When poor little fish meet AI, VR, robots, and drones!

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F. Mondada, *V. Papaspyros* (EPFL): AI, LureBot

P. Mitra (CSHL): AI without networks

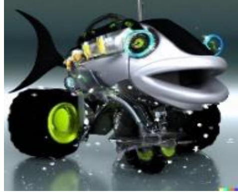
S. Sanchez (IRIT), R. Bastien (CRCA): VR for Fish

L. Lei (University of Shanghai): Cuboid Robots

G. Hattenberger, M. Verdoucq (ENAC): Drones

Collective motions of animals and robots – 27-31 May 2024 – Cargèse

Outline

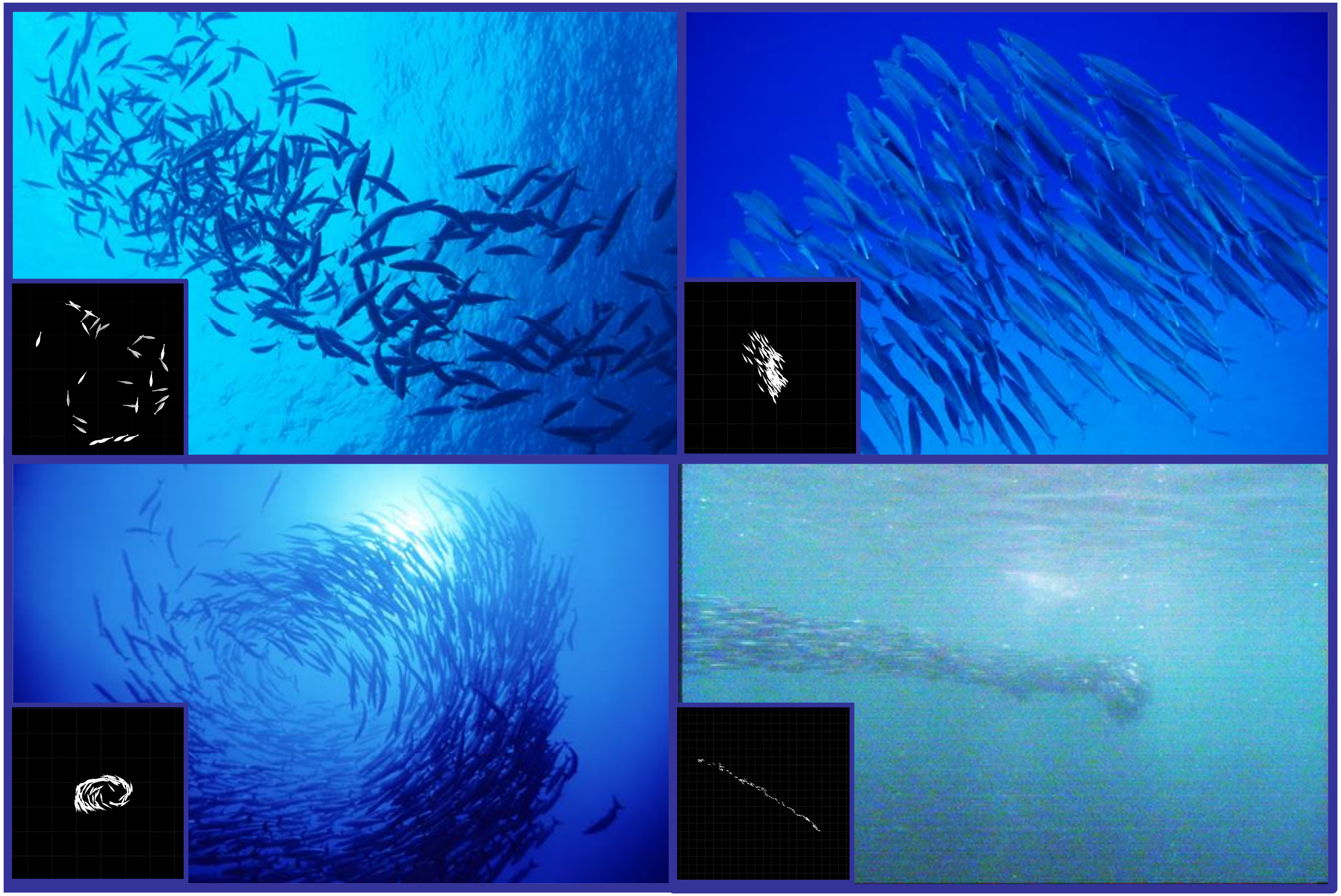


- **Generative models for collective motion**
  - Analytical models exploiting the reconstruction of the interactions with obstacles and conspecifics (+simplified interaction with the fluid)
  - Machine learning models trained on real trajectories
  - Kernel interpolation models

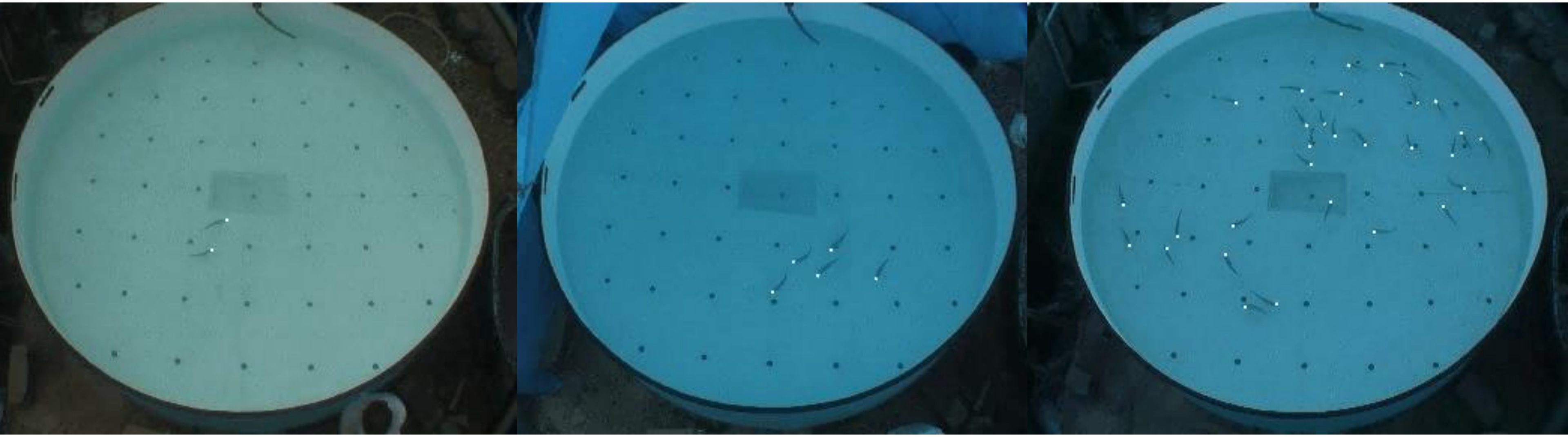
- **3 applications of generative models**
  - The LureBot
  - VR for fish
  - Drones

Collective motion in fish schools

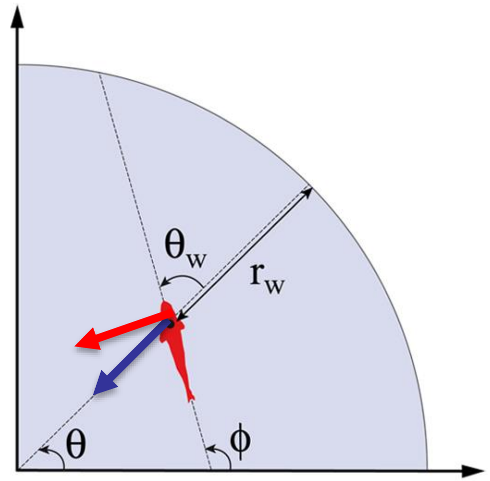
Swarming, schooling, milling



Measuring social interactions



How to measure the fish interaction with the wall?



$$\delta\phi = \delta\phi_{\mathrm{Random}} + \delta\phi_{\mathrm{W}}$$

$$\delta\phi_{\mathrm{W}} = f_{\mathrm{w}}(r_{\mathrm{w}}) \times O_{\mathrm{w}}(\theta_{\mathrm{w}})$$

where $O_{\mathrm{w}}(\theta_{\mathrm{w}}) \sim \sin(\theta_{\mathrm{w}})$ is an *odd* function of θ_{w}

Minimize $\Delta = \sum_{n=1}^{\#\,\mathrm{data}} [\delta\phi_n - f_{\mathrm{w}}(r_{\mathrm{w},n}) O_{\mathrm{w}}(\theta_{\mathrm{w},n})]^2$

(tabulating f_{w} and O_{w} on a grid for the r_{w} and θ_{w} variables)

PLOS Comp. Biol. 2018
Phil. Trans. 2020

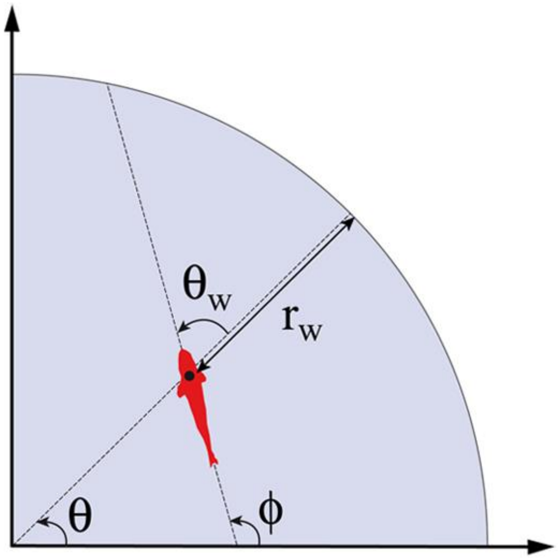
Measuring interactions for Hemigrammus

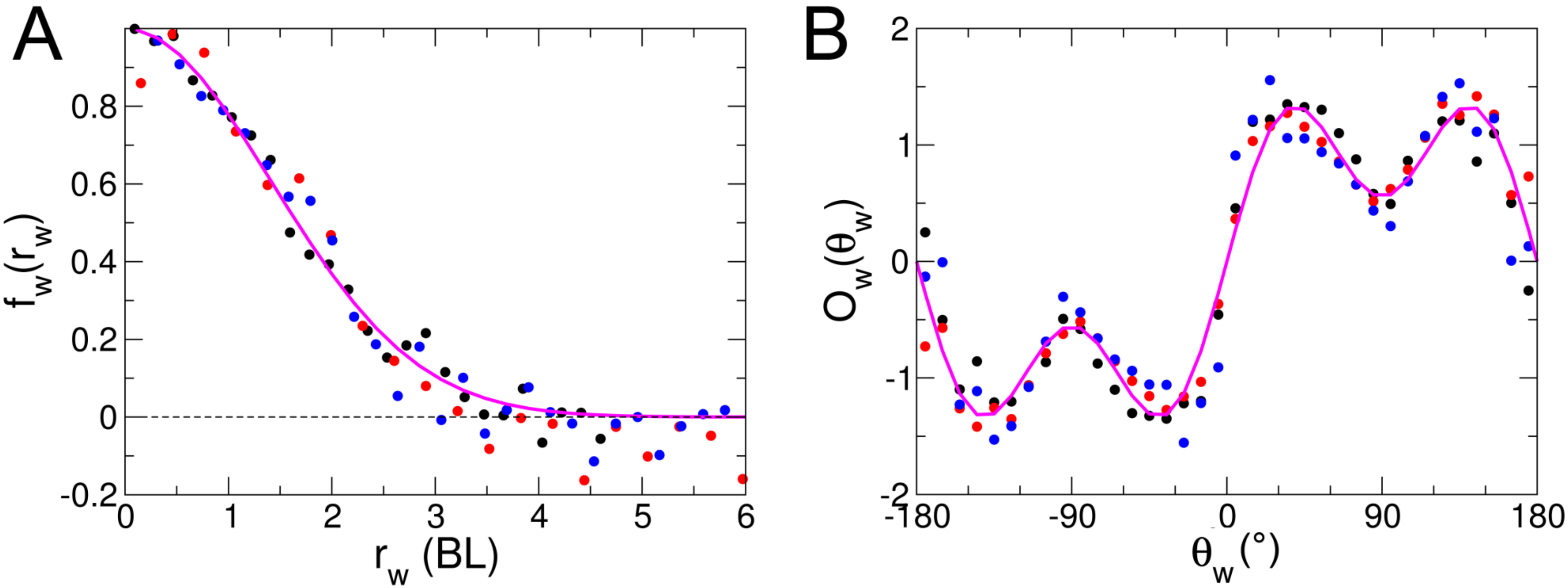
Interaction with the wall

$$\delta\phi_W = f_w(r_w) \times O_w(\theta_w)$$

$$f_w(r_w) \propto \exp[-(r_w / l_w)^2], \; l_w \approx 2\,\mathrm{BL} \sim 60\,\mathrm{mm}$$

