Motion coordination and information transmission in bio-groups

From frightened fish to mating mosquitoes

KITP: Active Processes in Living and Nonliving Matter

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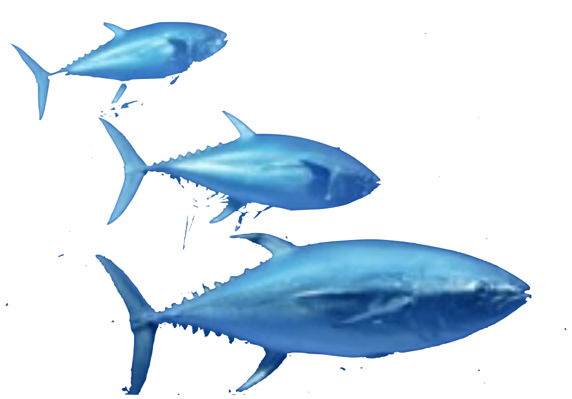
Overview of my research in bio-groups

Goal: Design and validate quantitative models of collective motion in groups of fish and mosquitoes



- **Objectives**: (1) apply tools from estimation theory and computer vision to reconstruct movement data; (2) use these data to construct dynamic models; and (3) conduct behavioral experiments to test model predictions

Outline of talk

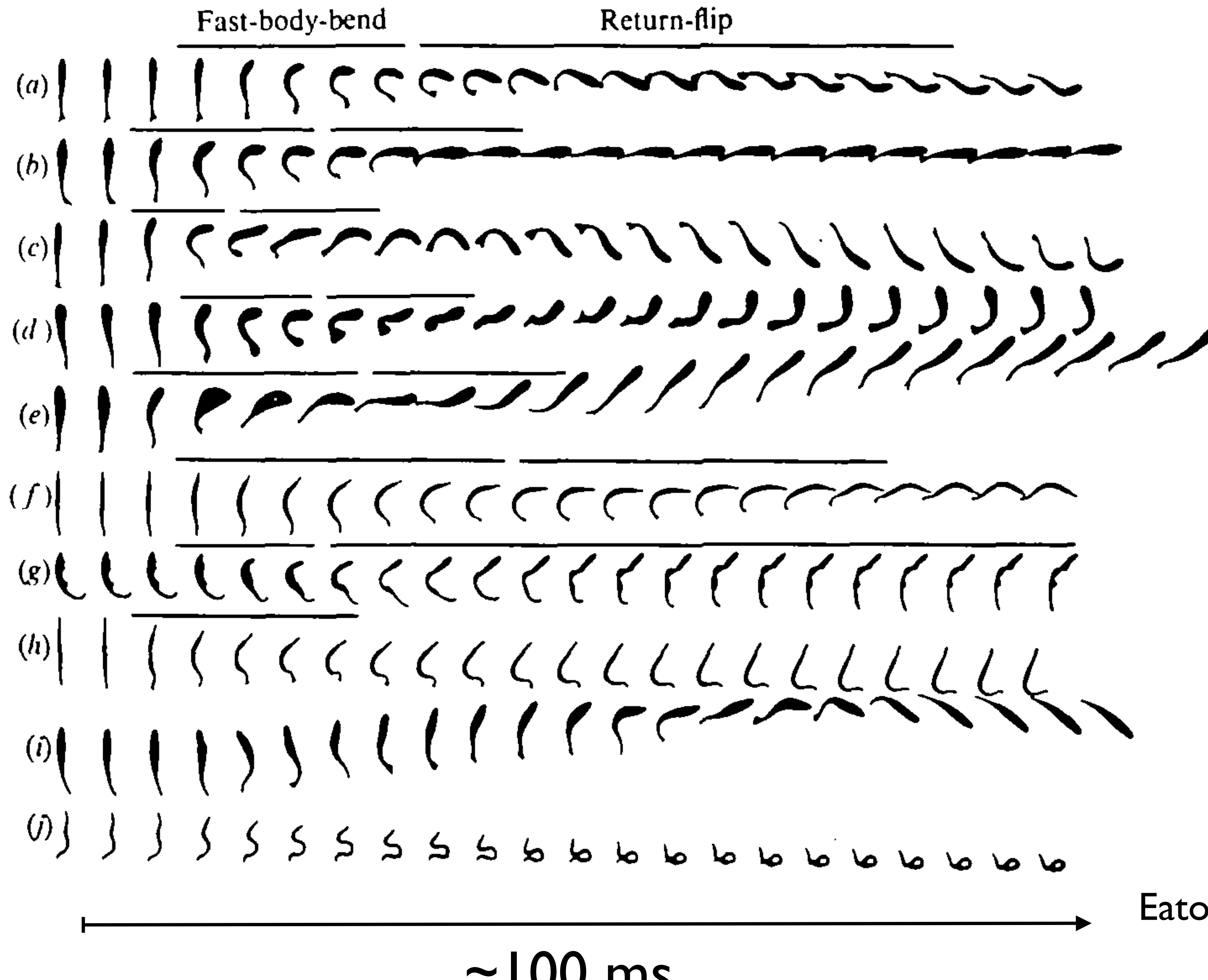
1. Information transmission in startled fish schools

   (Sachit Butail, Amanda Chicoli, Sheryl Coombs @ BGSU)

2. Motion coordination in mosquito mating swarms

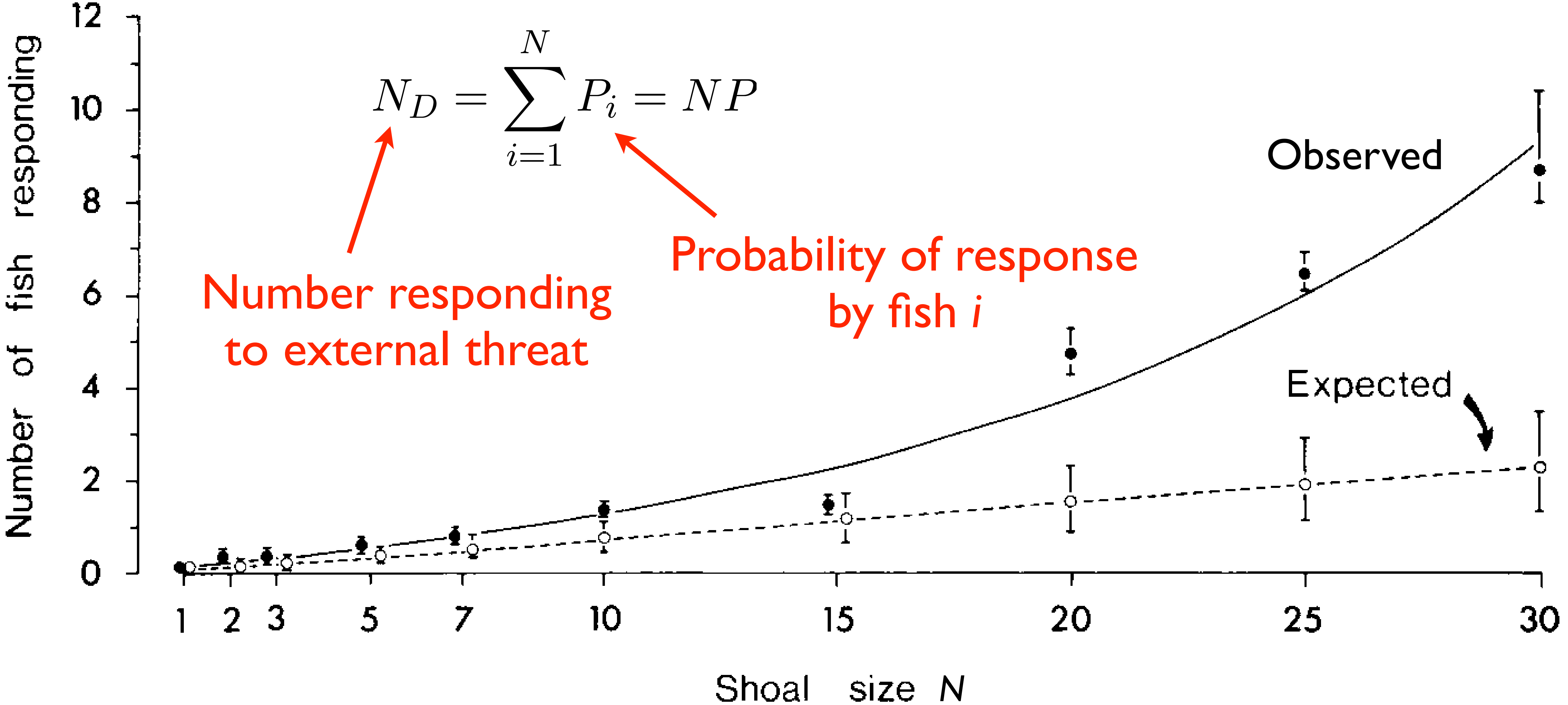
   (Sachit Butail, Daigo Shishika, Nick Manoukis @ NIH)

