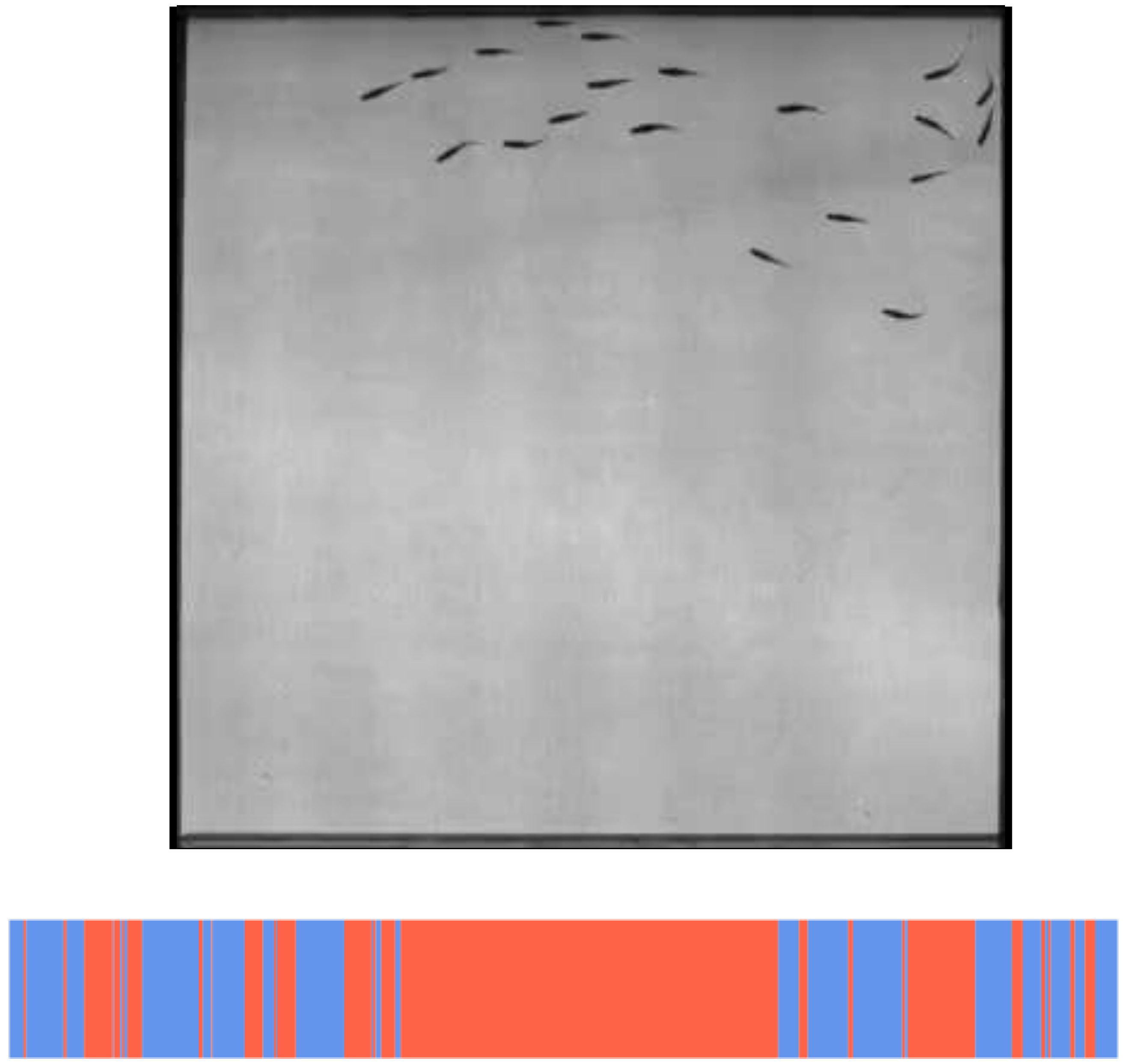
×10

N = 20 fish

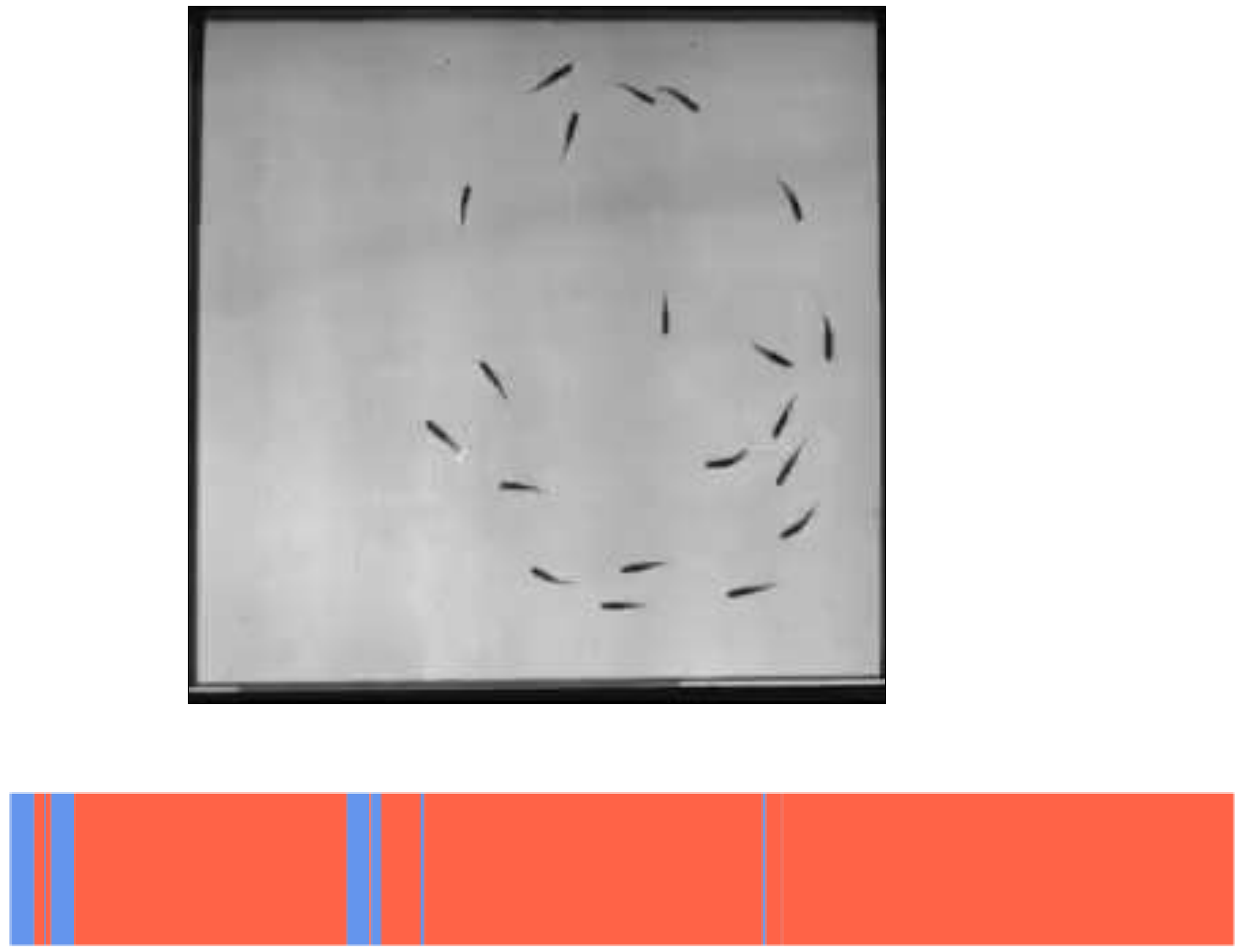
S = 1 m²