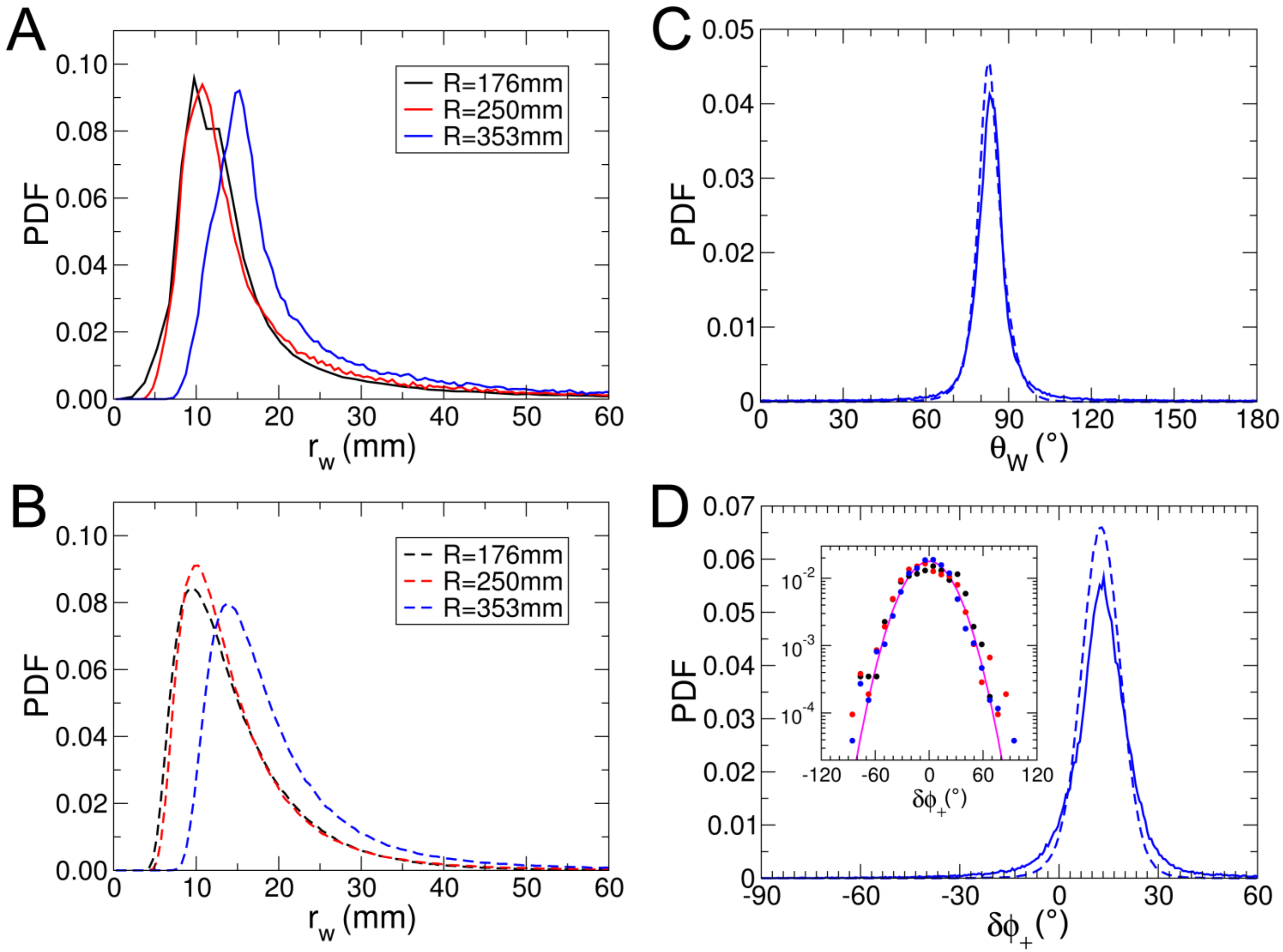
$$O_w(\theta_w) \propto \sin\theta_w [1 + \epsilon_2 \cos 2\theta_w], \; \epsilon_2 \approx 0.7$$





1-fish experiments vs model (dashed lines)

PDF of the distance to the wall (3 arenas; A & B); for R=353 mm, PDF of the angle to the wall (C) & PDF of the angle change (D)



Measuring interactions in Hemigrammus

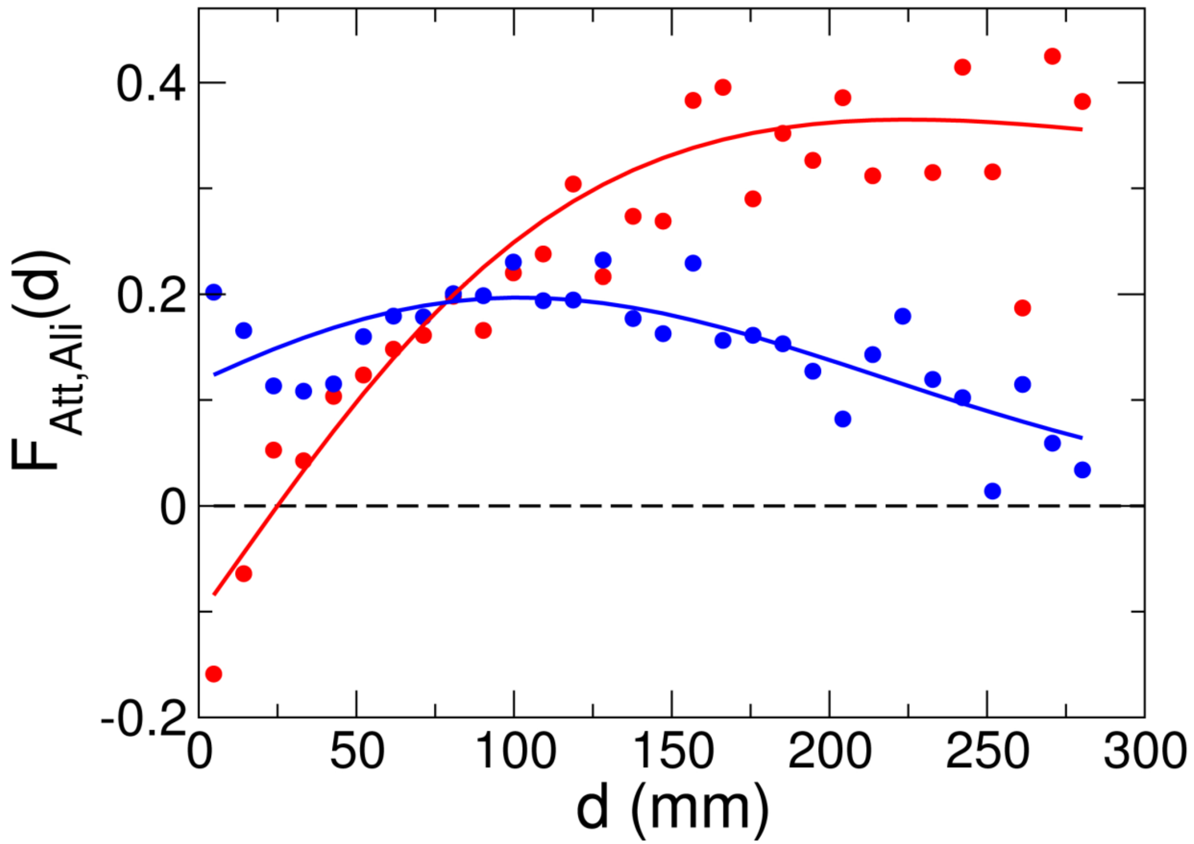
Attraction and *alignment* interactions between fish *vs* their distance

$$F_{\mathrm{Att}}(d) \propto \frac{(d-a)/l_{\mathrm{Att}}}{1+(d/l_{\mathrm{Att}})^2}, \qquad F_{\mathrm{Ali}}(d) \propto \left(\frac{d}{l_{\mathrm{Ali}}}+c\right)\exp[-(d/l_{\mathrm{Ali}})^2]$$

$$l_{\mathrm{Att}} \approx l_{\mathrm{Ali}} \approx 200\,\mathrm{mm}$$

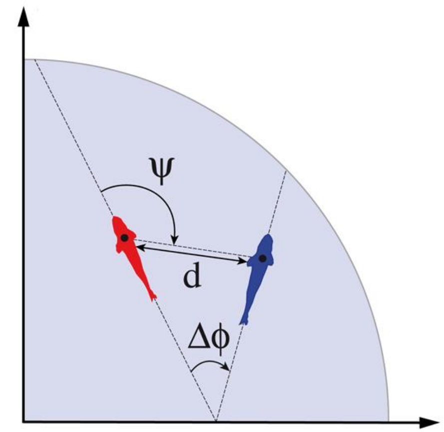
$$a \approx 1\mathrm{BL} \approx 30\,\mathrm{mm}$$

$$c \approx 0.4$$



Measuring interactions in Hemigrammus

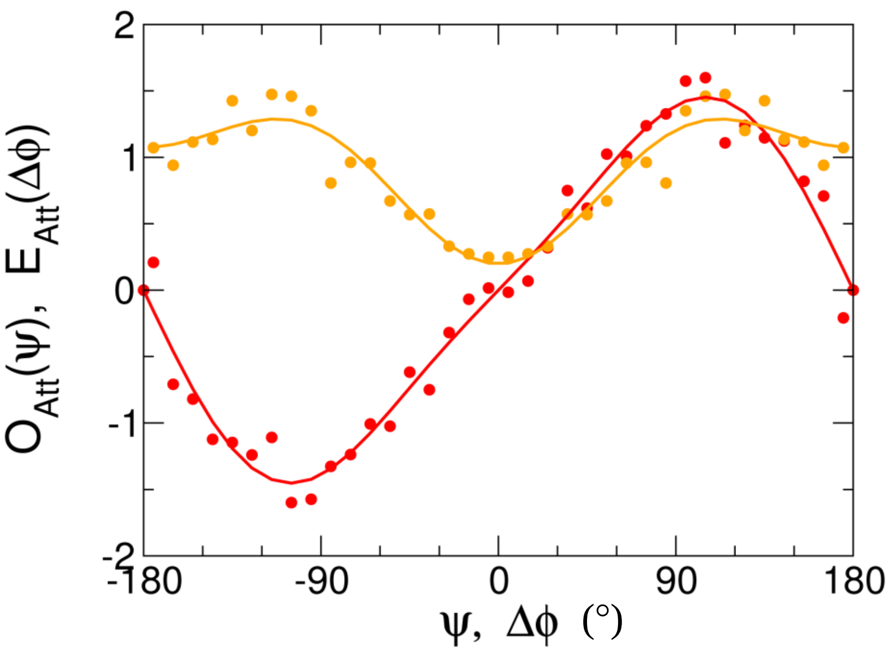
Attraction and ***alignment*** **interactions between fish**
vs **viewing angle and relative heading**

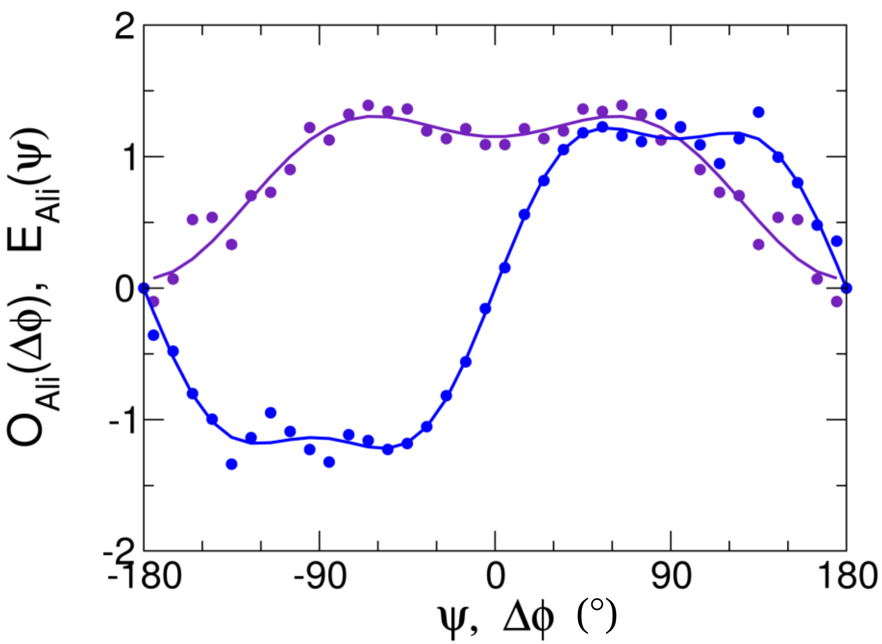


$$\delta\phi_{\mathrm{Att}} = F_{\mathrm{Att}}(d)\,O_{\mathrm{Att}}(\psi)\,E_{\mathrm{Att}}(\Delta\phi)$$

$$\delta\phi_{\mathrm{Ali}} = F_{\mathrm{Ali}}(d)\,O_{\mathrm{Ali}}(\Delta\phi)\,E_{\mathrm{Ali}}(\psi)$$