Startle-response behavior in fish



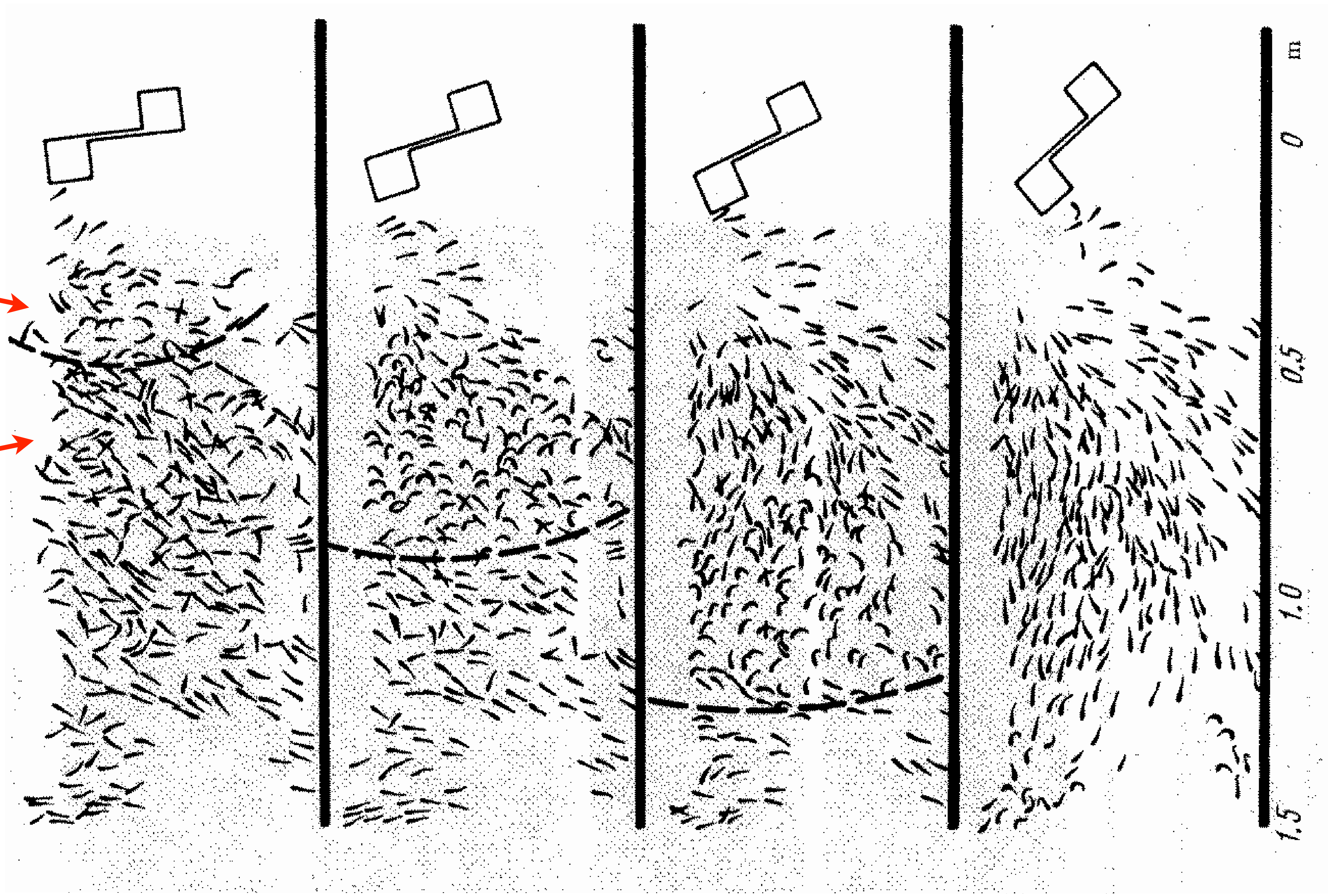
Eaton, 1977

Classical model fails to predict the number of fish responding



Godin et al., 1988

A fish school can transmit information



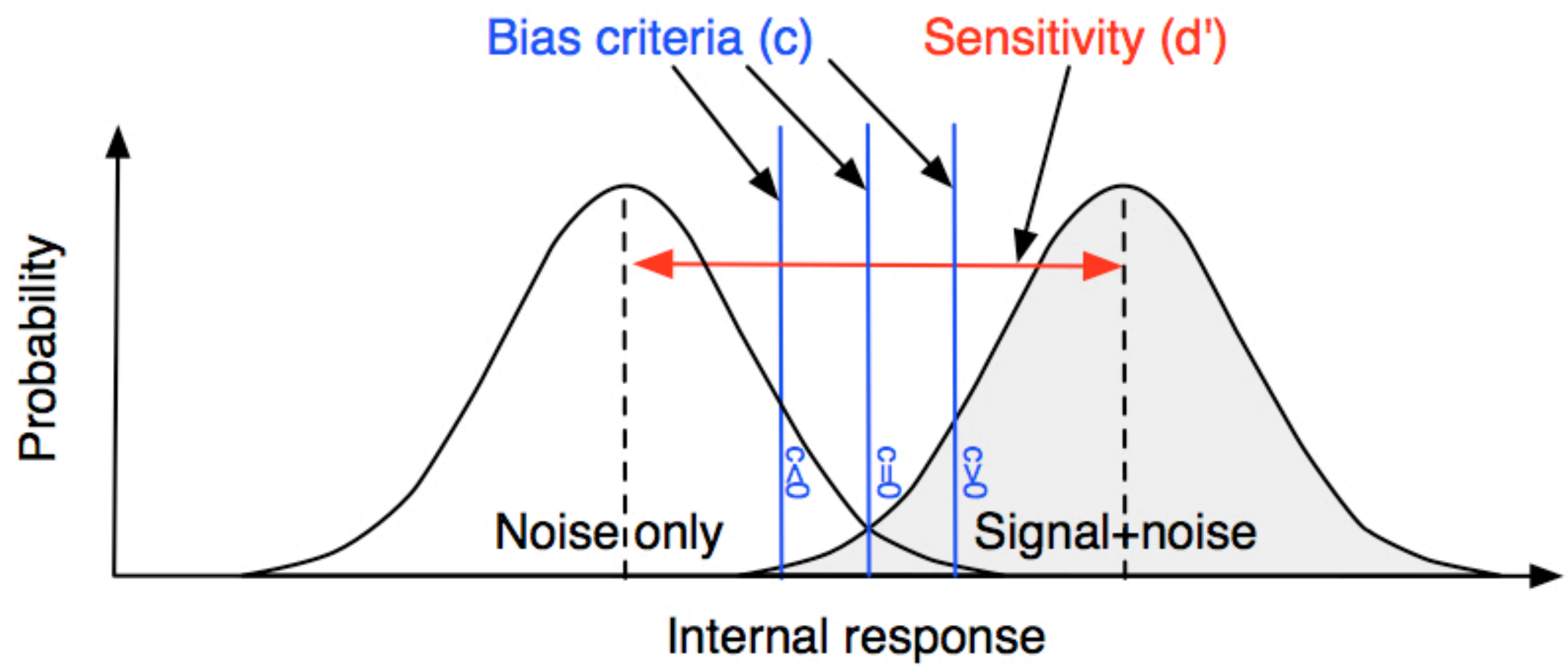
Startled fish

Not (yet) startled

Radakov, 1973

Cooperative threat detection

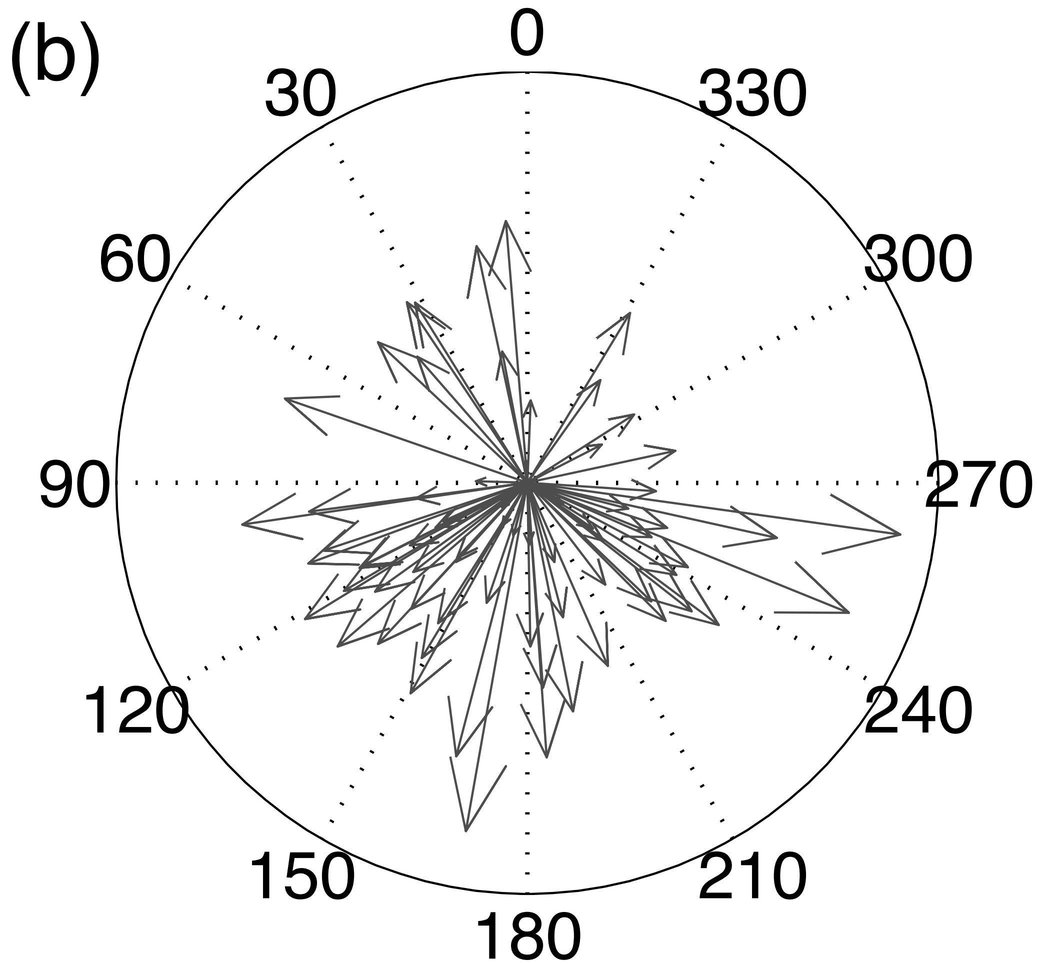
- **Aim**: Quantify the benefits of schooling in a signal-detection framework that distinguishes *bias* and *sensitivity*



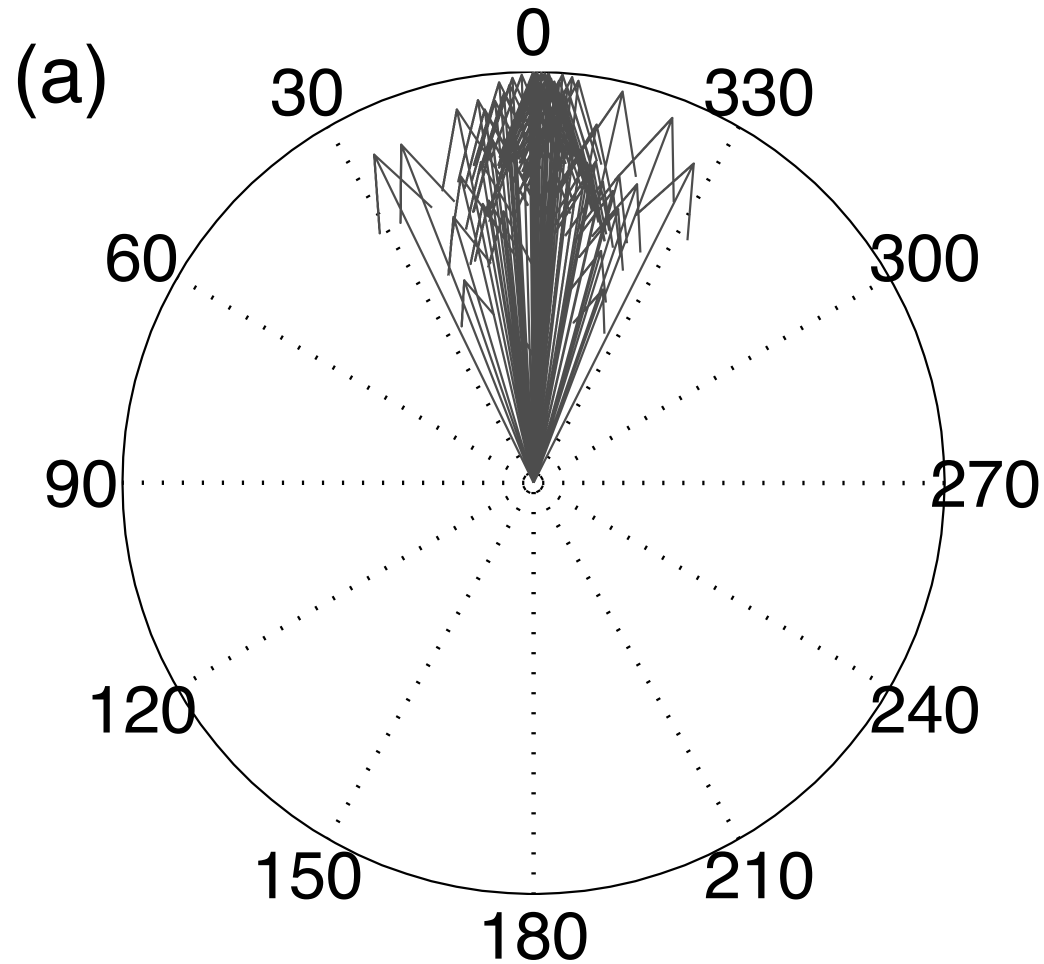
- **Approach**: Use an artificial threat to startle a school whose *density* is manipulated by school size and whose *polarization* is manipulated by an external flow