S = 0.5 m²



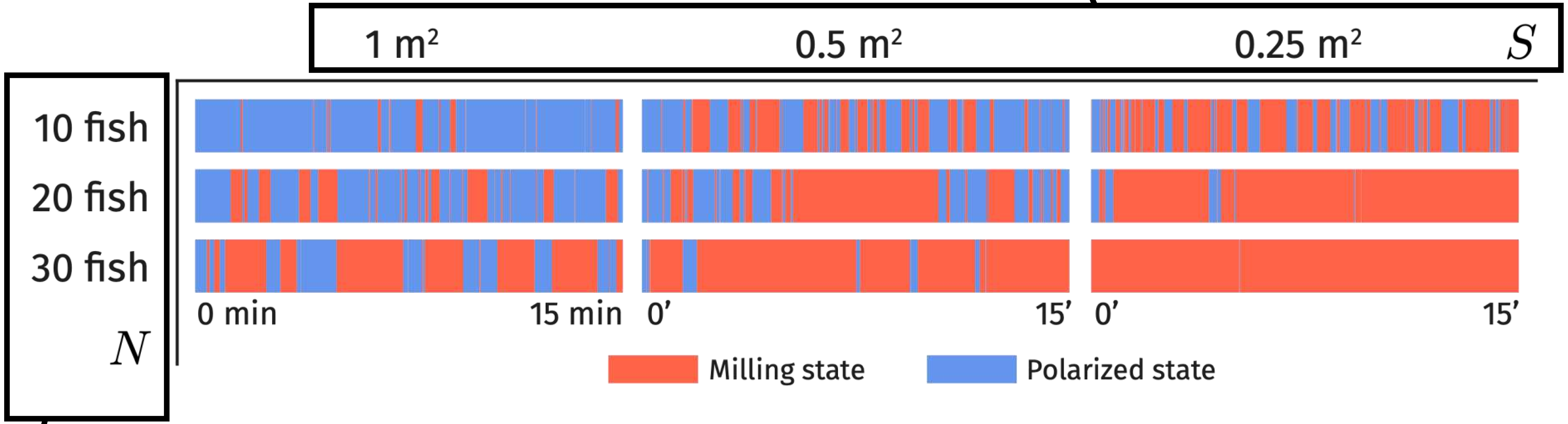
S = 0.25 m²



Polarized state   Milling state

A state diagram