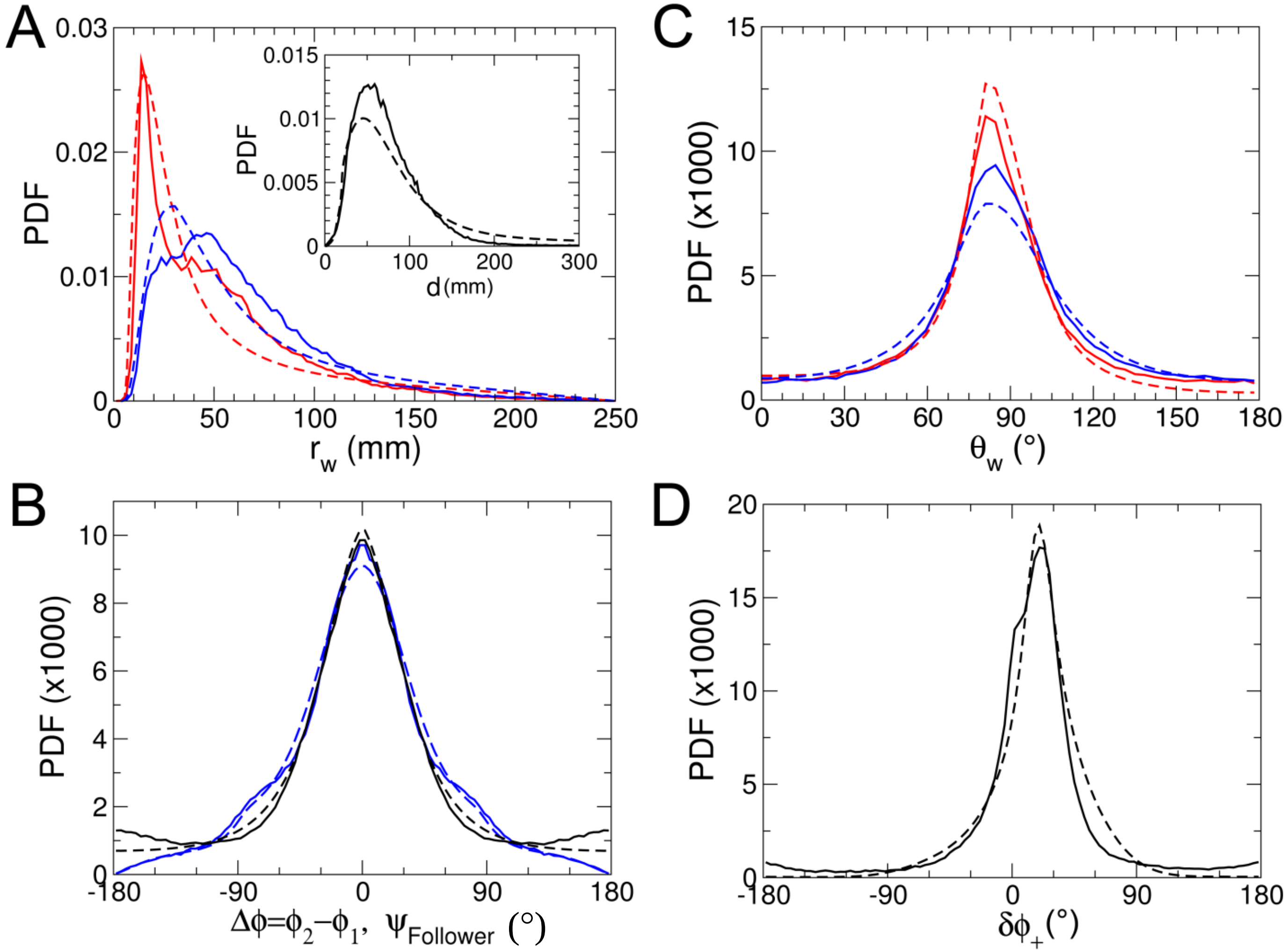
(O = Odd; E = Even)





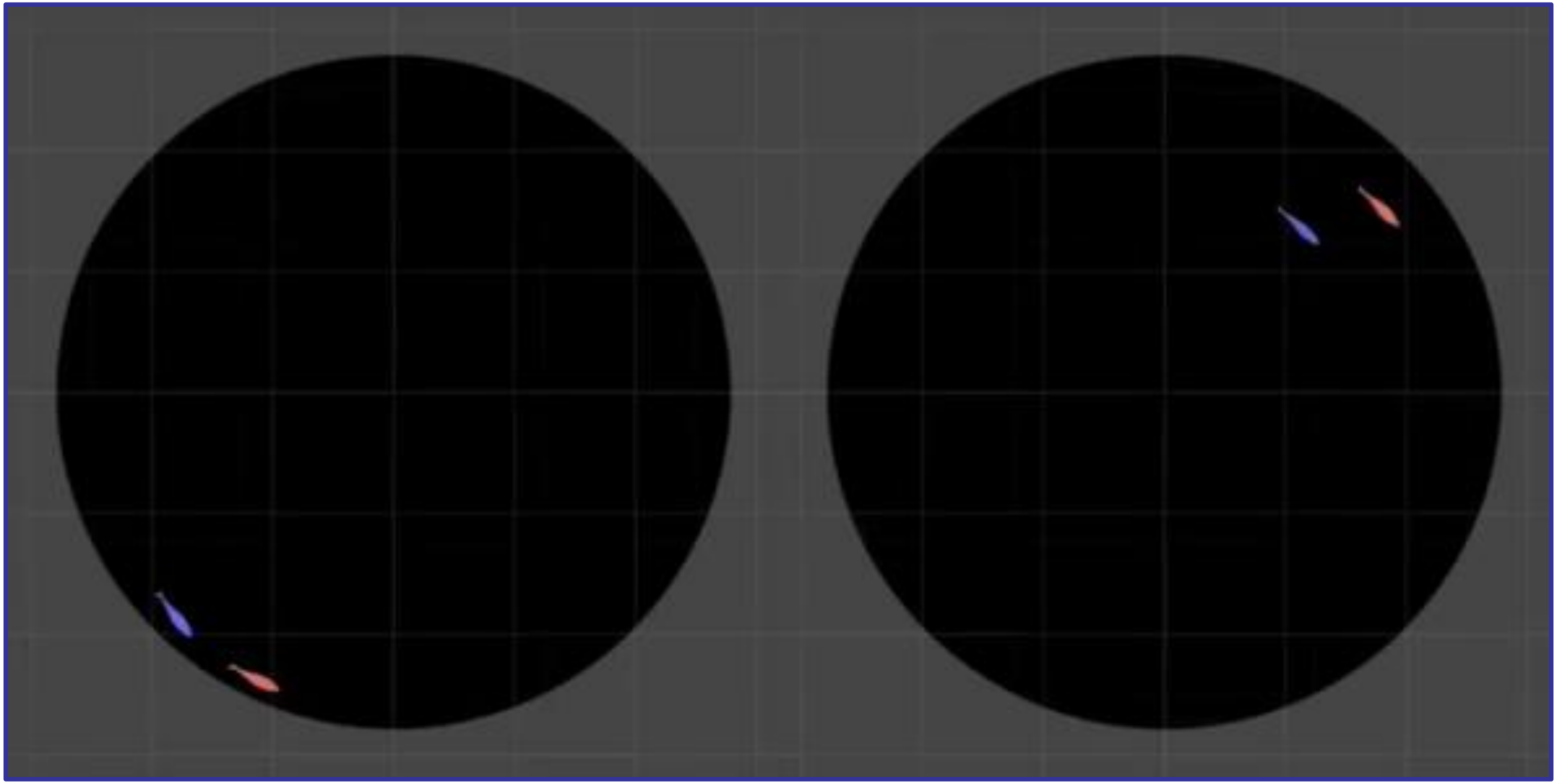
2-fish experiments vs model (dashed lines)

PDF of the distance (A) and angle (C) to the wall (leader *vs* follower); PDF of the heading difference (B; black) and the follower angle of view (B; blue), and of the angle change (D)



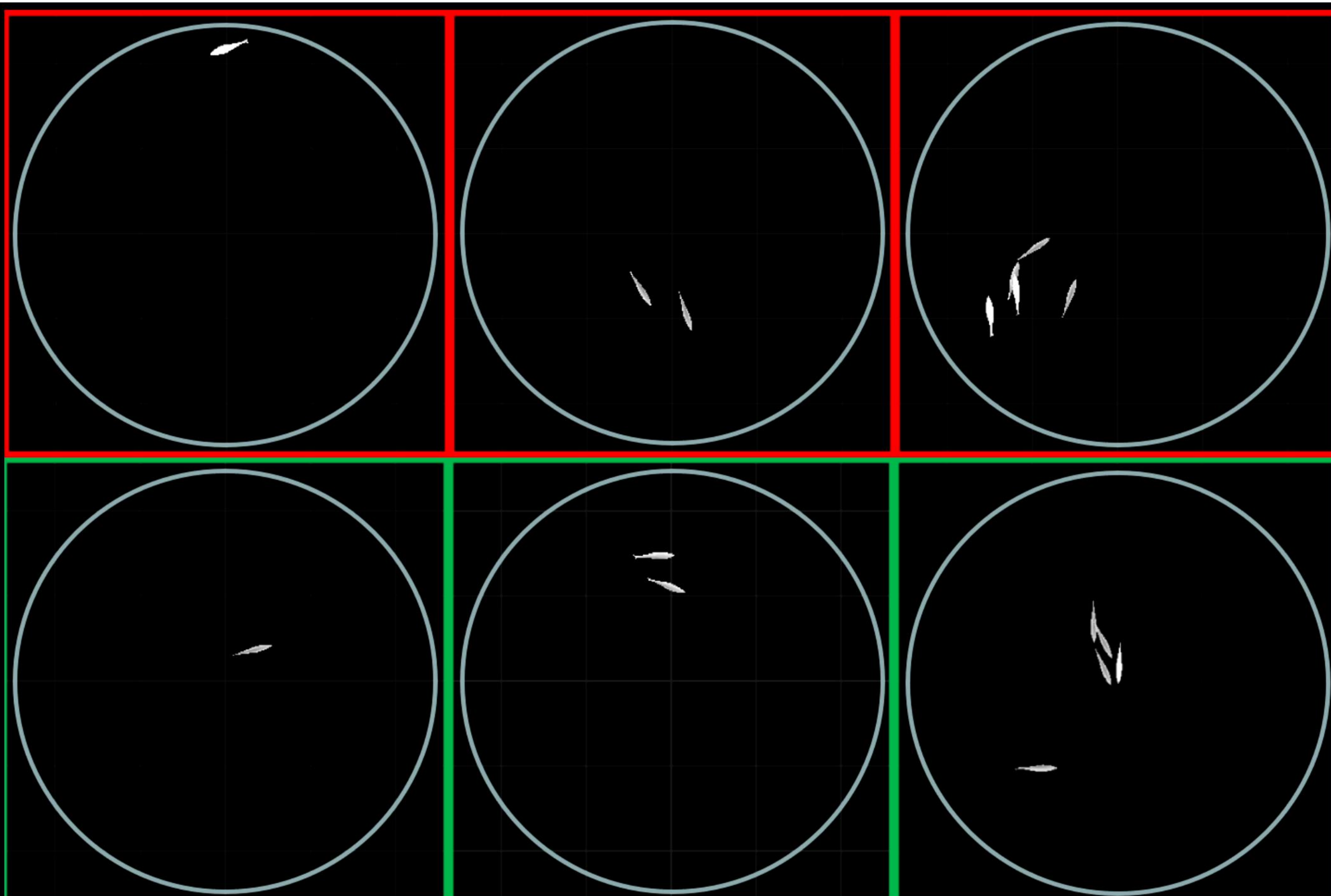
Model vs experiment ("Turing test")

Experiment **Model simulations**

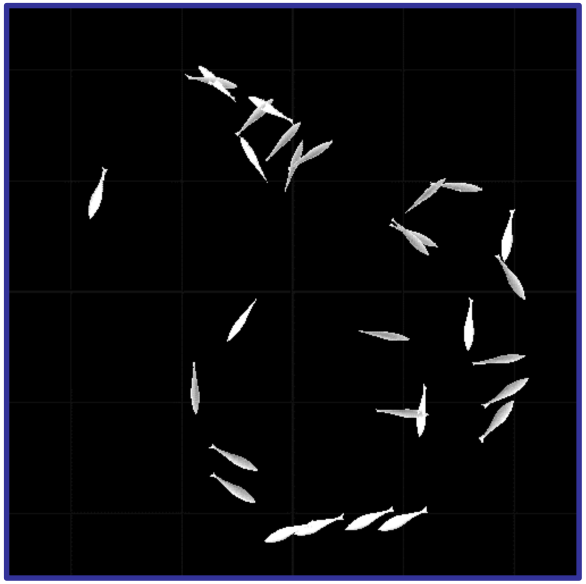


Model vs experiment ("Turing test")