Tracking two fish with occlusion

Fish orient upstream in flow (rheotaxis)

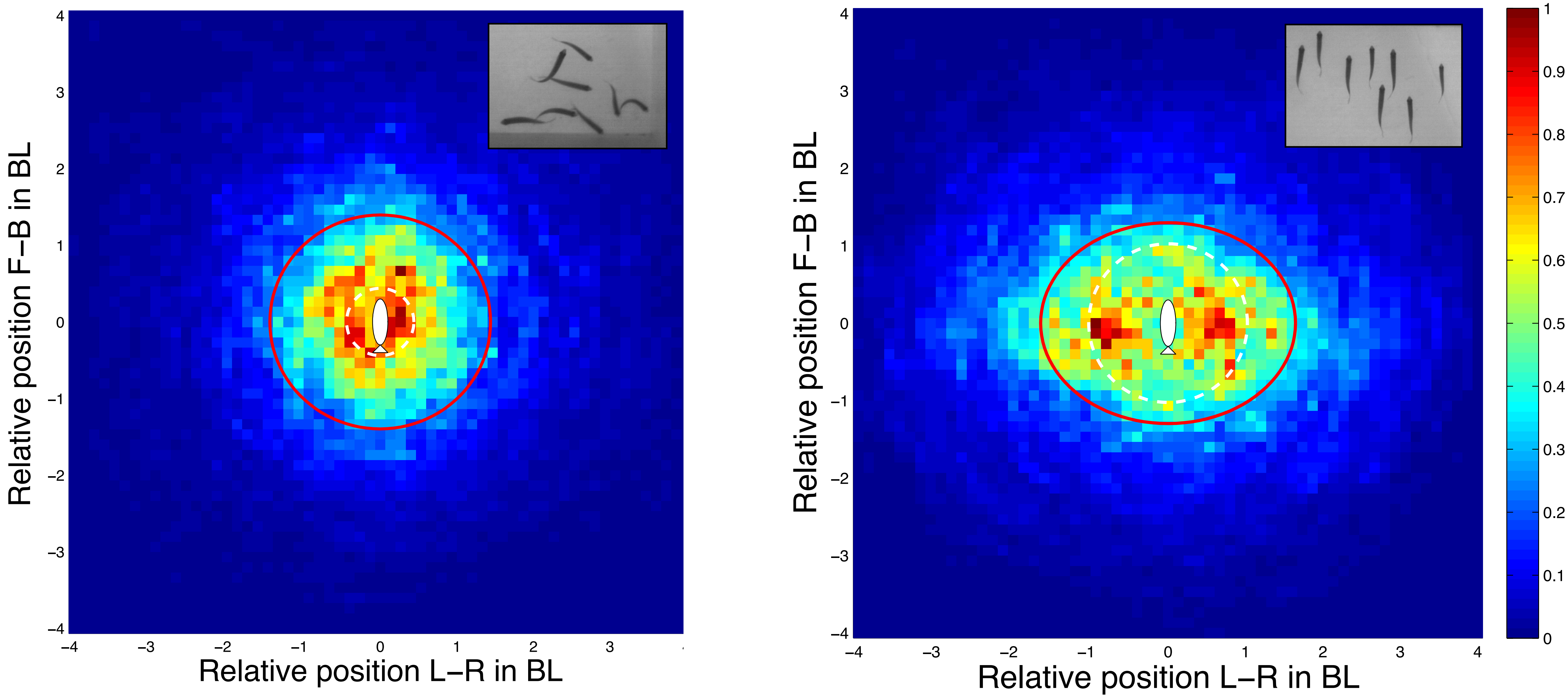


No flow



Flow

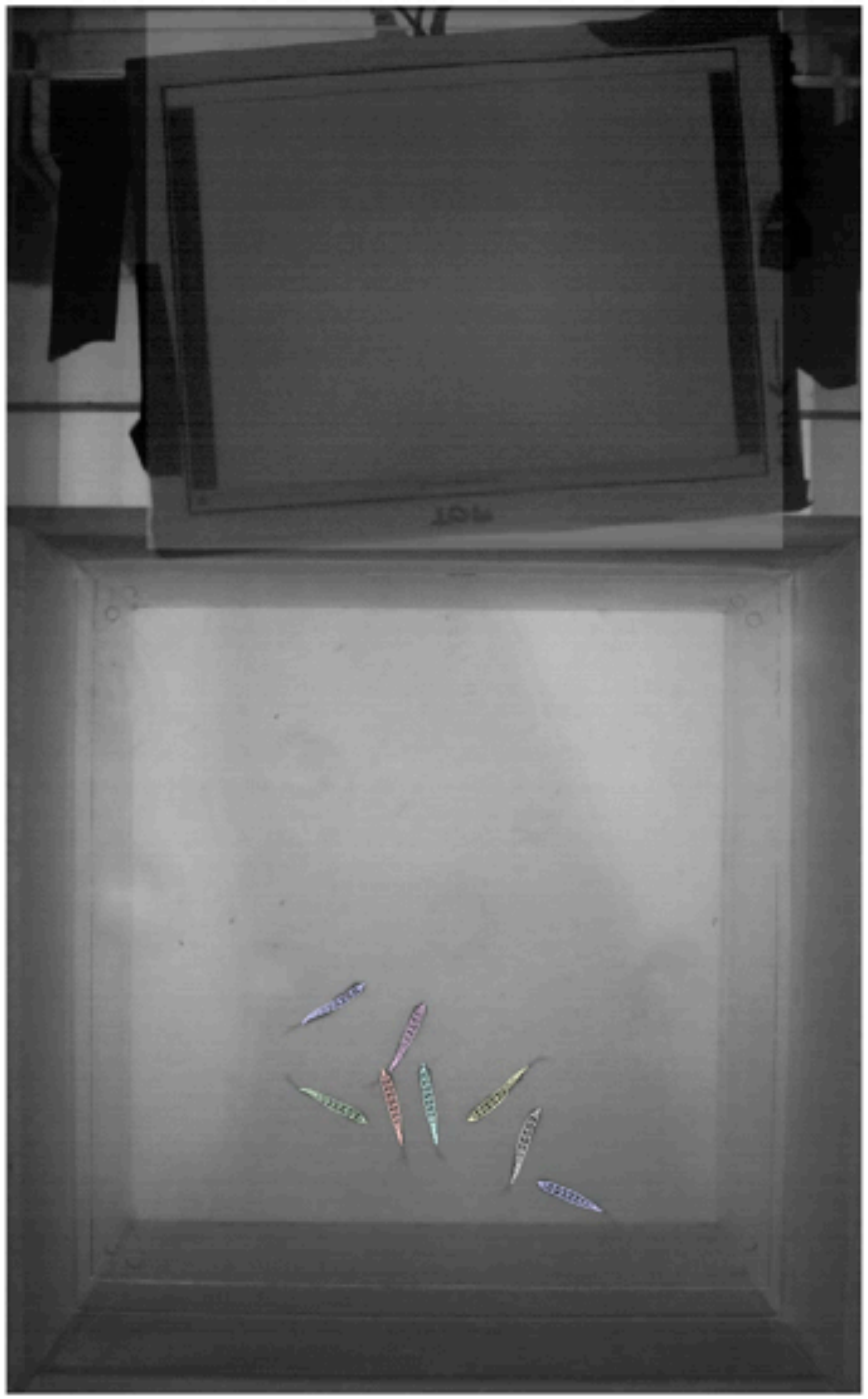
… and the distribution of neighbor position changes