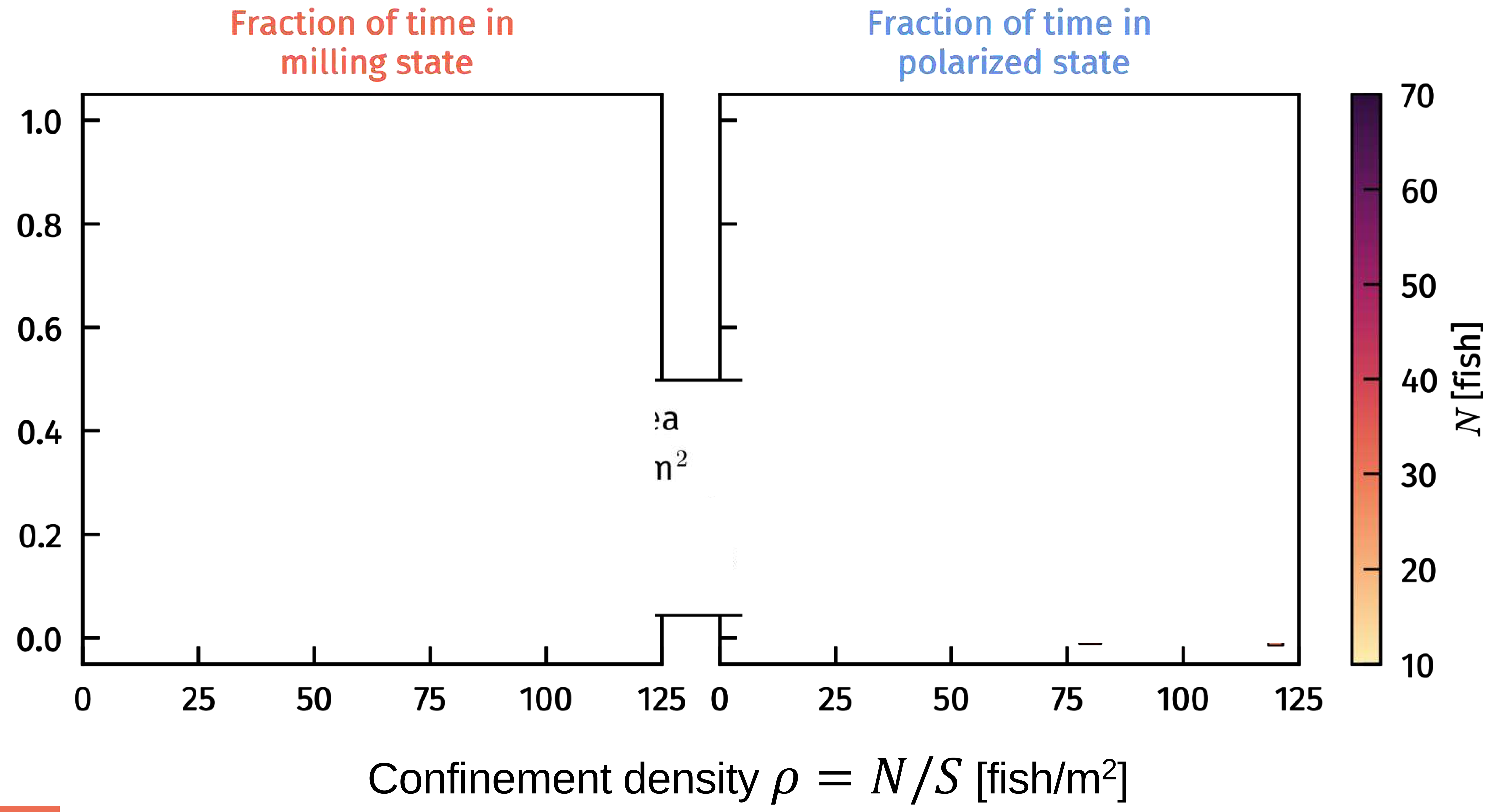
Role of S
New



Role of N
Becco *et al.* (Physica A, 2005)