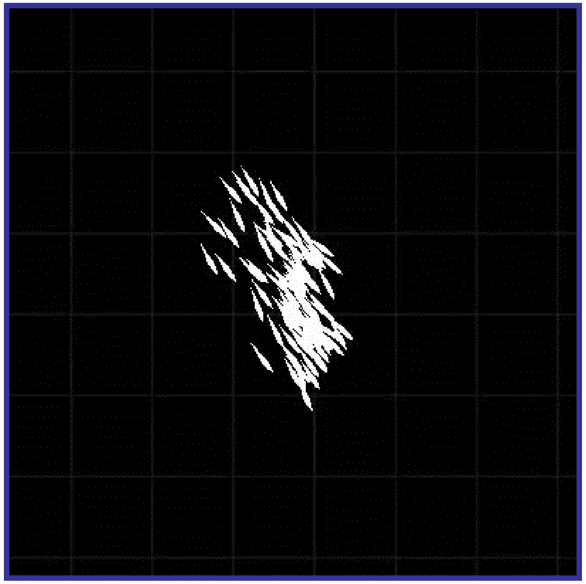
Experiments *vs* model simulations



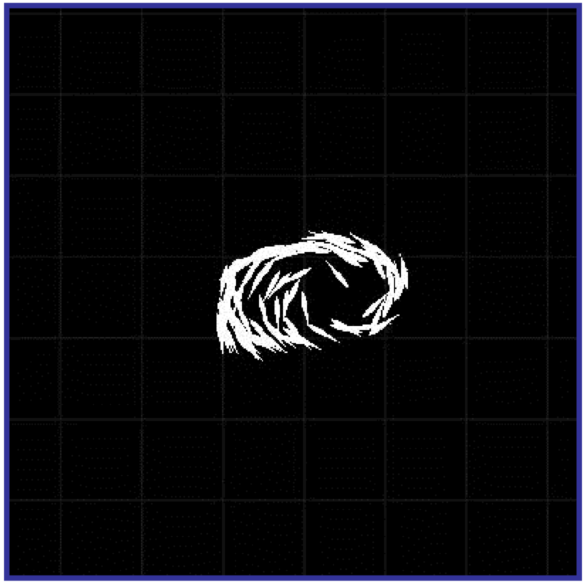
Collective phases in fish schools



Disordered

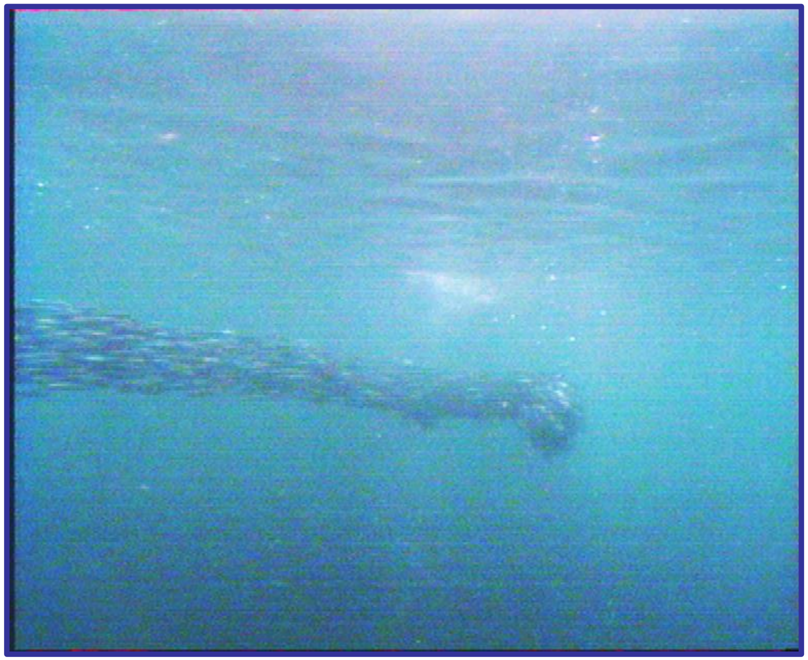


Schooling

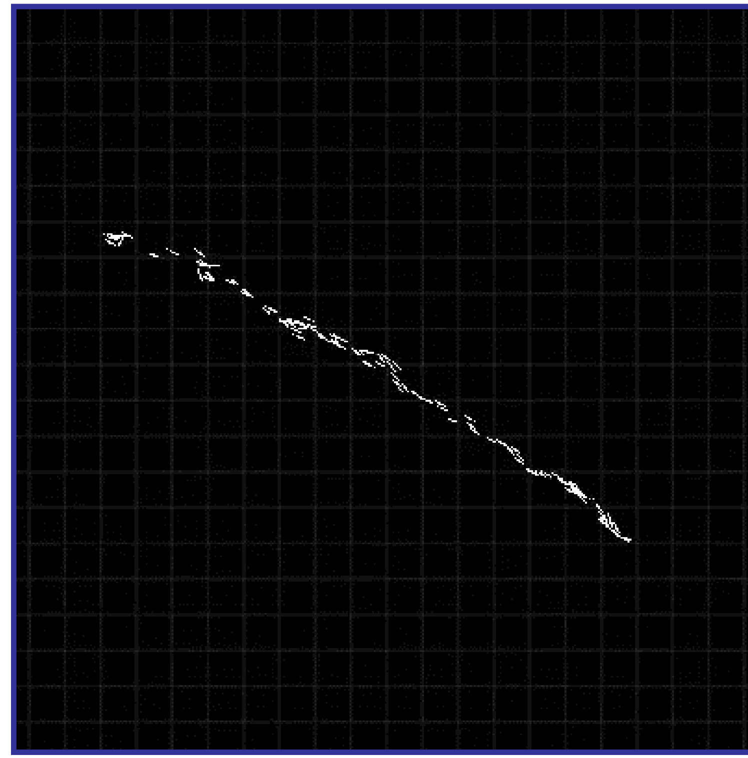


Milling

The elongated phase

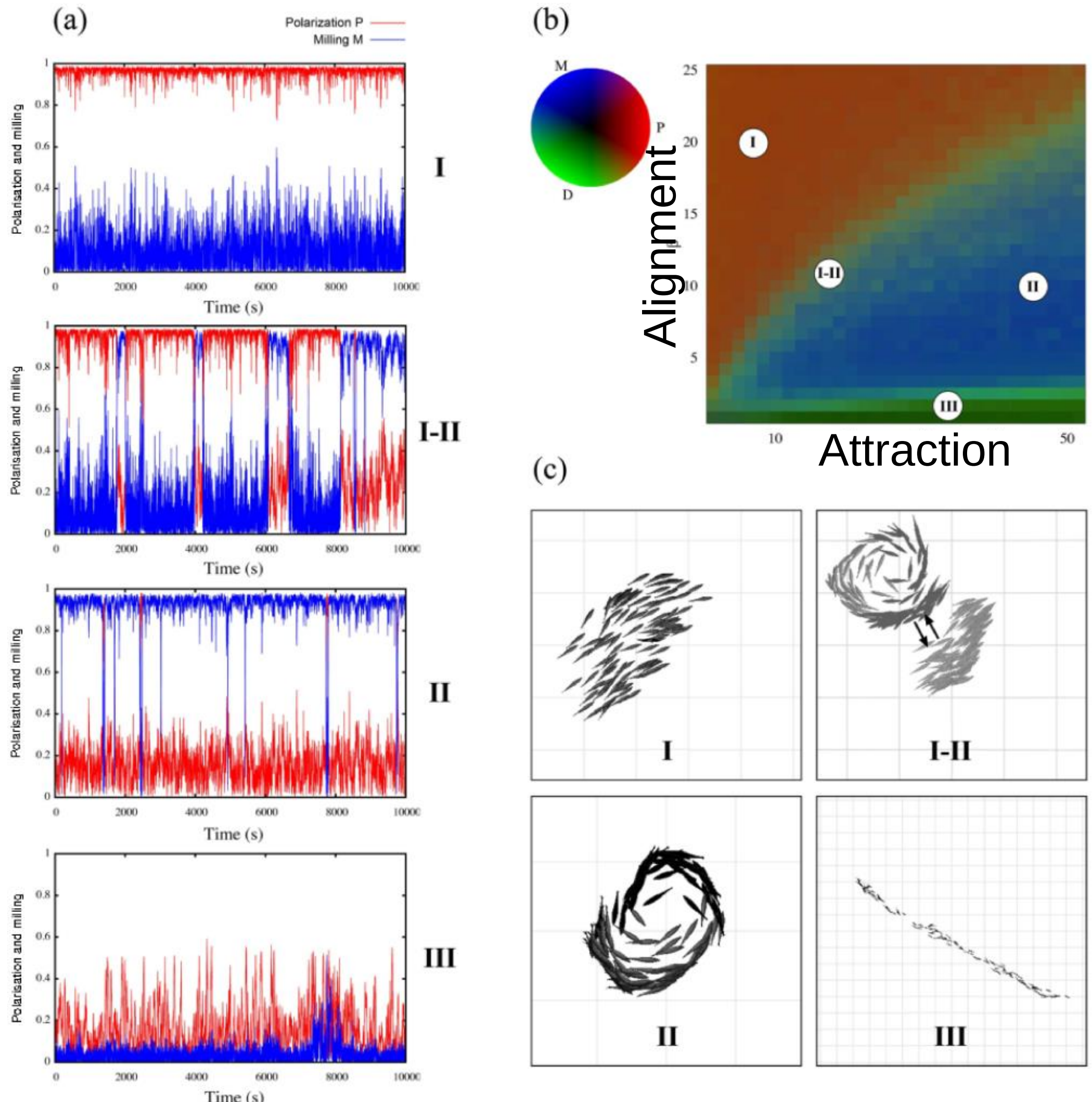


School of herrings (Clupea harengus)
Photo P. Brehmer - IRD



Phase diagram for fish schools

New J. Phys. 2014; J. Roy. Soc. Interface 2015; PLOS Comp. Biol. 2022



Order Parameters

$$P = \frac{1}{N}\left|\sum_i \frac{\vec{v}_i}{|\vec{v}_i|}\right|$$

$$M = \frac{1}{N}\left|\sum_i \frac{\vec{r}_i \times \vec{v}_i}{|\vec{r}_i|\,|\vec{v}_i|}\right|$$

Phase diagram for fish schools

Behavioral model coupled to a simple fluid model (with C. Eloy, E. Kanso, et al.) ***Phys Rev. Lett. 2018***

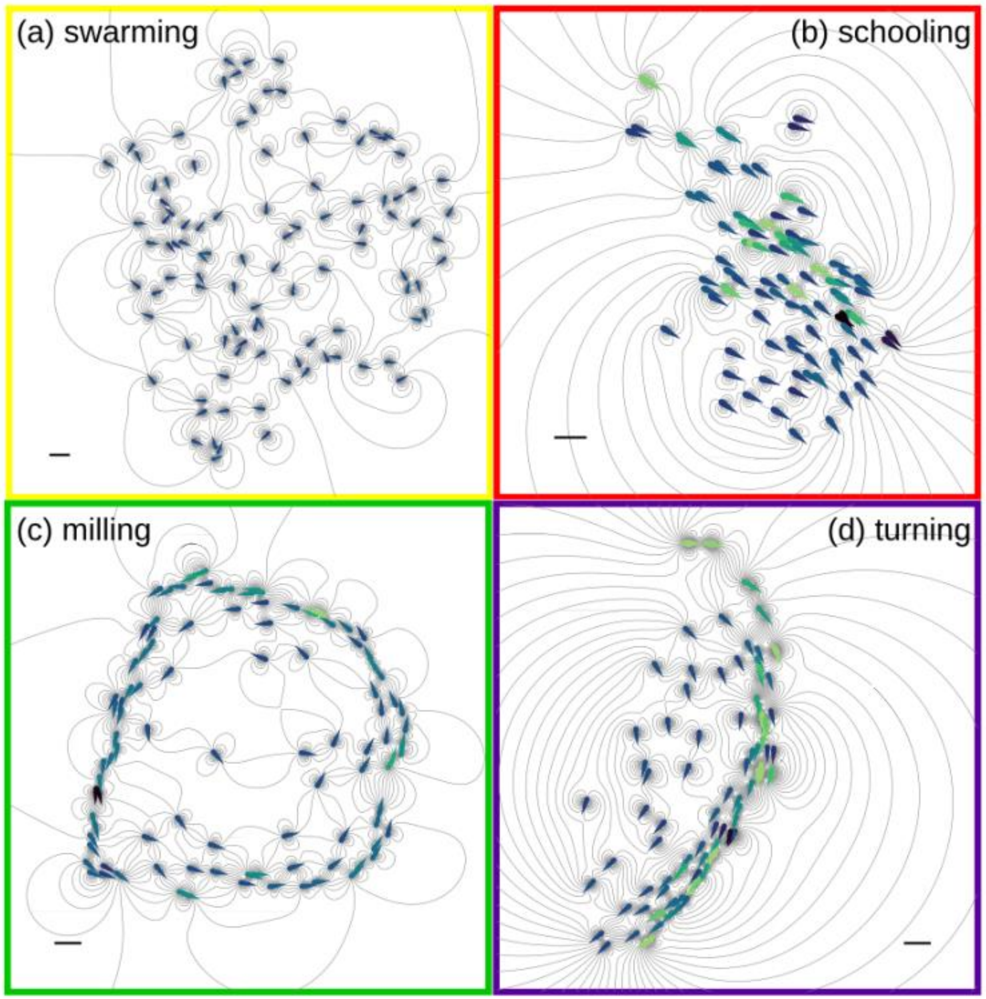
- **Fish seen as fluid dipole**: **transported** by the resulting velocity field, and **rotated** by the local velocity gradient

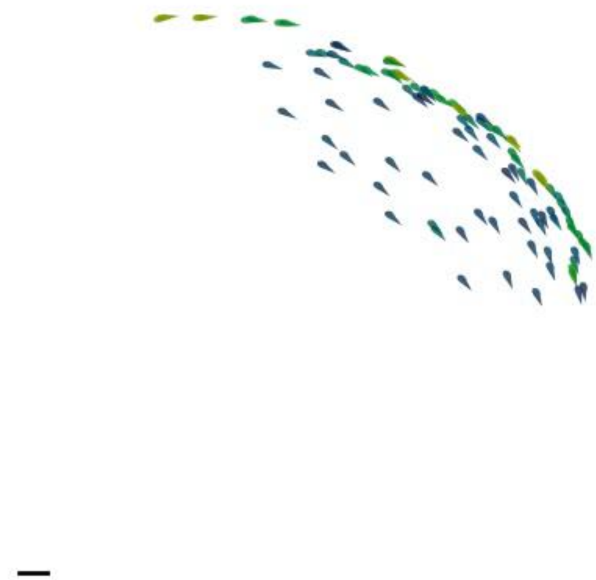
- **Main results**
  - The **phase diagram** is very similar to that of the behavioral model + “turning phase”
  - The fish move **faster** in an ordered state
  - Ordered schools acquire some **internal structure**
  - The **fluid velocity fluctuations** act similarly to the “cognitive noise” in the behavior model

Phase diagram for fish schools

Phys Rev. Lett. 2018

- **Behavioral model coupled to a simple fluid model (with C. Eloy, E. Kanso, et al.)**





Deep learning "models" of fish

- ML model reproducing **short- and long-term fish dynamics**
- The structure of the network includes some **biological insight**
- Straightforward to train with **other species**
- Possibility to **open the ML "black box"** in this context

J. Roy. Soc. Interface 2024

Predicting long-term collective animal behavior with deep learning

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[3] Centre de Recherches sur la Cognition Animale, Centre de Biologie Intégrative, CNRS, Université de Toulouse — Paul Sabatier

[4] VITA group, École polytechnique fédérale de Lausanne

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Hilbert interpolation scheme (with P. Mitra)

Consider n (training) configurations C_i of a system, corresponding to some observable O_i

- $C = pixels\ of\ an\ image;\ O = classifier$
- $C = position / velocity\ of\ N\ fish;\ O = acceleration\ of\ the\ N\ fish$
- ...