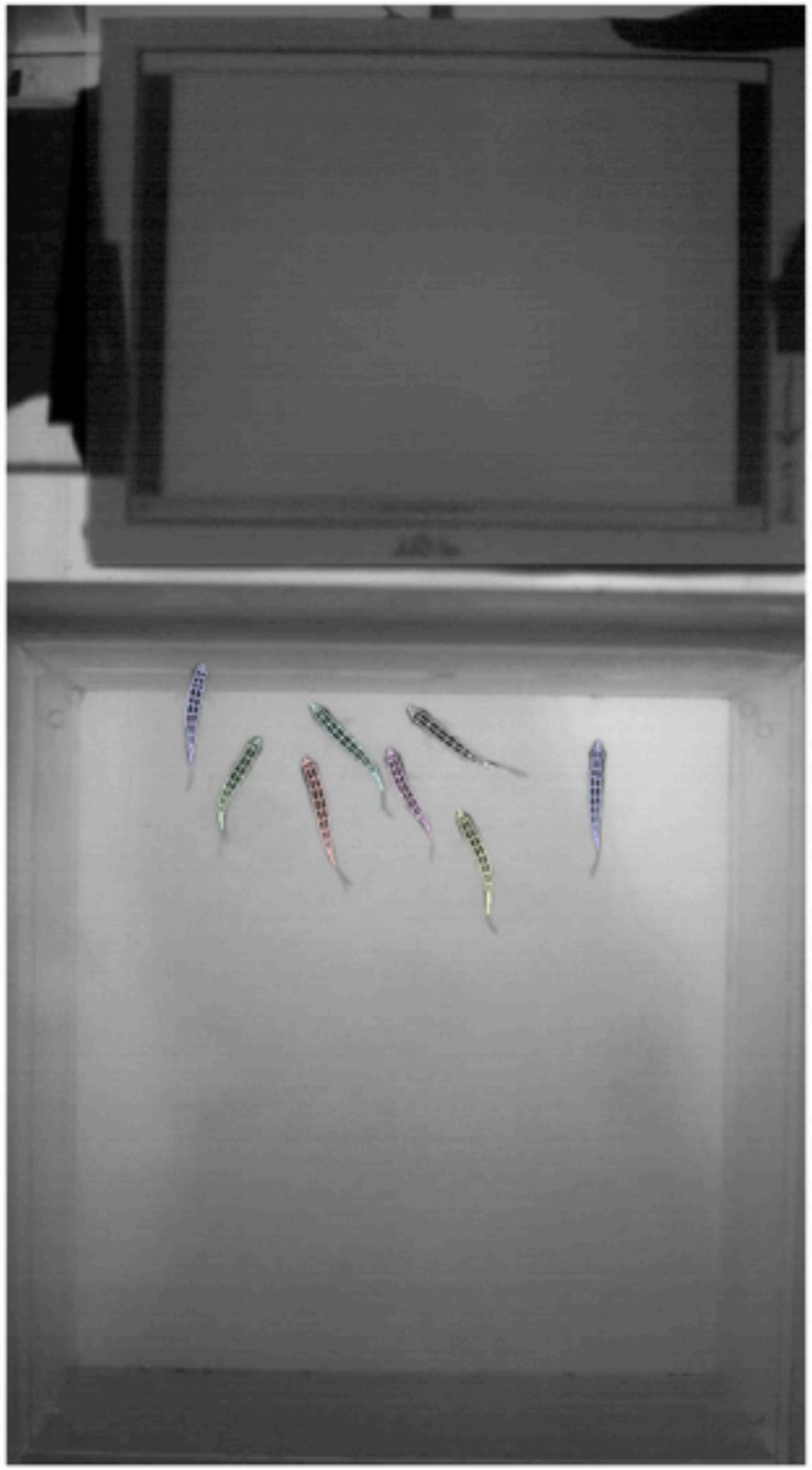
No flow

Flow

Startle response to visual fright stimulus

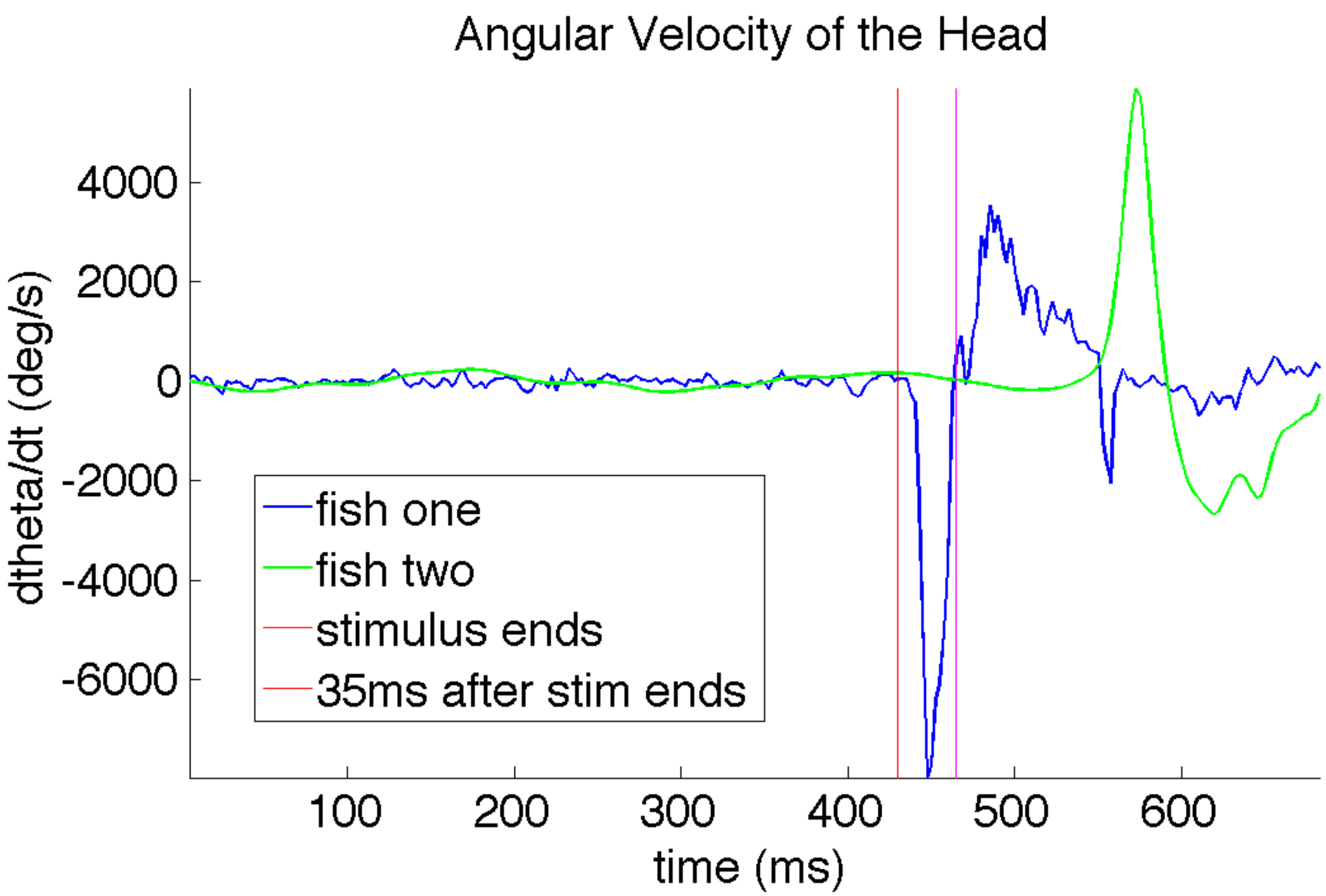


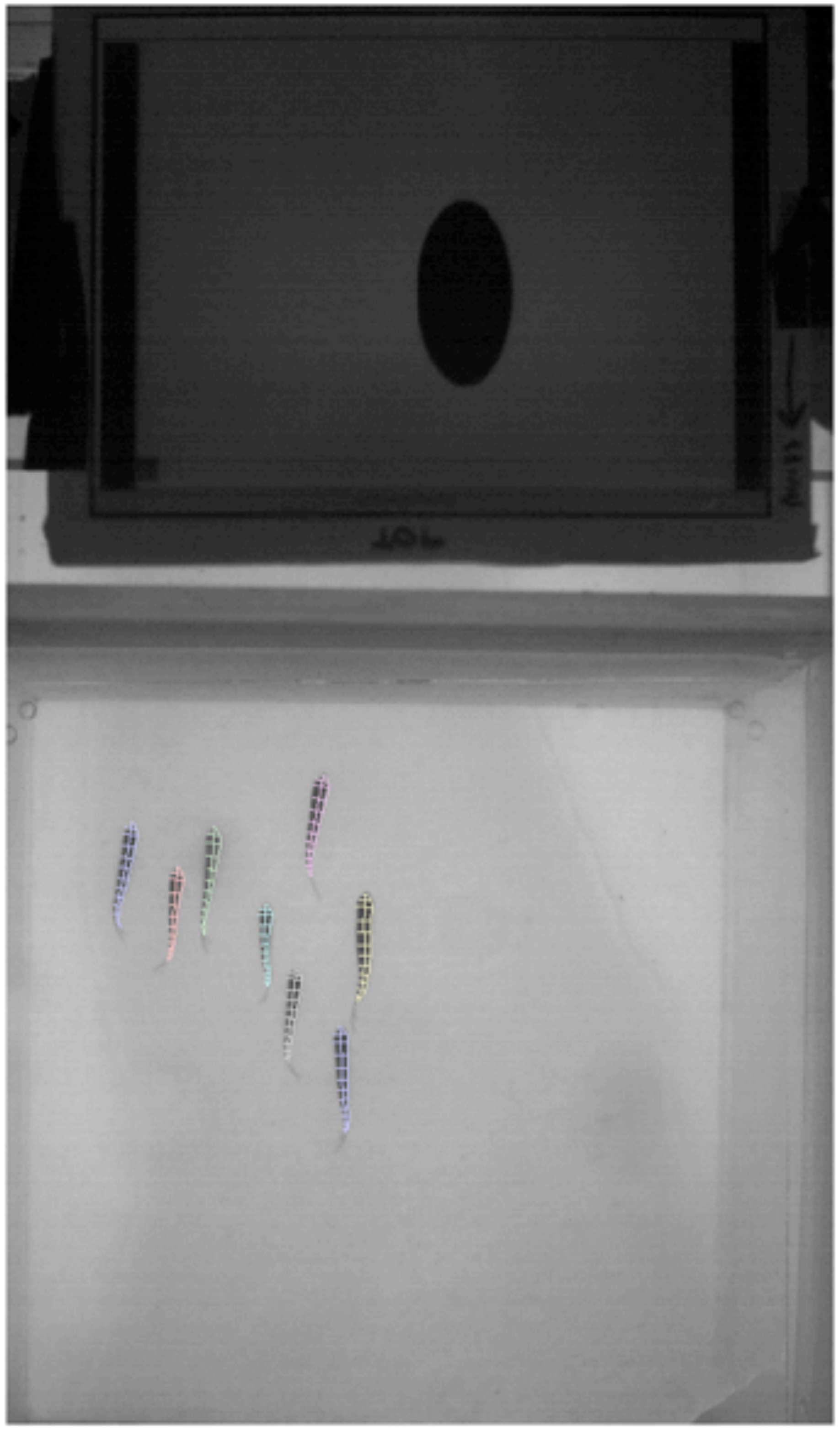
No flow



Flow

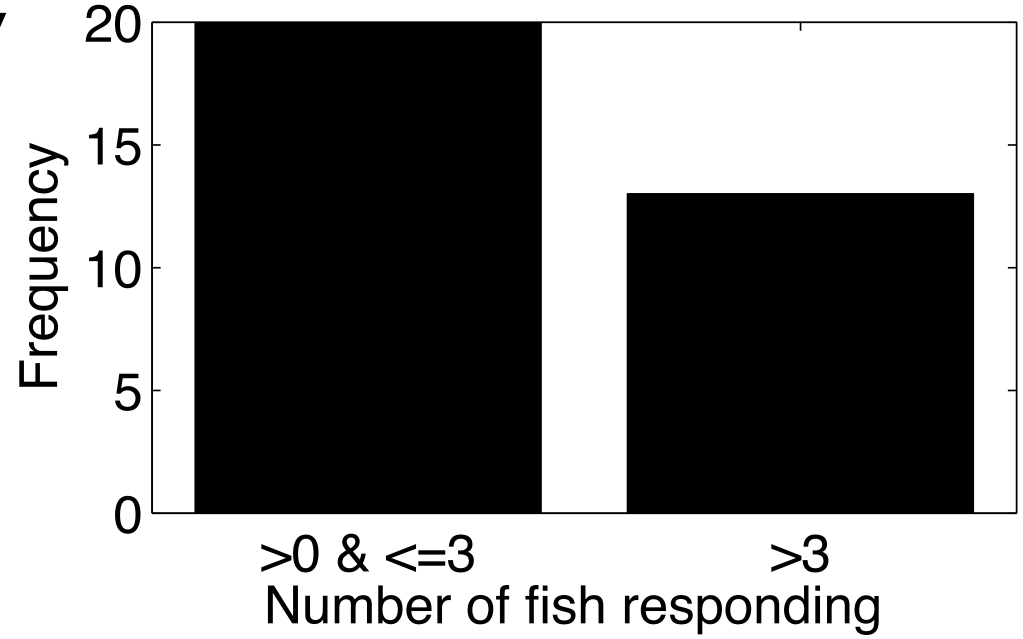
Evidence for internal transmission of information