Tunstrøm *et al.* (PLOS Comp. Bio., 2013)

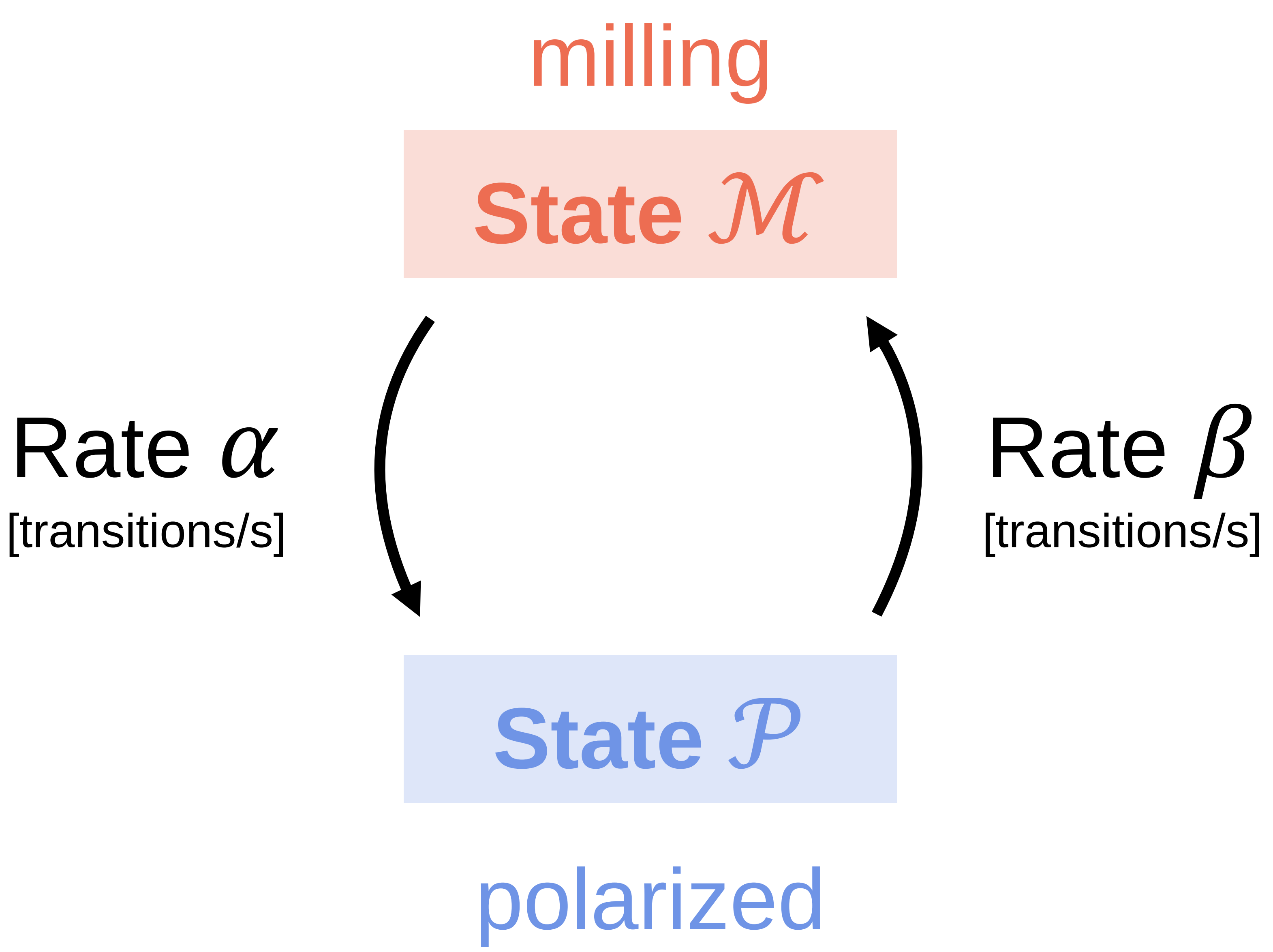
Role of **confinement density** ?
$\rho = N/S$