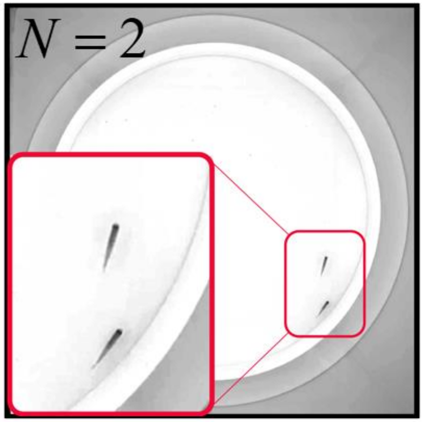
$$\hat{O}(C) = \sum_{i=1}^{n} w_i(C) O_i, \quad w_i(C) = \frac{\left\| C - C_i \right\|^{-d}}{\sum_{j=1}^{n} \left\| C - C_j \right\|^{-d}}, \quad d = \dim(C)$$

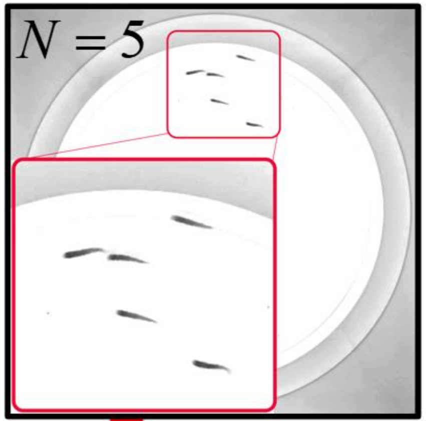
Many rigorous mathematical results

- $Statistical\ consistency\ with\ a\ prediction\ error \sim 1/\ln(n)$
- ...

Interpolation "models" of fish (with P. Mitra)

Implementation flowchart of Hilbert Interpolation as a fish trajectory generative model





Prepare the N Hilbert fish in a reasonable initial state

$$x(0) = (\boldsymbol{R}_1(0), V_1(0), V_1(-\Delta t), \ldots, \boldsymbol{R}_N(0), V_N(0), V_N(-\Delta t))$$

Construct the present state of the N Hilbert fish

$$x(t) = (\boldsymbol{R}_1(t), V_1(t), V_1(t-\Delta t), \ldots, \boldsymbol{R}_N(t), V_N(t), V_N(t-\Delta t))$$

Compute the distance $\|x(t) - x_i\|$ between the present state of the N Hilbert fish and the observed states of N real fish

$$x_i = (\mathbf{r}_1(t_i), \mathbf{v}_1(t_i), \mathbf{v}_1(t_i - \Delta t), \ldots, \mathbf{r}_N(t_i), \mathbf{v}_N(t_i), \mathbf{v}_N(t_i - \Delta t))$$

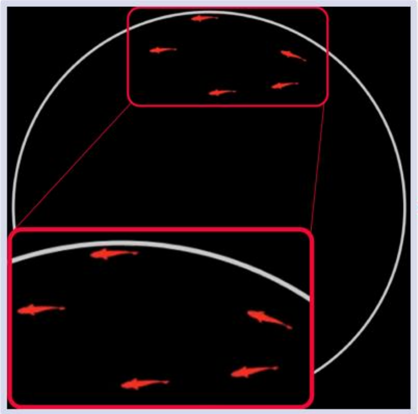
Compute the predicted acceleration of the Hilbert fish

$$A_k(t) = \frac{\sum_{i=1}^{n} \|x(t) - x_i\|^{-d} \boldsymbol{a}_{i,k}}{\sum_{i=1}^{n} \|x(t) - x_i\|^{-d}} \quad (k = 1, \ldots, N)$$

Update the positions and velocities of the N Hilbert fish

$$V_k(t+\Delta t) = V_k(t) + A_k(t)\Delta t \quad (k = 1, \ldots, N)$$

$$\boldsymbol{R}_k(t+\Delta t) = \boldsymbol{R}_k(t) + V_k(t)\Delta t + A_k(t)\frac{\Delta t^2}{2}$$



Interpolation "models" of fish (with P. Mitra)

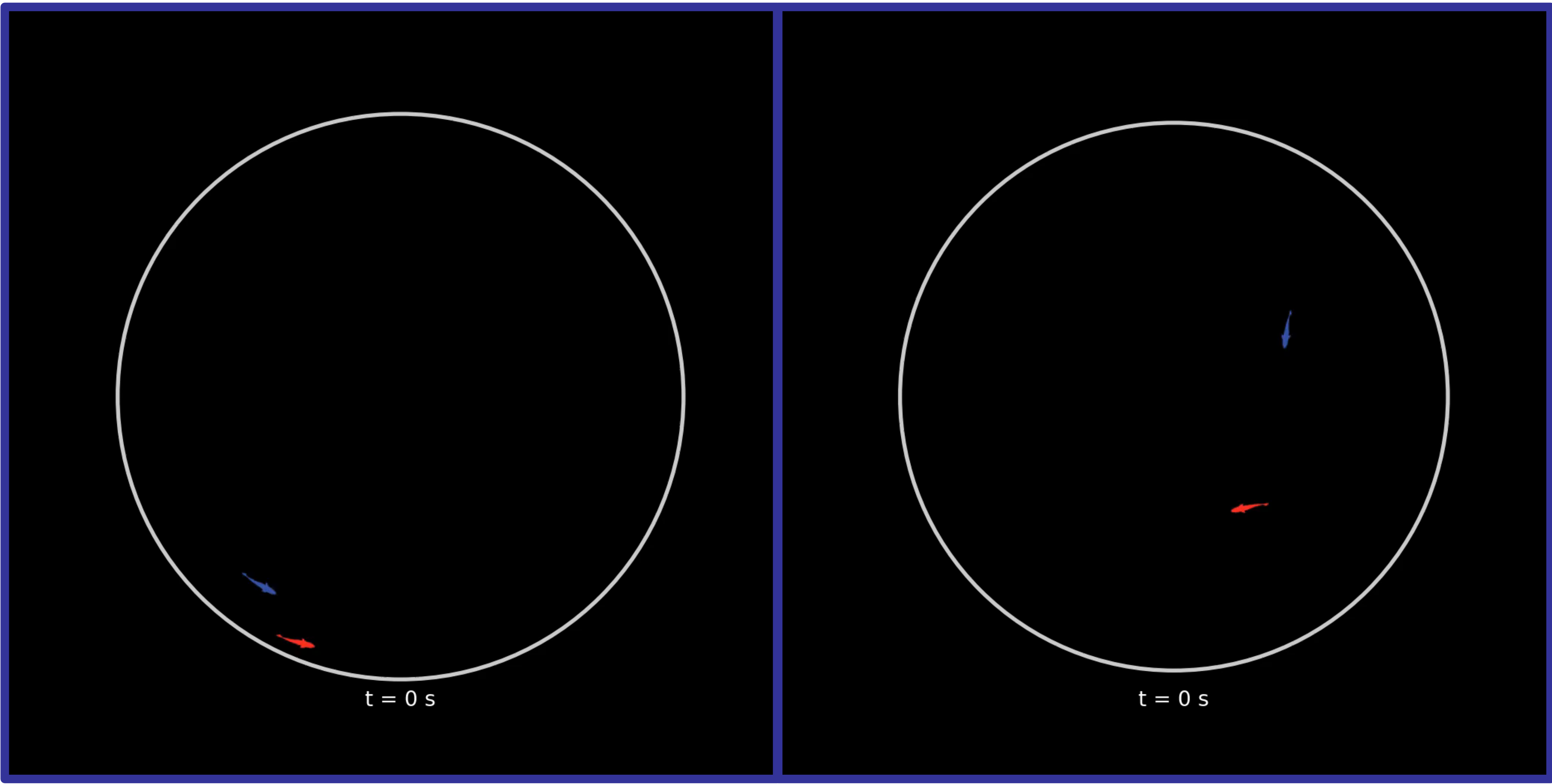
- **No training phase!**
- Explicit formulation **without any parameter**
- Like ML, straightforward to apply to **other species**
- Like ML, can augment the **experimental dataset**
- Like ML, interpolation models are **only generative**

Interest of our scheme in the scientific context:

- Straightforward to **implement/code** and to **port/share**
- Strictly **reproducible** results
- **Update/create** the training dataset **live (robotic applications)**
- **Credit assignment:** evaluate the relative importance of different experimental configurations (the most typical and the most biologically relevant)

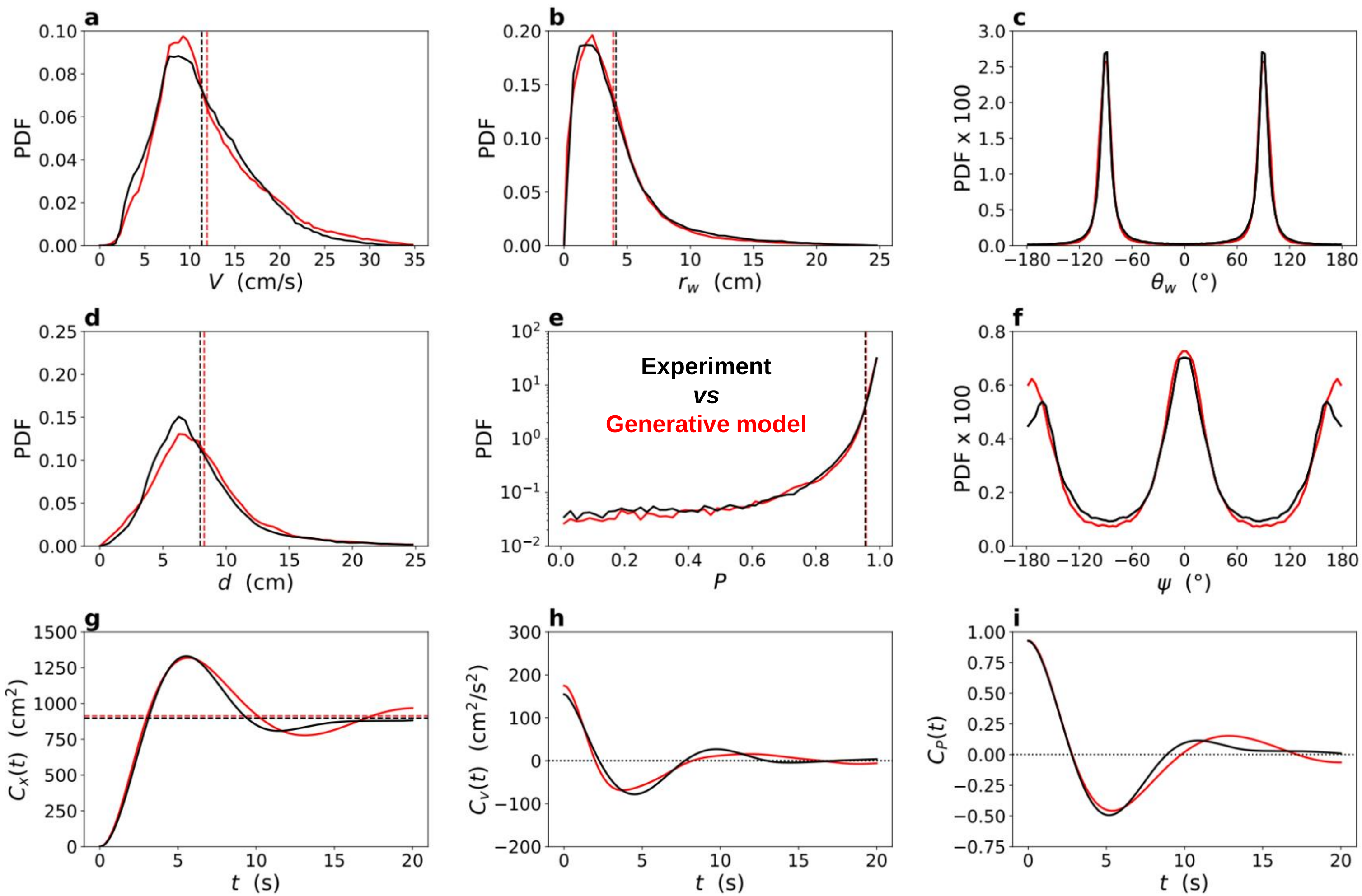
Interpolation "models" of fish (with P. Mitra)