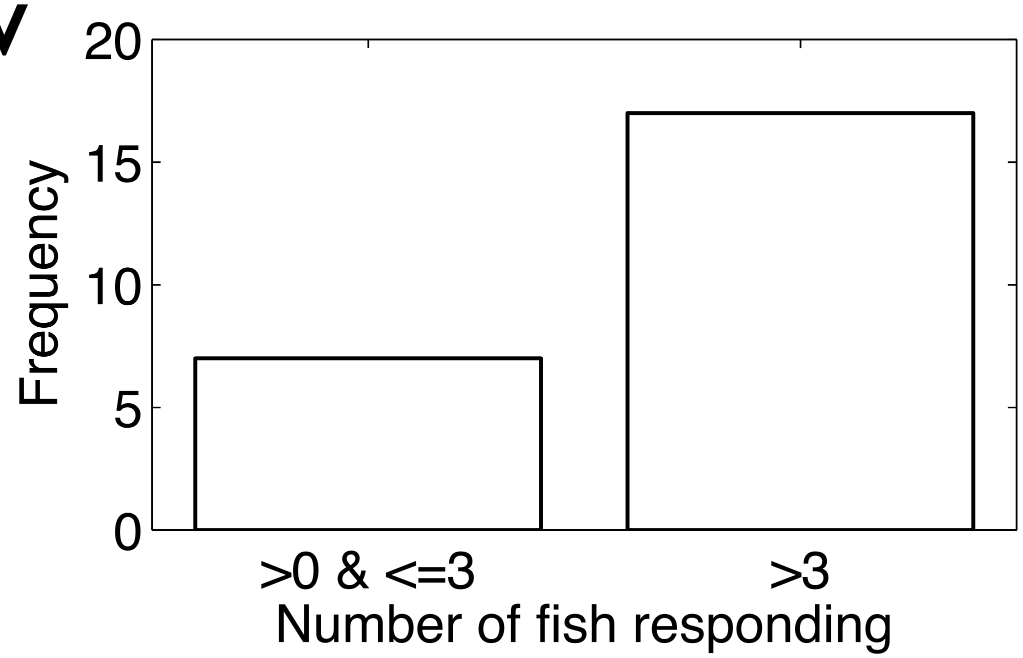


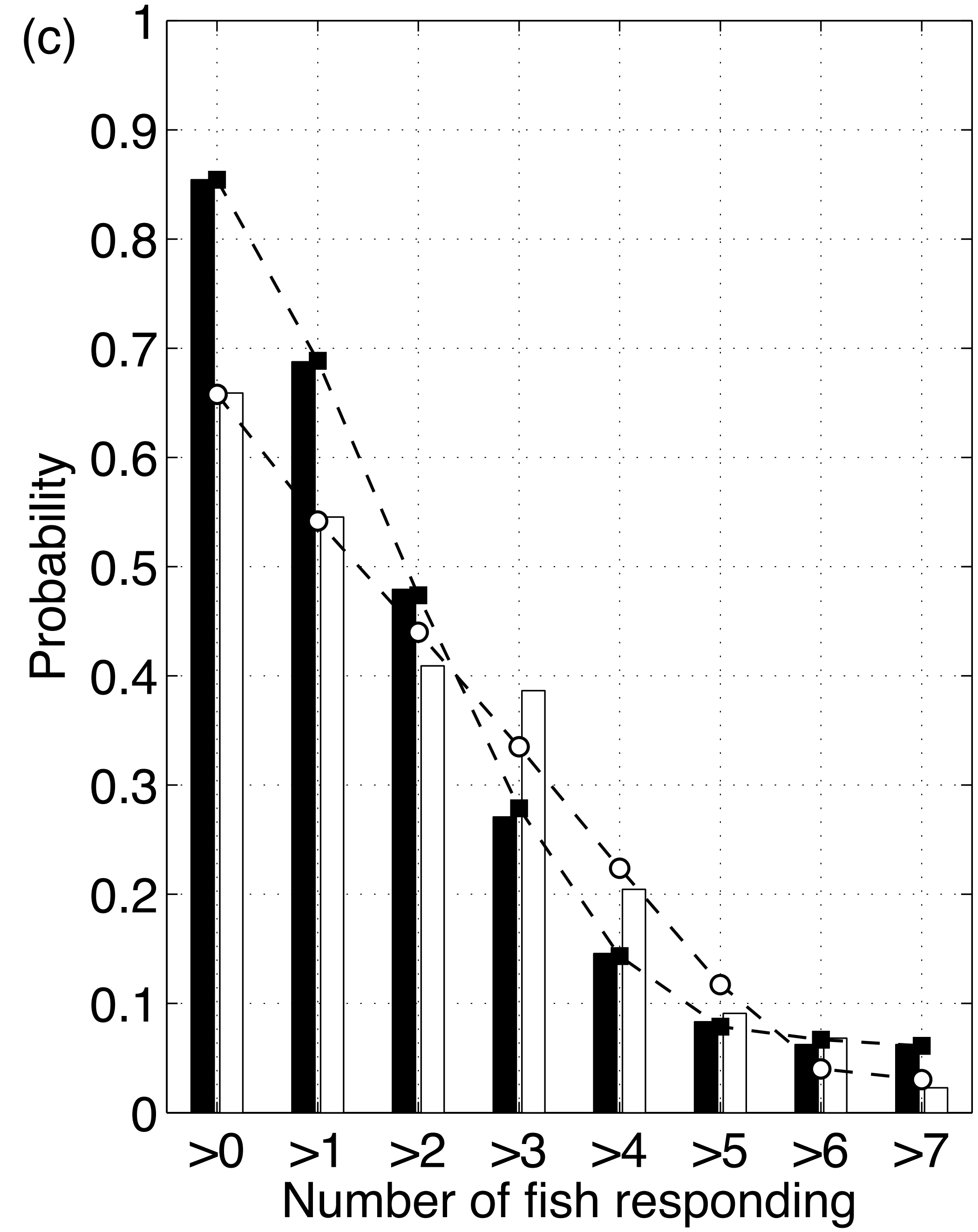
Experimental finding: Number of fish responding changes in flow

Flow



No flow





Probabilistic model predictions

A time-dependent model of startle response captures the probability of direct detection, indirect detection, and false alarms.

$$P_i(t) = 1 - (1 - P^{(far)})(1 - P^{(sus)} P_i(t-1)) \prod_{j \in \mathcal{N}_i(t)} (1 - P^{(int)} P_j(t-1)(1 - P_i(t-1)))$$