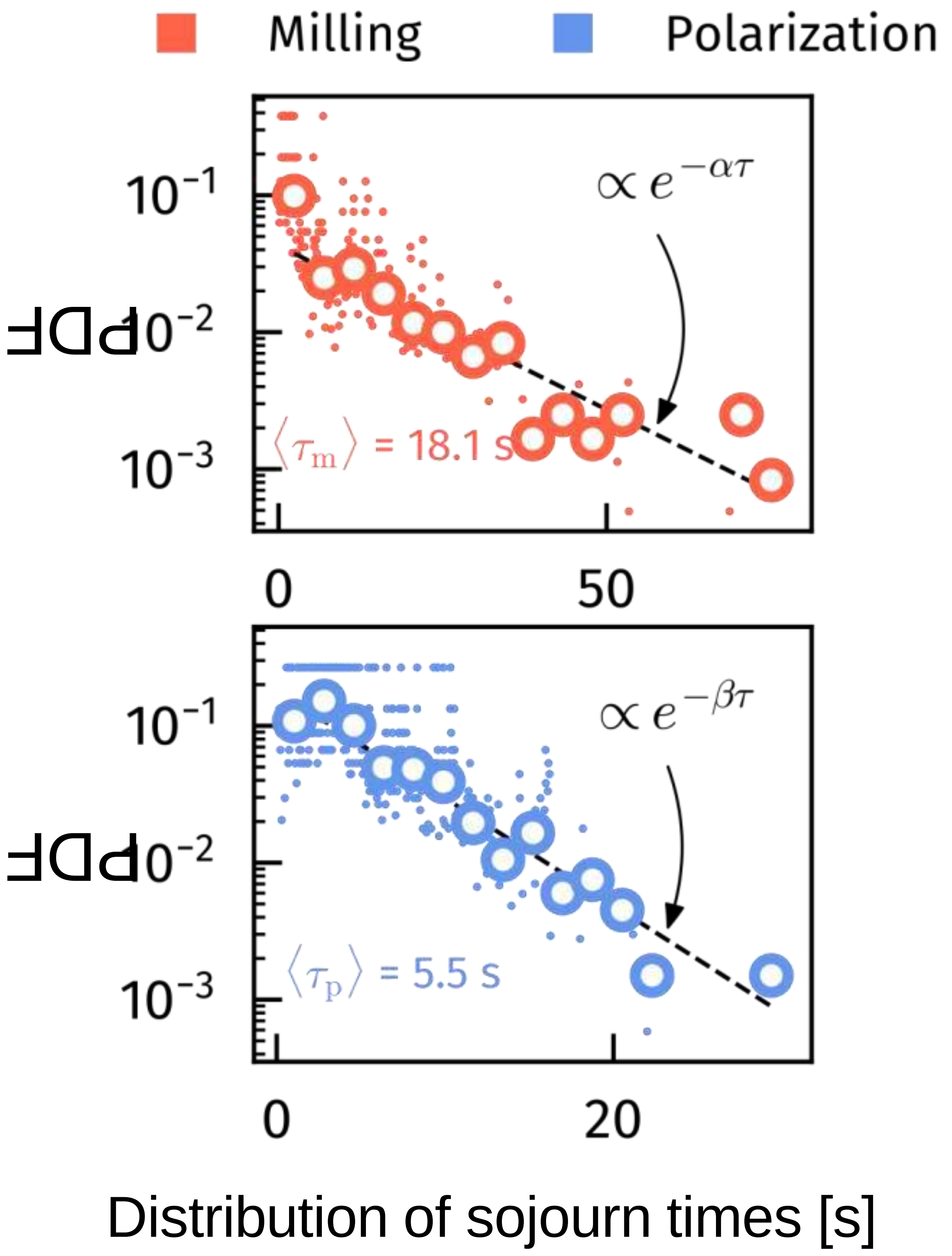
Confinement density $\rho = N/S$ controls the transition