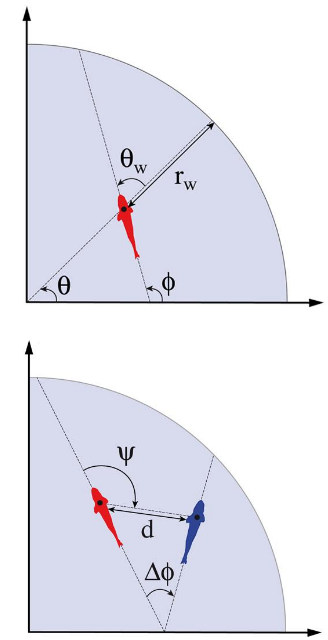
The Hilbert fish have learned the presence of the wall



Interpolation "models" of fish (with P. Mitra)

Quantification of the agreement with experiment for 2 fish





$$P = \frac{1}{N}\left\| \sum_{i=1}^{N} \frac{\mathbf{v}_i}{\|\mathbf{v}_i\|} \right\| \underset{N=2}{=} \sqrt{\frac{1+\cos(\Delta\phi)}{2}}$$

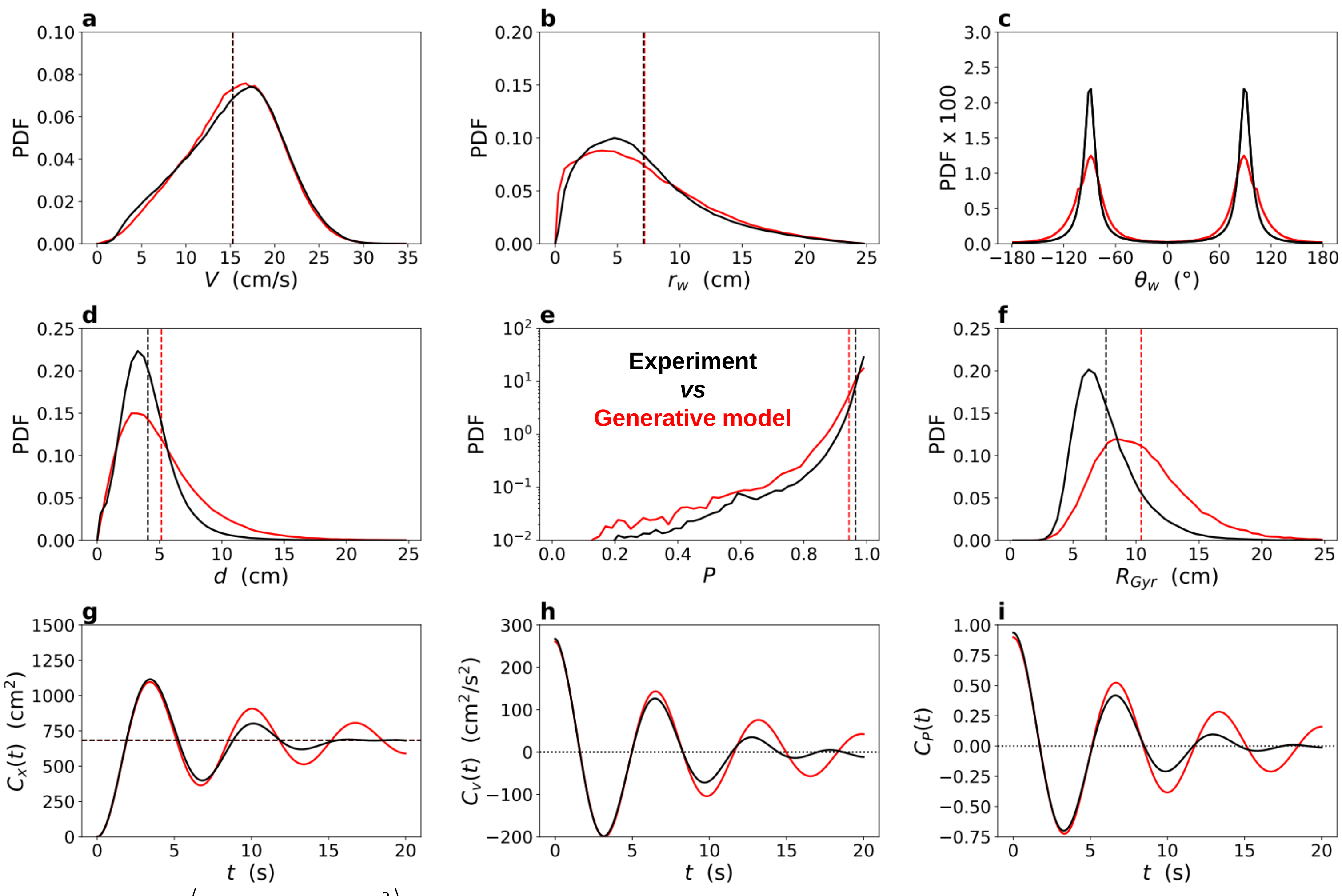
$$C_x(t) = \left\langle \left\| \boldsymbol{r}(t+T) - \boldsymbol{r}(T) \right\|^2 \right\rangle$$

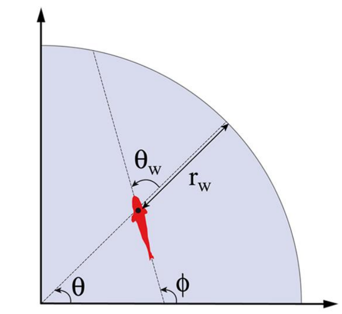
$$C_v(t) = \left\langle \boldsymbol{v}(t+T).\boldsymbol{v}(T) \right\rangle$$

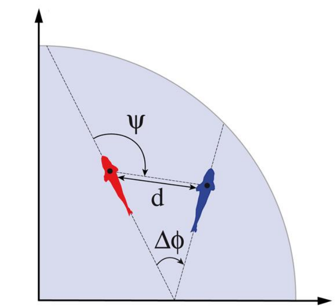
$$C_v(t) = \left\langle \boldsymbol{P}(t+T).\boldsymbol{P}(T) \right\rangle$$

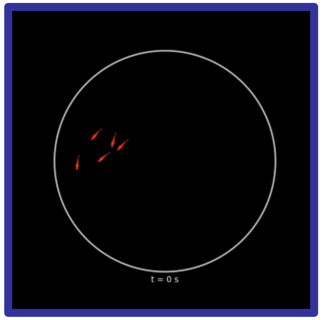
Interpolation “models” of fish (with P. Mitra)

Quantification of the agreement with experiment for 2 fish









$$C_x(t) = \left\langle \left\| \boldsymbol{r}(t+T) - \boldsymbol{r}(T) \right\|^2 \right\rangle$$

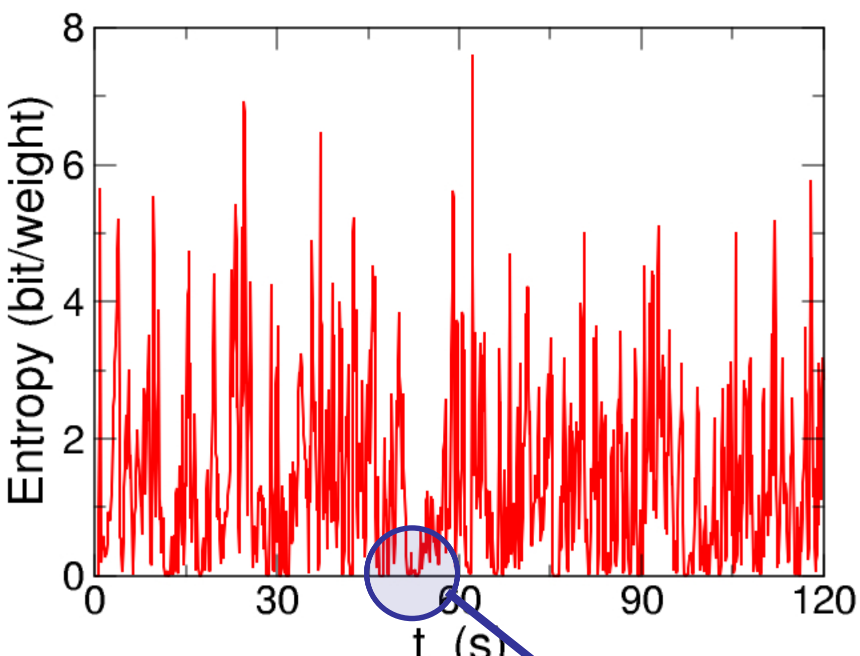
$$C_v(t) = \left\langle \boldsymbol{v}(t+T).\boldsymbol{v}(T) \right\rangle$$

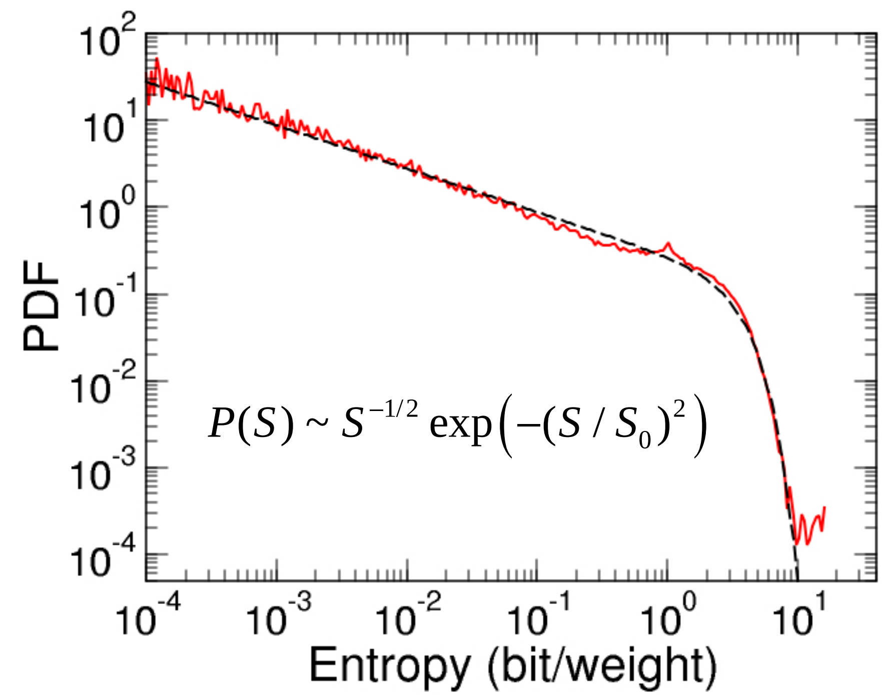
$$C_v(t) = \left\langle \boldsymbol{P}(t+T).\boldsymbol{P}(T) \right\rangle$$

Interpolation “models” of fish (with P. Mitra)

Entropy of sampled configurations

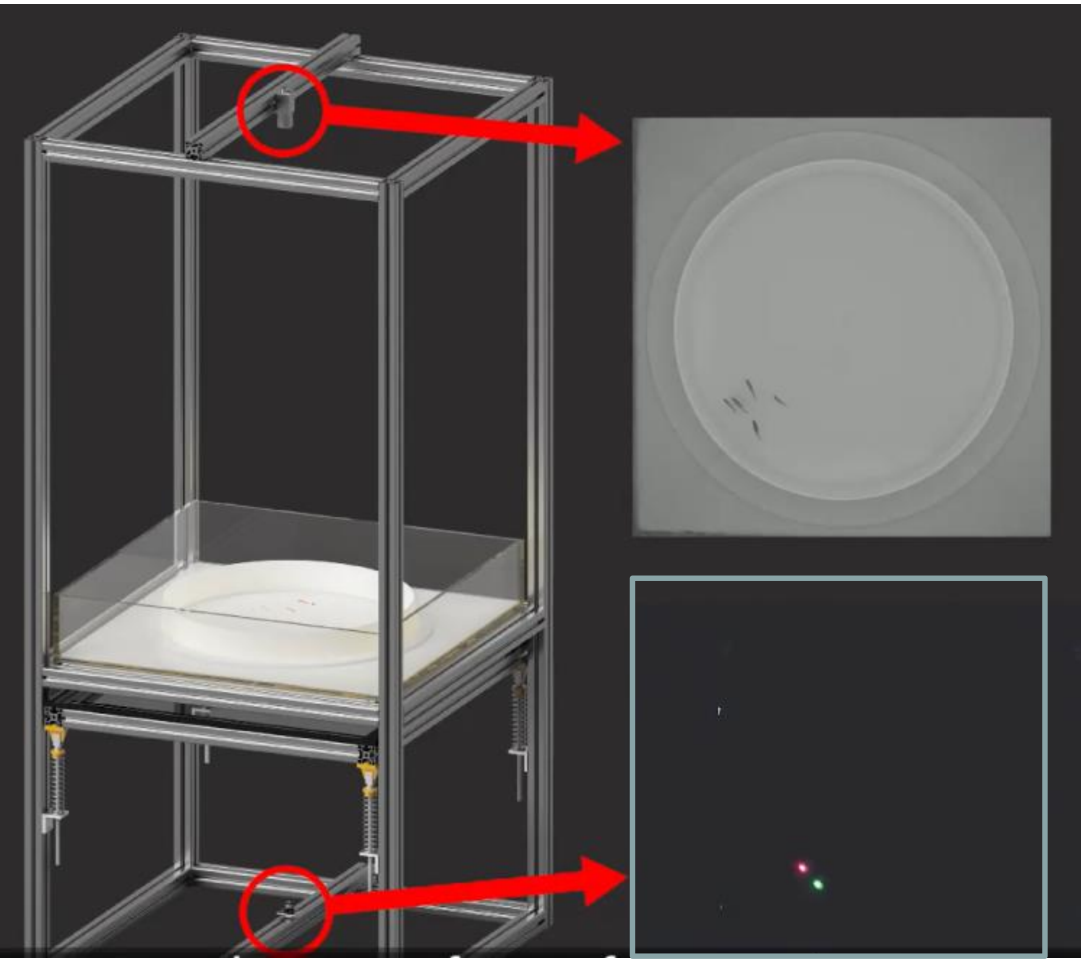
- $S(t) = -\sum_{i=1}^{n} w_i(\boldsymbol{x}(t)) \log_2 \left[w_i(\boldsymbol{x}(t)) \right]$
- Quantifies the **effective number of data** used for the prediction: $\mathcal{N} = 2^S$
- The weights allow to asses the **most typical and biologically relevant configurations**
- $\mathbb{E}[S] \underset{n \to +\infty}{\sim} \log_2(\sqrt{n})$ in the pure regression context