Probability of response by fish i at time *t*

Probability of false alarm

Probability of sustaining a startle

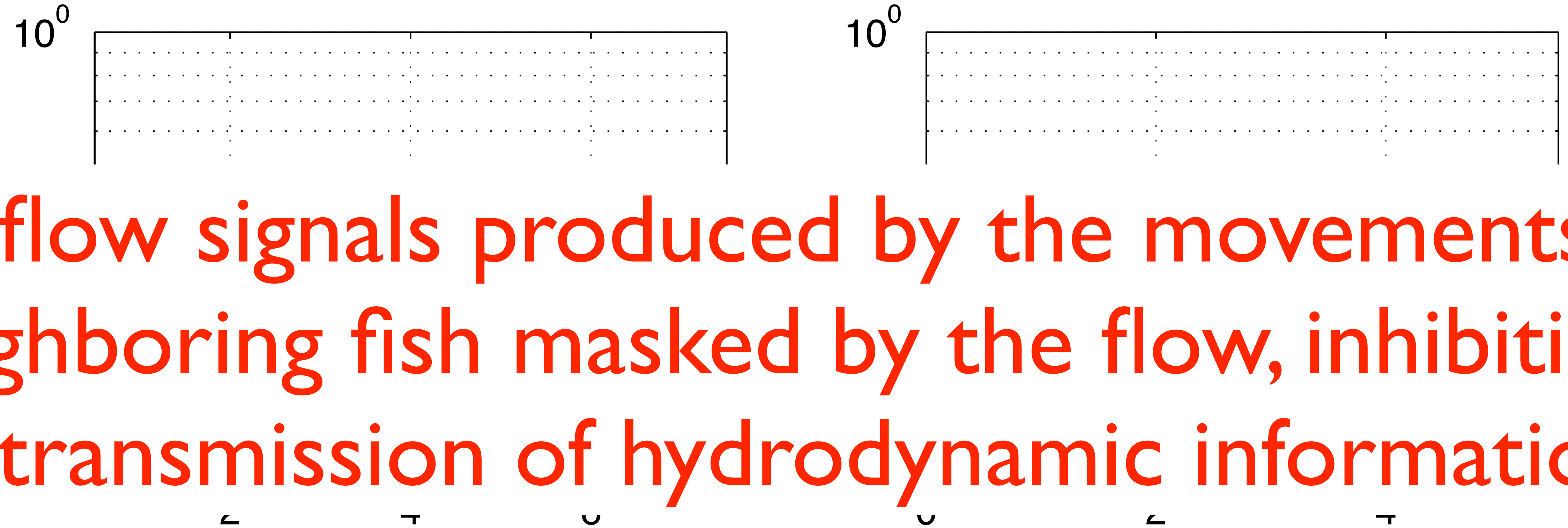
Neighbors of fish *i* at time *t*

Probability of internal information transfer

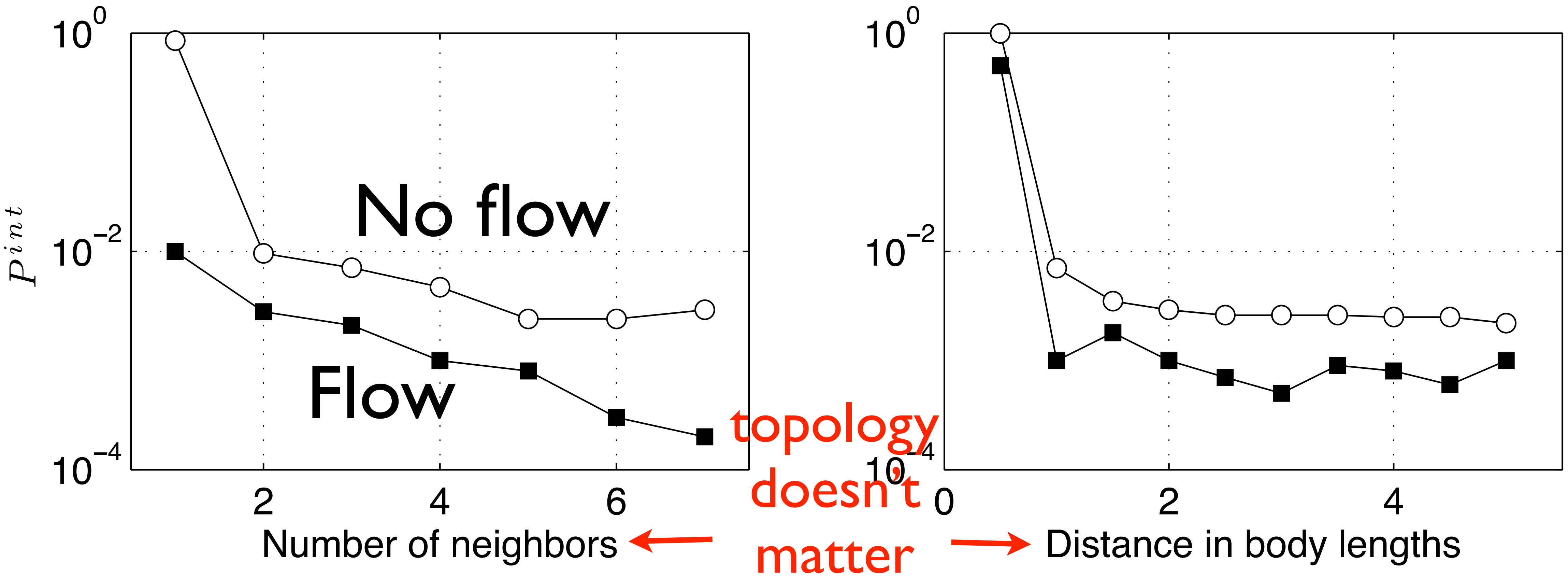
$$P_i(0) = P^{(ext)}$$

Probability of detection of external threat

Results from fitting model output to data



Are flow signals produced by the movements of neighboring fish masked by the flow, inhibiting the transmission of hydrodynamic information?



Outline of talk

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   (Amanda Chicoli, Sheryl Coombs @ BGSU)

2. Motion coordination in mosquito mating swarms

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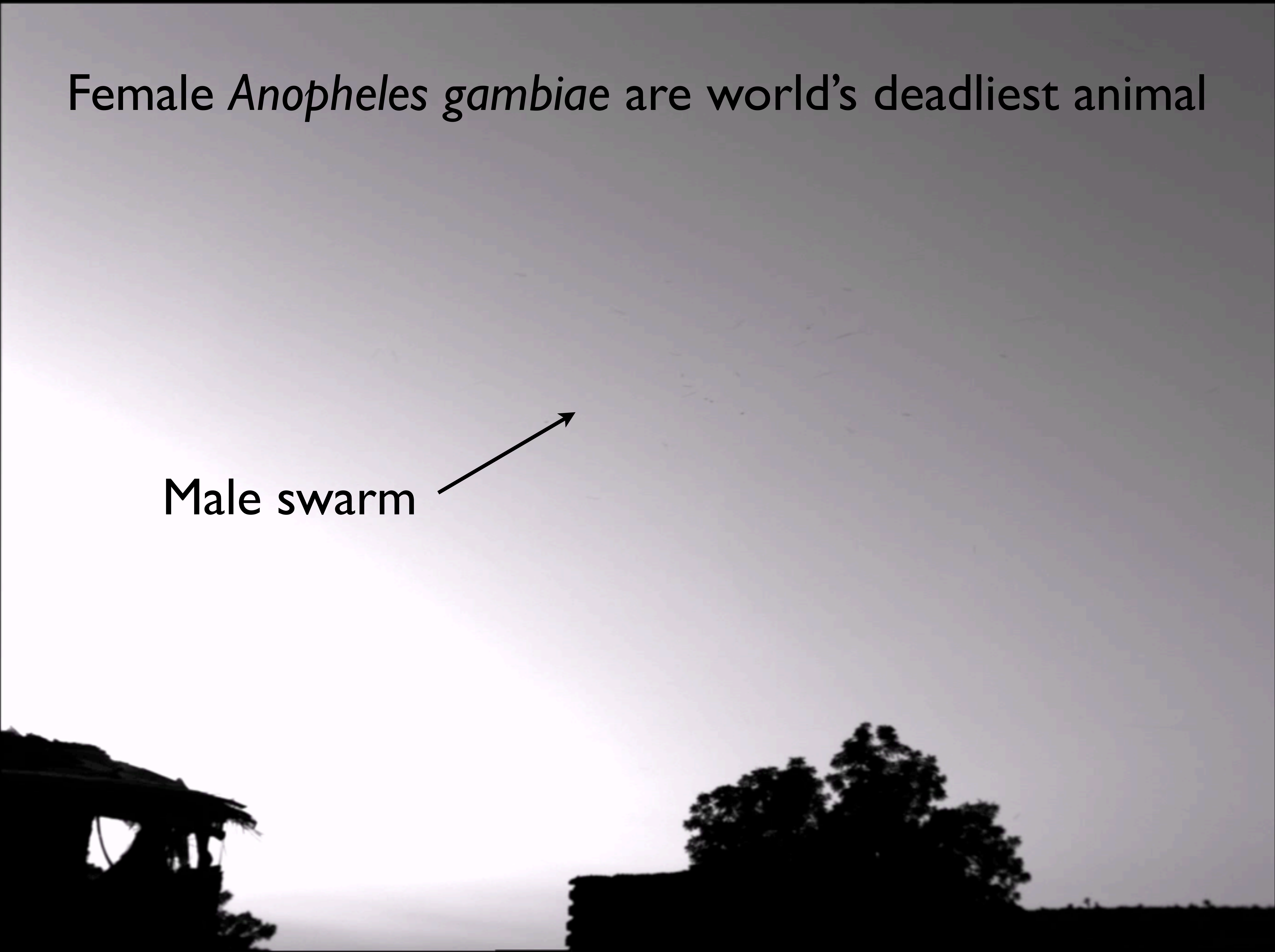
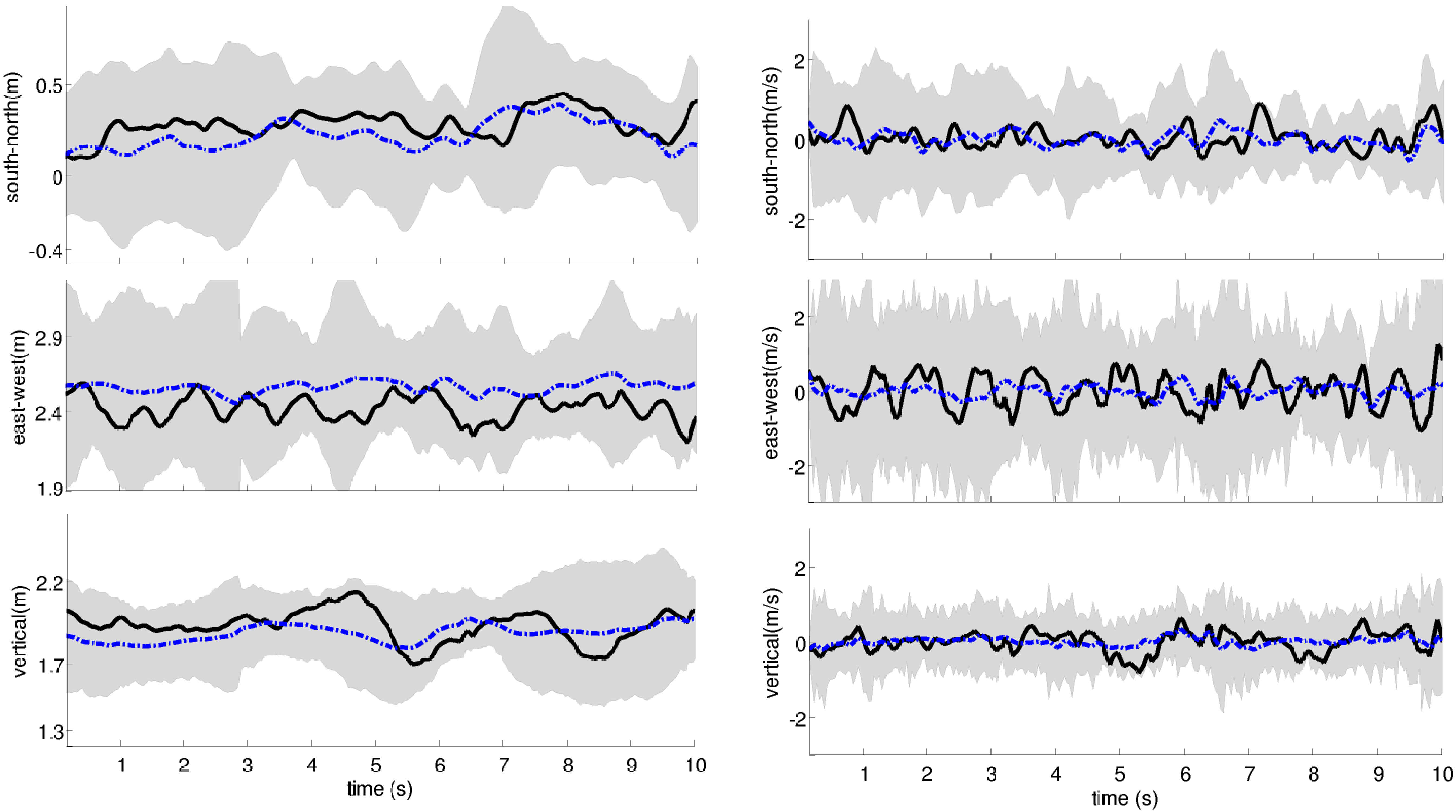