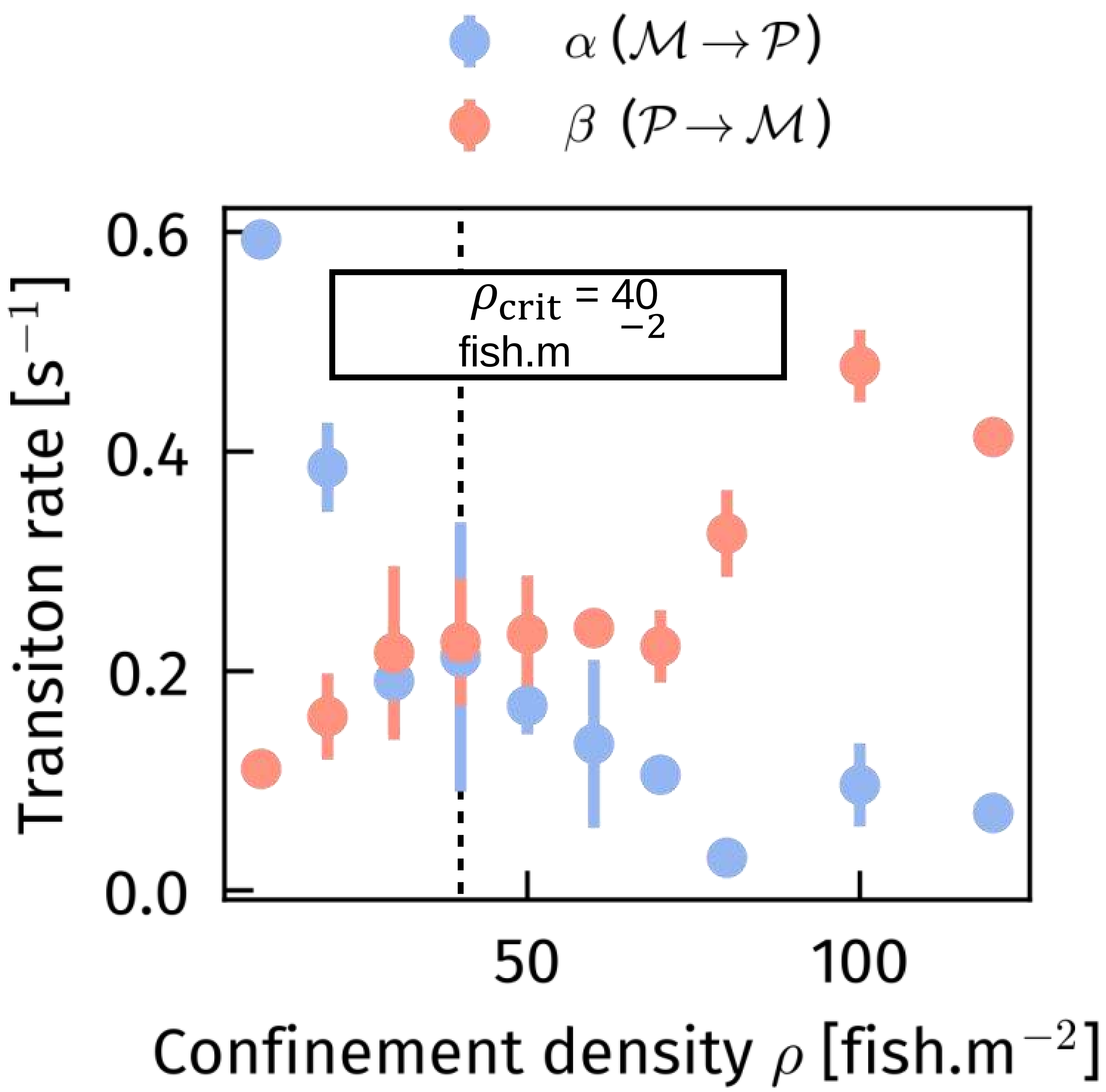


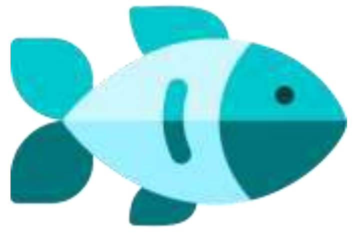
Each (N, S) = 3 replicates
77 experiments (15')