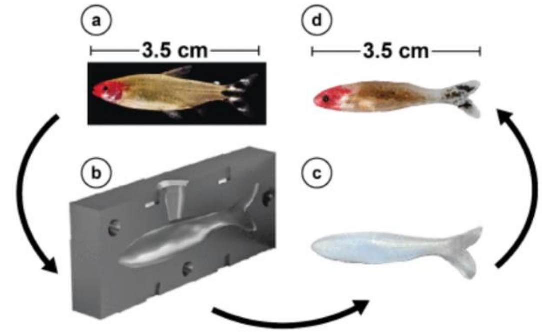




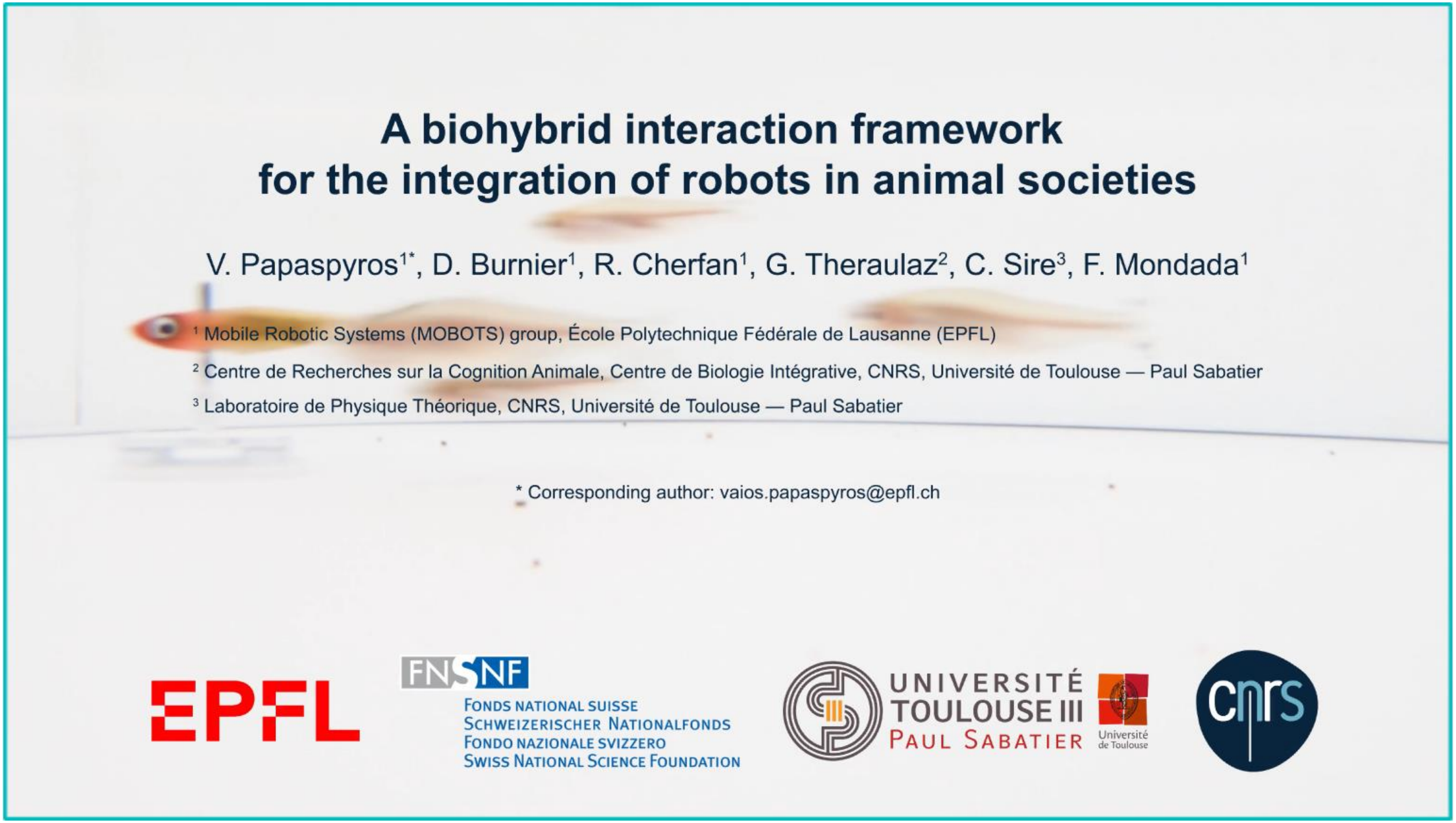
Copying ($S = 0$; $\mathcal{N} = 1$)

Fish model(s) implemented in the LureBot





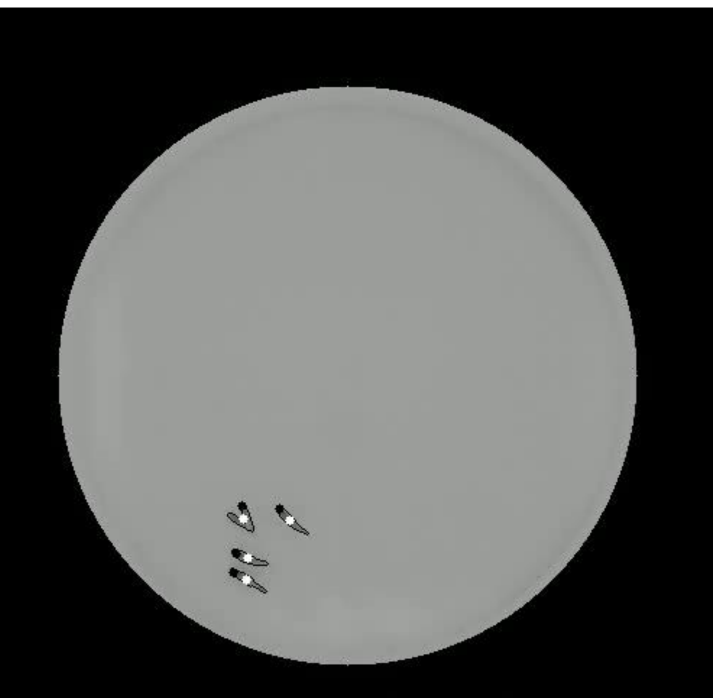
Fish model implemented in the LureBot

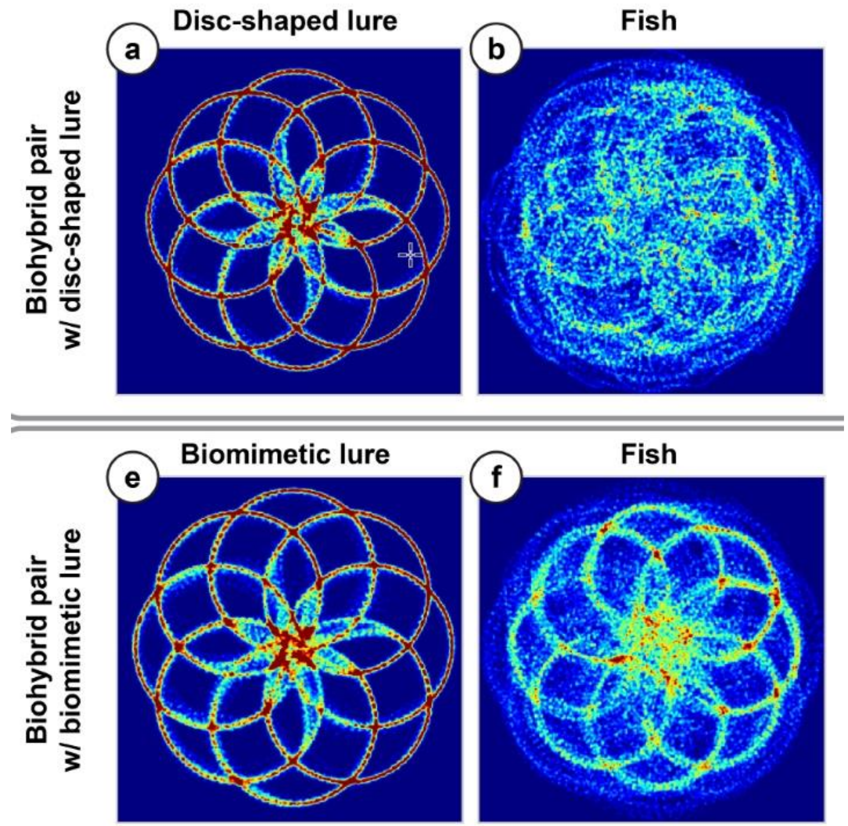


IEEE Access 2023; Bioinspiration & Biomimetics 2024

Fish model implemented in the LureBot

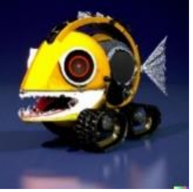
- **The *LureBot* is very well accepted by the fish**
- **Need to measure the *fish-LureBot* interactions**
- **A controlled perturbation to study fish schools**