Female *Anopheles gambiae* are world's deadliest animal
Male swarm

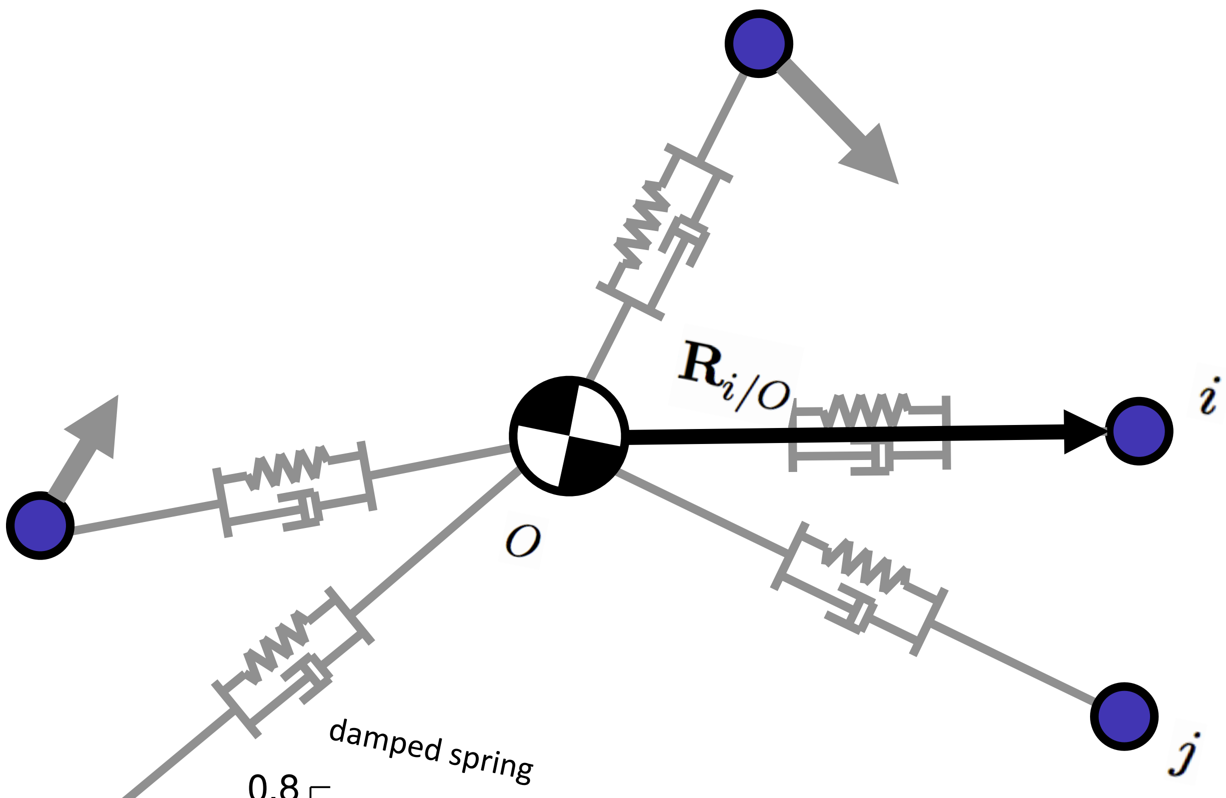
Graduate student Sachit Butail filming in Mali (2010)

Male trajectories



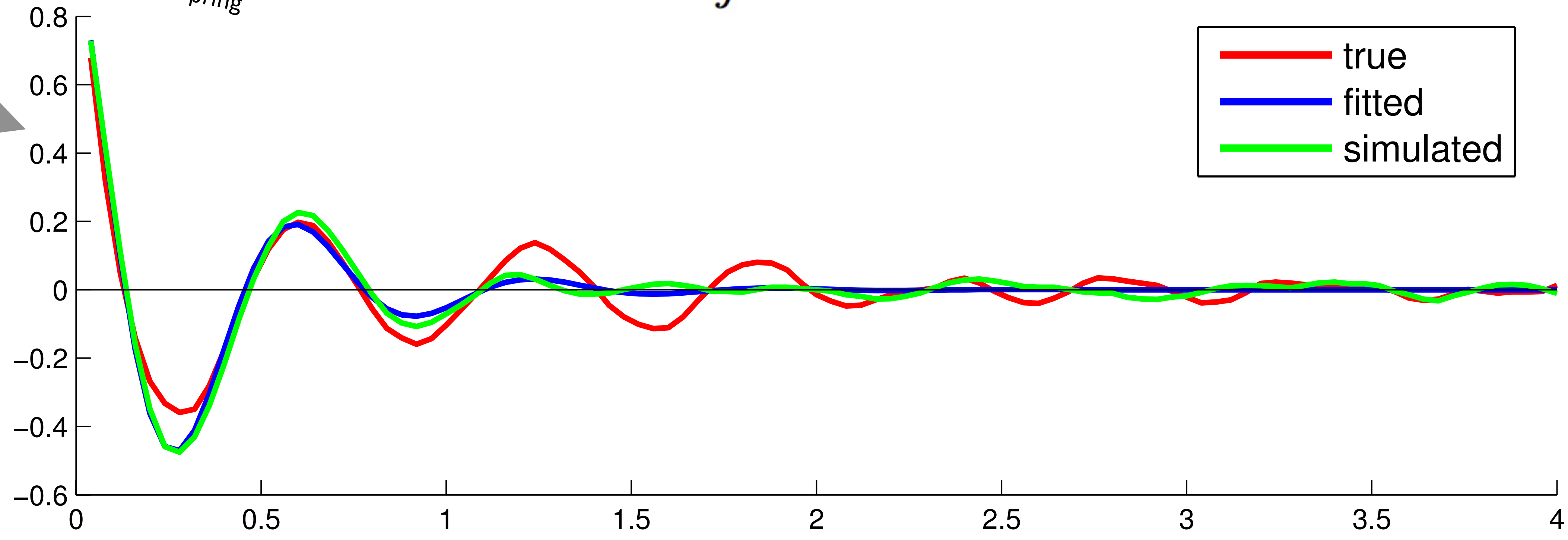
black = single male blue = swarm centroid