A simple 2-states model





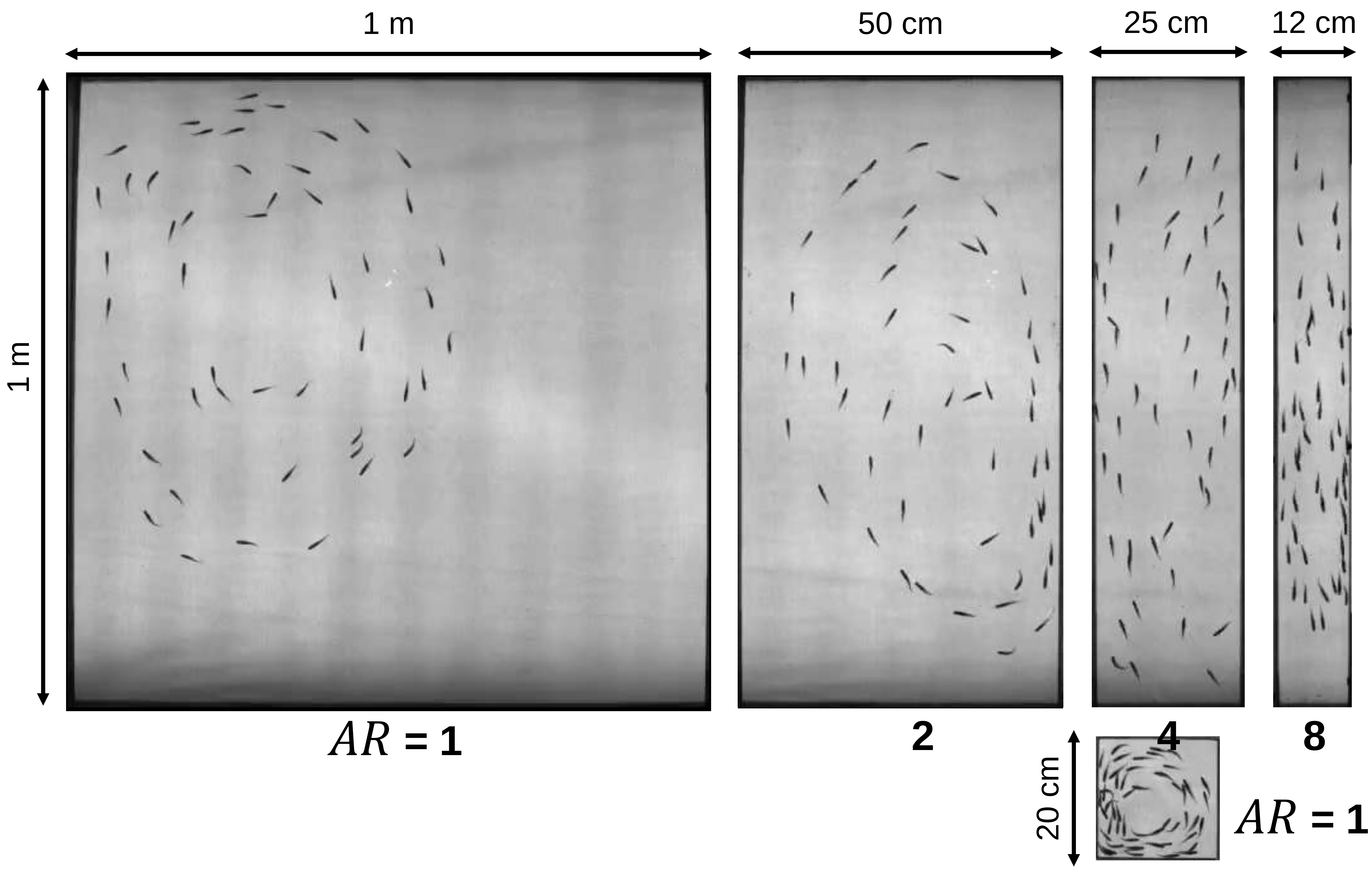


> Fits a  distribution !

Role of the aspect ratio AR

▶▶ ×10

N = 50 fish



Conclusion on confinement

- $\rho = N/S$ shapes the $\mathcal{P} \leftrightarrow \mathcal{M}$ transition statistics
- The **shape of the swimming area** is also key
- Walls/confinement is a crucial parameter in collective state transition

Confinement is able to trigger collective state transition,
N and S have an comparable role

Perspective

How is a school confined in the wild ? Is this state transition useful ?

Perspective — Confinement and predation

Whales bubble-net hunting

University of Hawaii

Dolphins mud rings