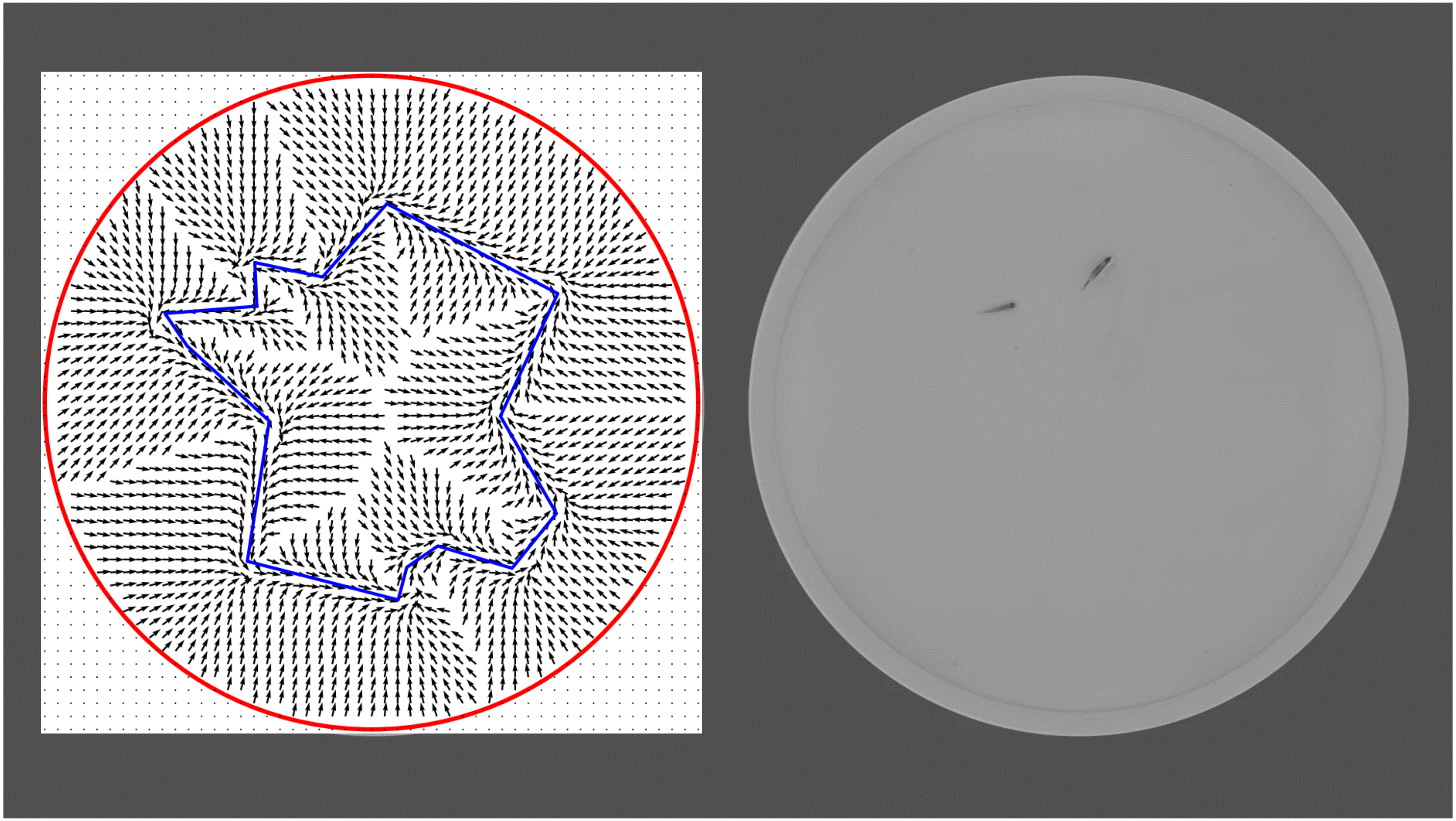




Density heat maps for the passive lure (disc-shaped or biomimetic) and the fish

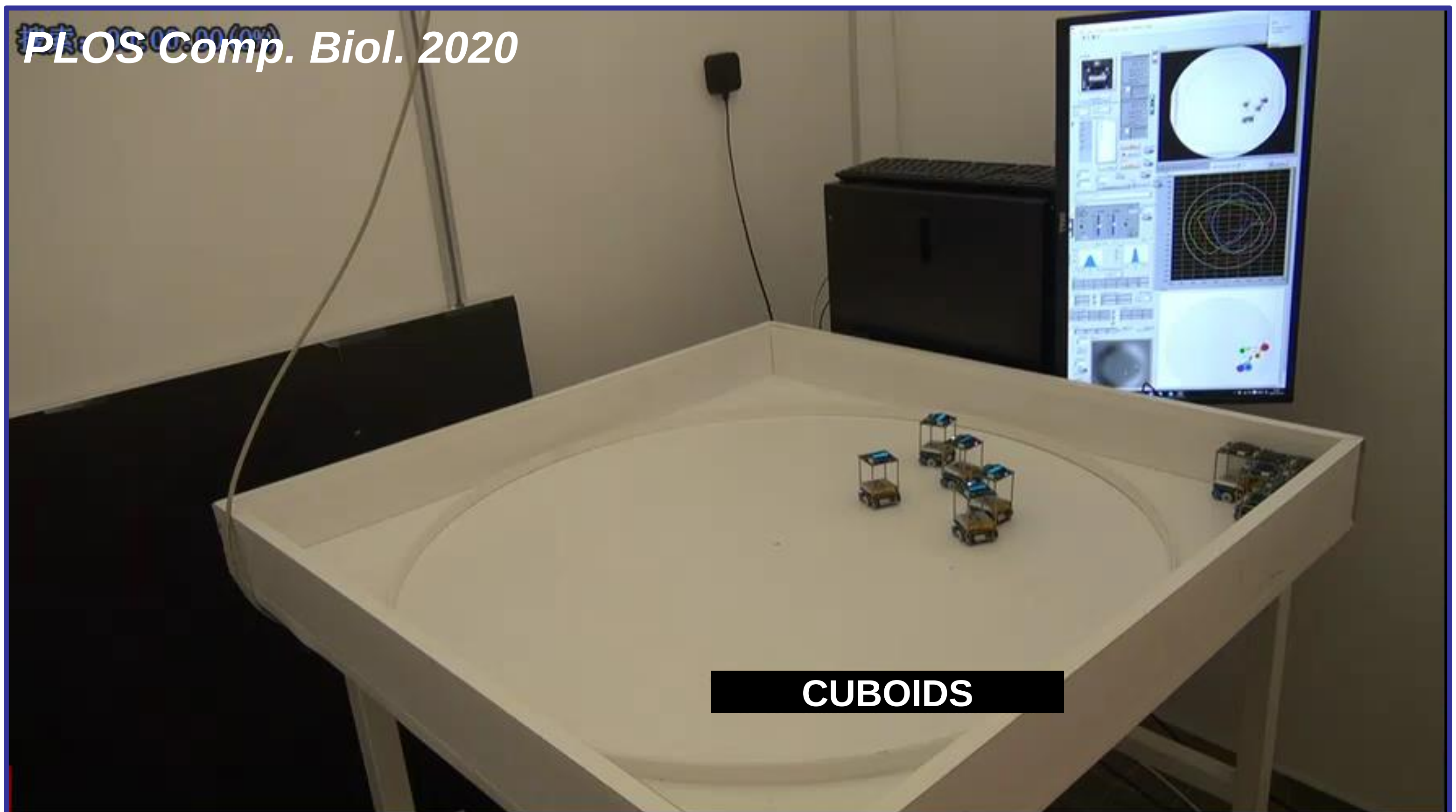
The LureBot and one fish in a "binational" fluid flow





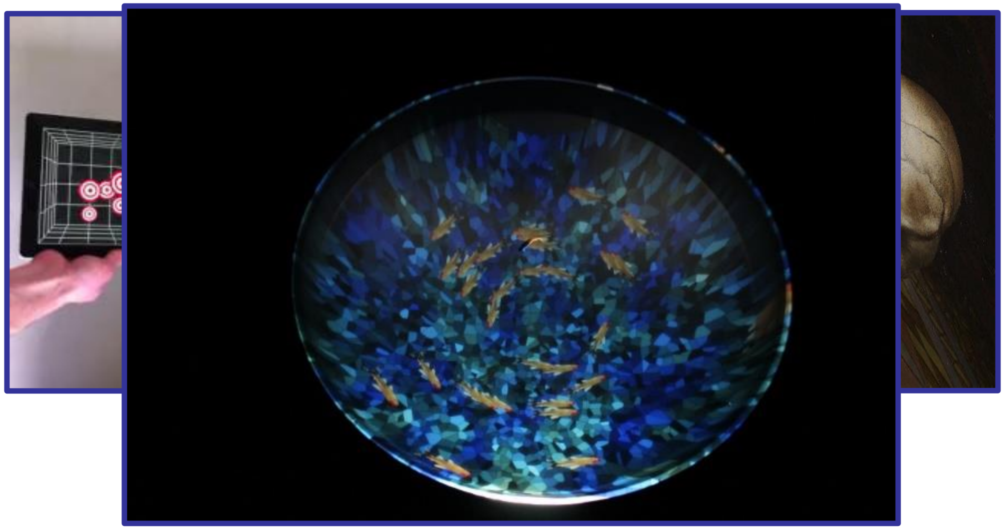
Fish model implemented in the CUBOID robots

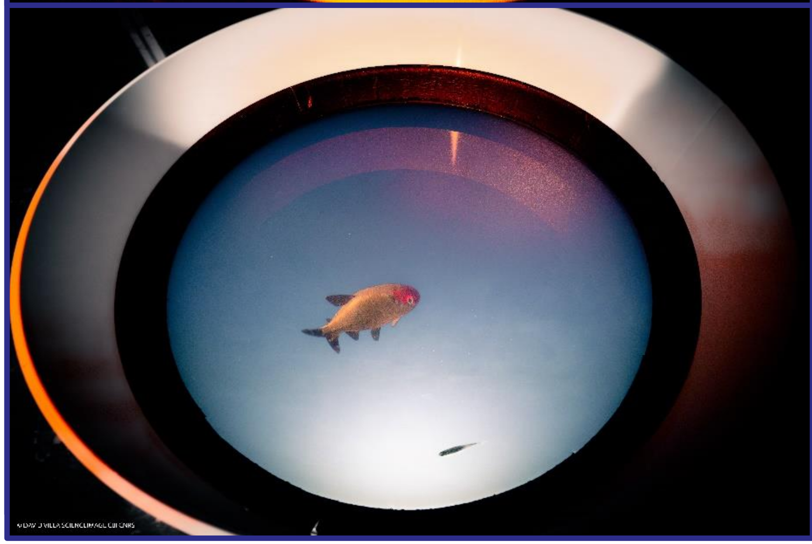
- Literal implementation of the fish model… but confronted to **real-life physical constraints**
- The main point of this work was actually to understand how **animals combine their interactions** (notion of **most influential neighbors**)



VR for Fish
(ANR VR-FISHSCHOOL – CRCA-LPT-IRIT)

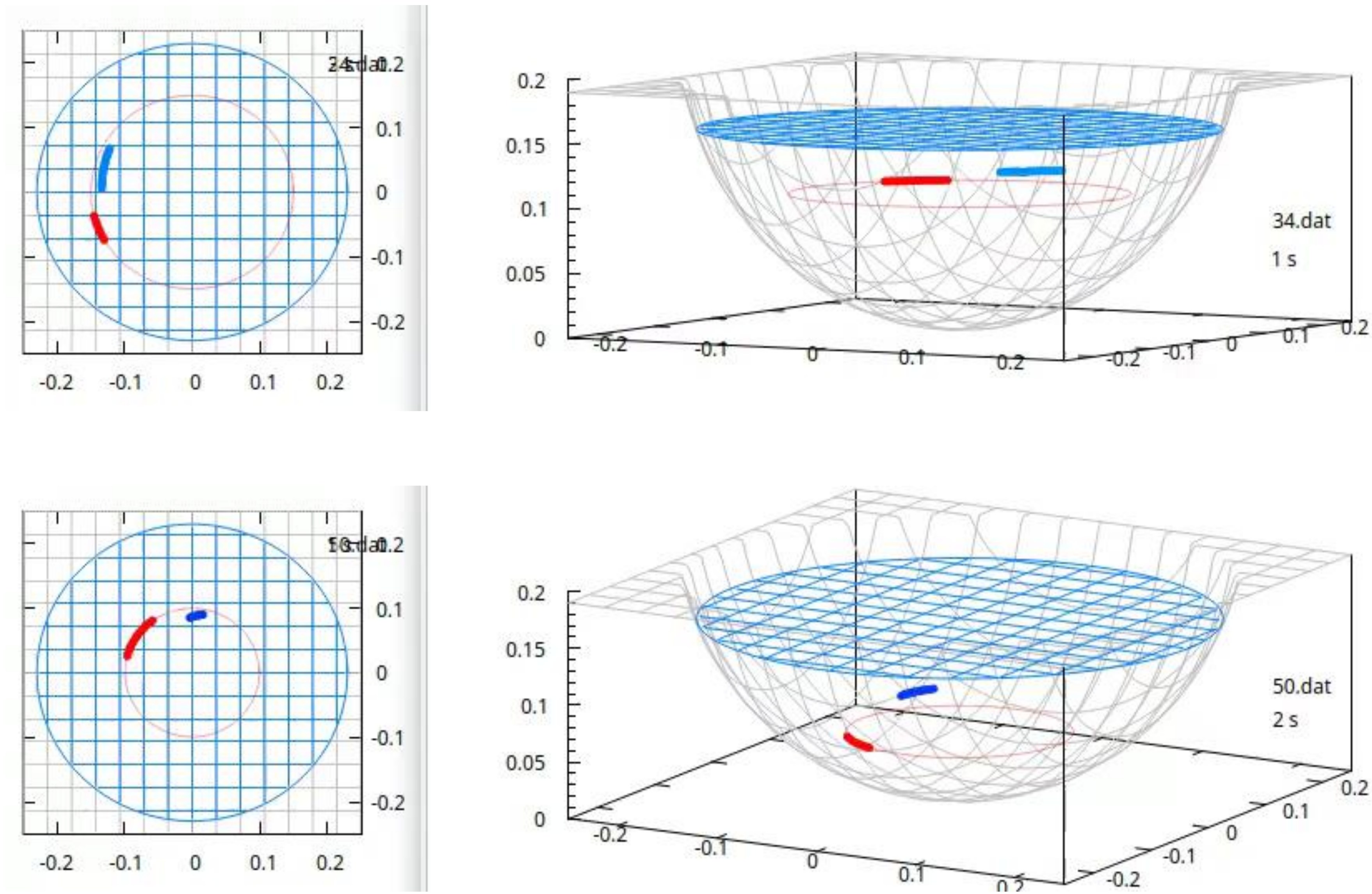
- **Realistic-looking lures are projected on the side of the bowl in anamorphic view**





- **3D tracking of the fish to feed the “3D” model driving the VR-fish in closed loop**
- **A tool to study the behavior of *one* fish in a (VR) school and to probe its response to controlled perturbations (complementary to the *LureBot*)**

VR for Fish
(ANR VR-FISHSCHOOL – CRCA-LPT-IRIT)



Bio-inspired 3D model implemented in drones

Bio-inspired 3D flocking algorithm with minimal information transfer for drones swarms

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IEEE ICUAS (2022) & IROS (2023)

Bio-inspired 3D model implemented in drones (with Dronisos)

We also ~~force~~ invite humans to ~~swim~~ walk in a circular ~~tank~~ arena

(But we do not plan – yet – to make them interact with AI or robots, or fly drones)

Phil. Trans. Roy. Soc. 2020; PLOS Comp. Biol. 2021; J. Roy. Soc. Interface 2021; PNAS 2017 & 2023

Conclusion

- The study of **collective phenomena** in animal groups is taking advantage of the **rapid progress in technology** (real-time tracking; AI; response of a fish school to a (Lure)bot; response of single fish to a VR-school; drones…)

- Reconstruction and modelization of **social interactions**… but which must also adapt to **real-life physical conditions and constraints**

- Biomimetic **inspiration for robots/drones**: no need to implement the actual forms of animal social interactions in robots/drones… but they can still provide neat ideas in this robotic context

- A very **interdisciplinary research** (ethologists, computer scientists, roboticists… and a theoretical physicist!)

Conclusion

- **1 and 2 fish experiments** (~45h and ~30h of data used)
- **Characterization** of the **spontaneous burst-and-coast swimming**
- **Unprecedented characterization** (exploiting **symmetries**) and **precision measurement** of the fish-wall and fish-fish **interactions**
- **“Repulsion”** of the wall: **Gaussian** dependence with the **distance** to the wall; **“comfort” angle** of 85°; **burst-and-coast swimming** nonetheless forces a fish to **remain close to the wall**
- **Short distance repulsion** (~1 BL) and **long-range attraction** (vision?) between fish; **alignment** interaction dominates up to **2.5 BL** and then vanishes; attraction and alignment interactions **modulated** by viewing and relative heading **angles**; **leader** *vs* **follower**
- **Explicit model** guiding the **data analysis** and in good **qualitative** (videos) and **quantitative** (various PDF) **agreement** with **experiments**