Ramos *et al.* (Marine Mammal Science, 2022)

→ Bistability (criticality) can be an advantage

Is « predator confinement » of the same as wall confinement ?

General conclusion

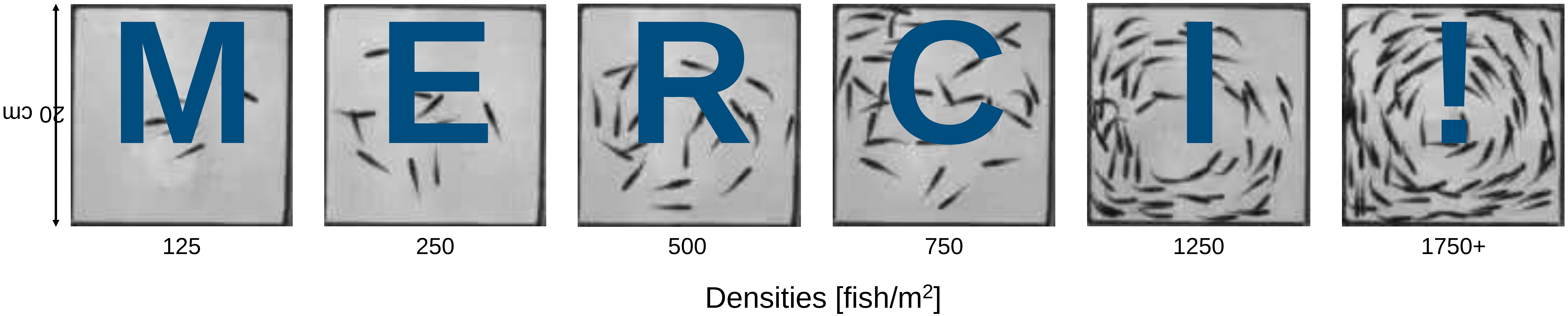
Conclusion

How do **perturbations** of the environment influence **collective motion**?

Continuous collective state transitions & **school organization are influenced**:

- by an **imposed external flow** (hydrodynamics)
- by altering **inter-individual interactions** (vision)
- by altering **domain boundaries** (confinement)

→ offers novel ingredients for **modelling interactions** in **collective motion**


MERCI!
20 cm
125
250
500
750
1250
1750+
Densities [fish/m^2]