Velocity autocorrelation model

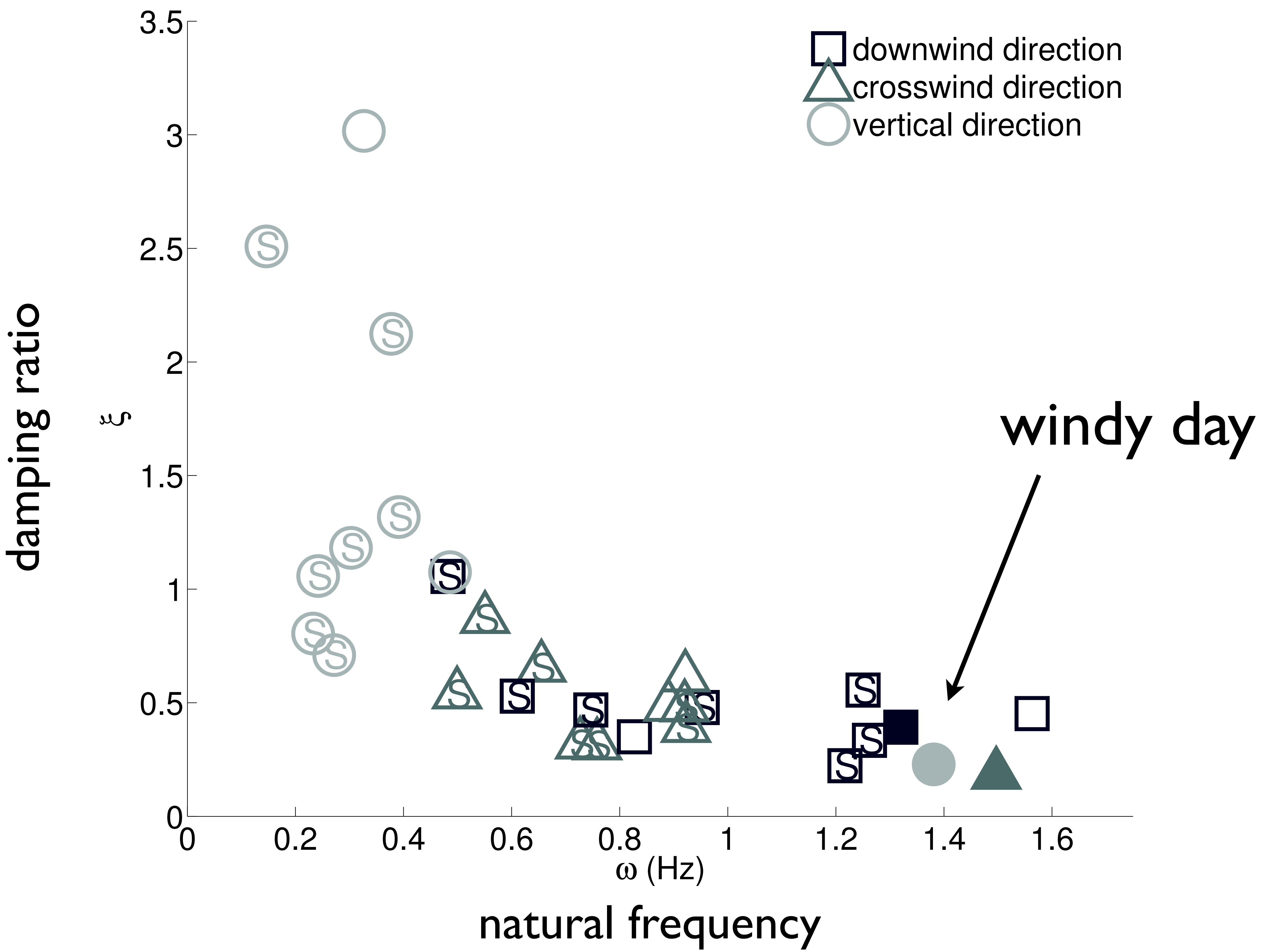


$$\ddot{r} + 2\xi\omega_0\dot{r} + \omega_0^2 r = W$$

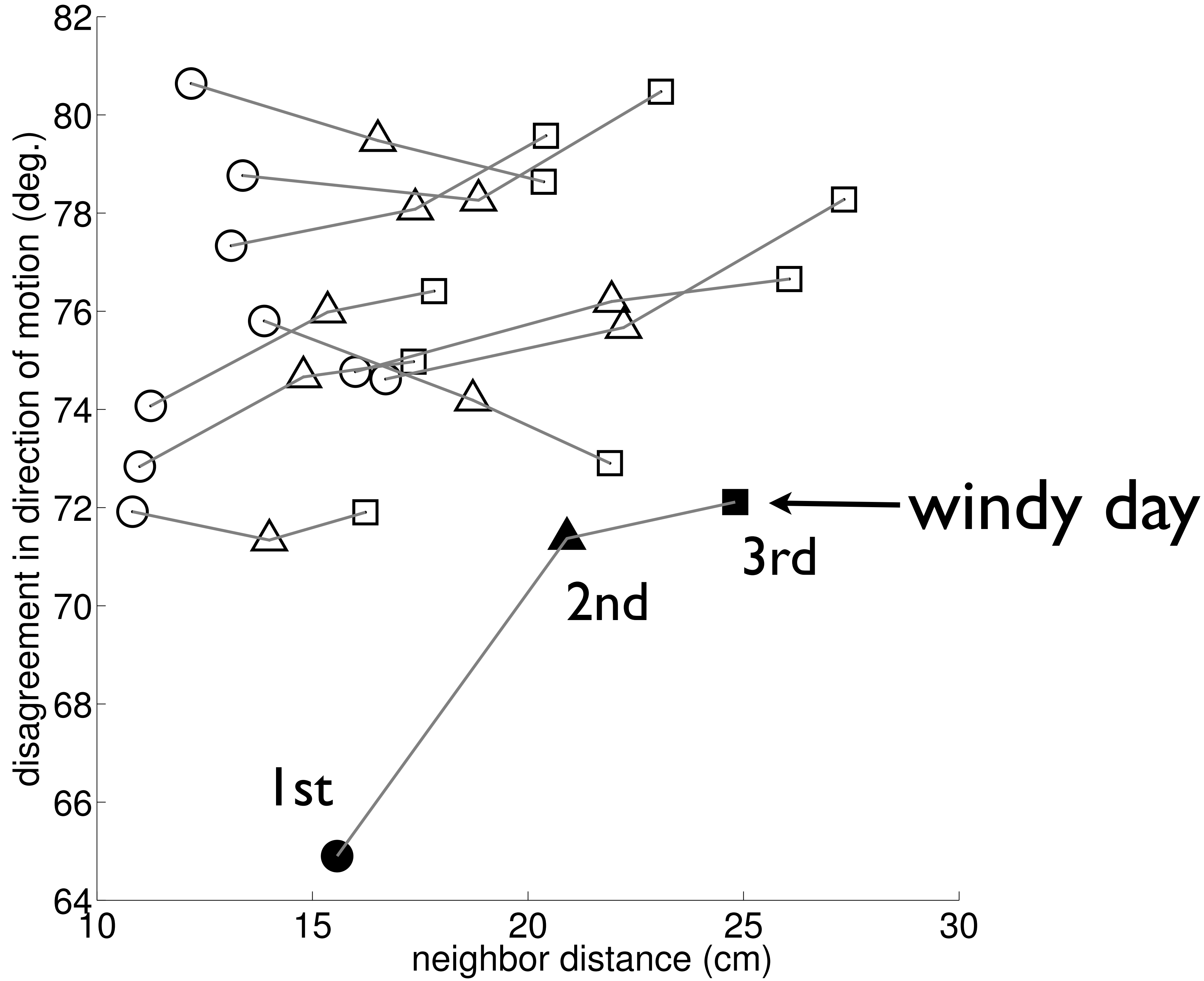
Okubo, 1986



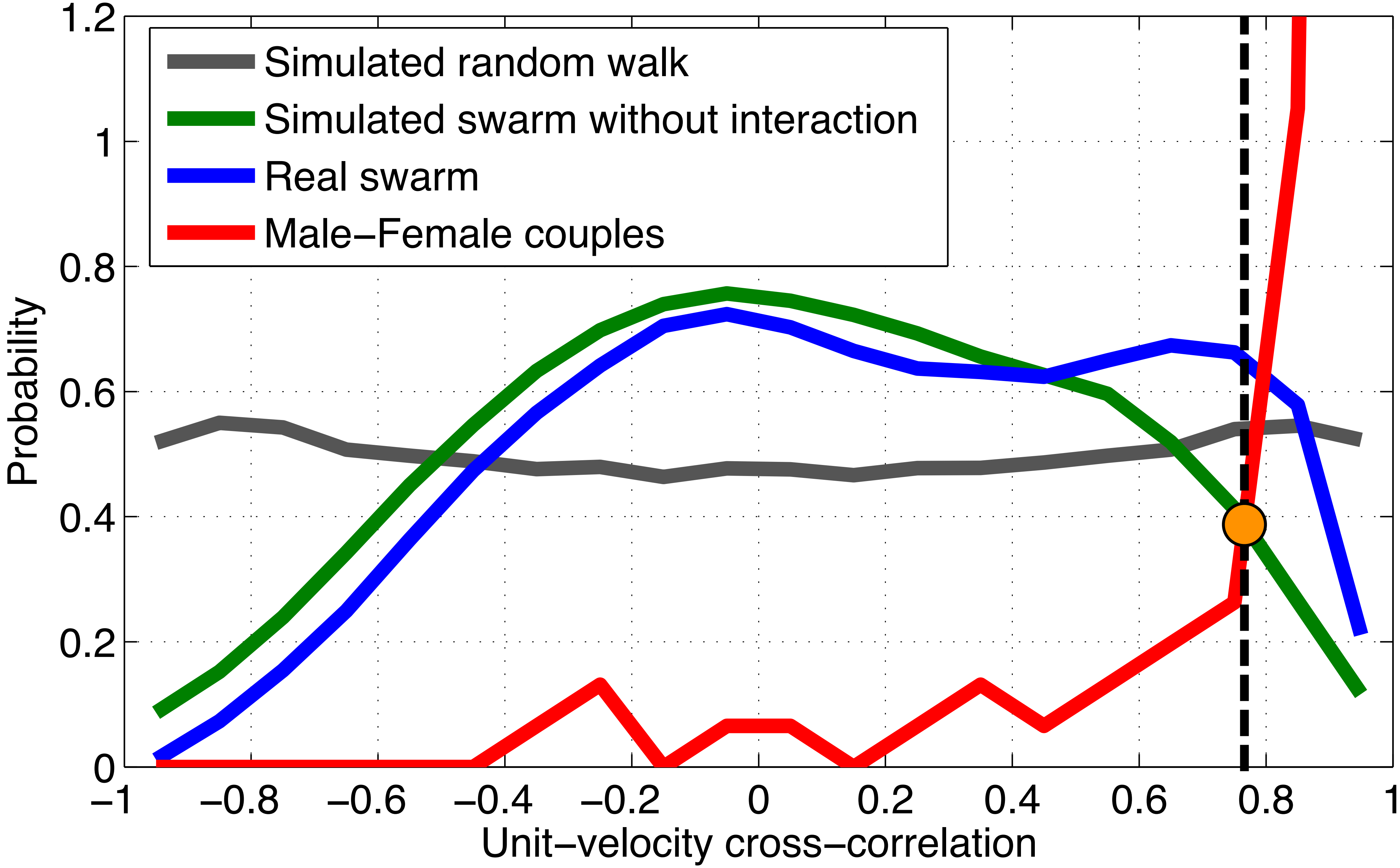
2nd-order model fits



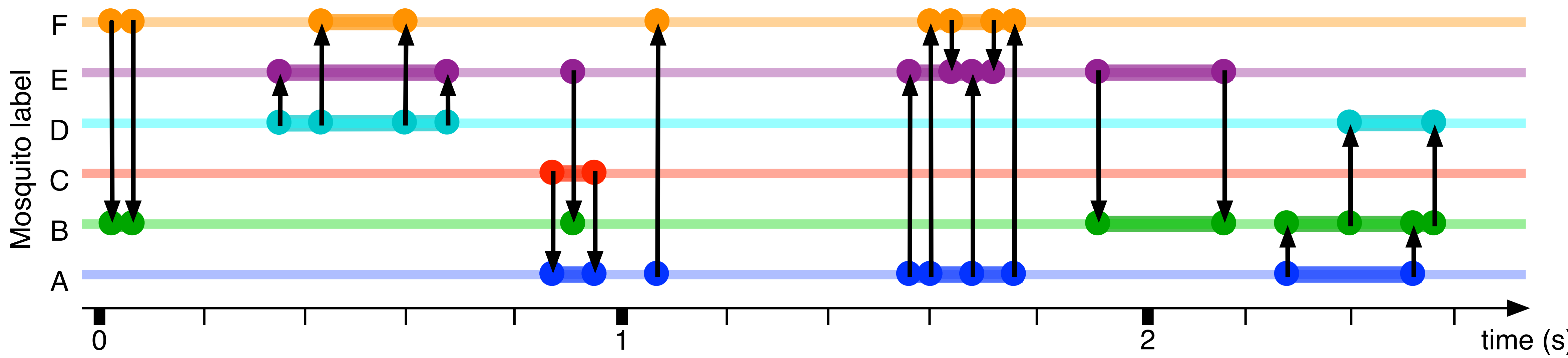
“Okay, but aren’t they *interacting*?”



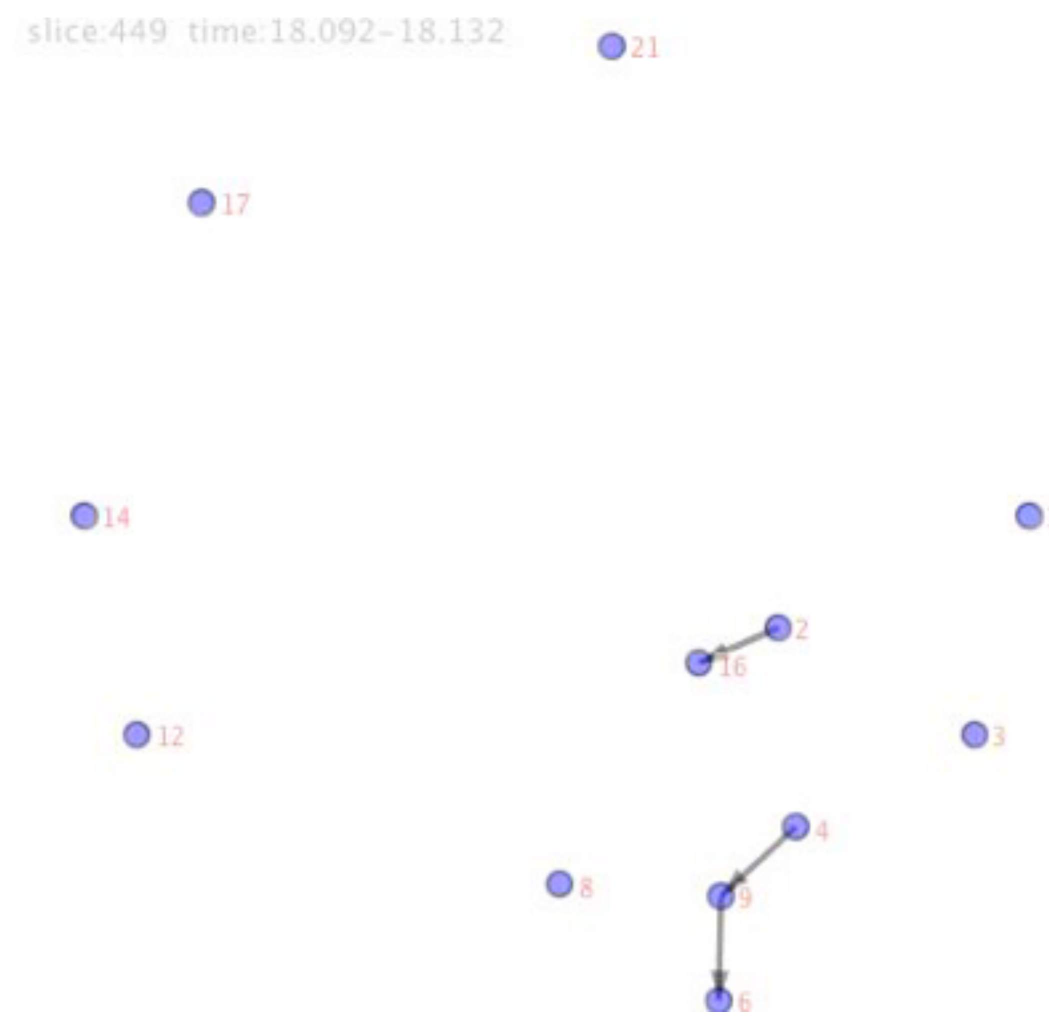
Swarming model without local interaction



Correlation-induced interaction graph

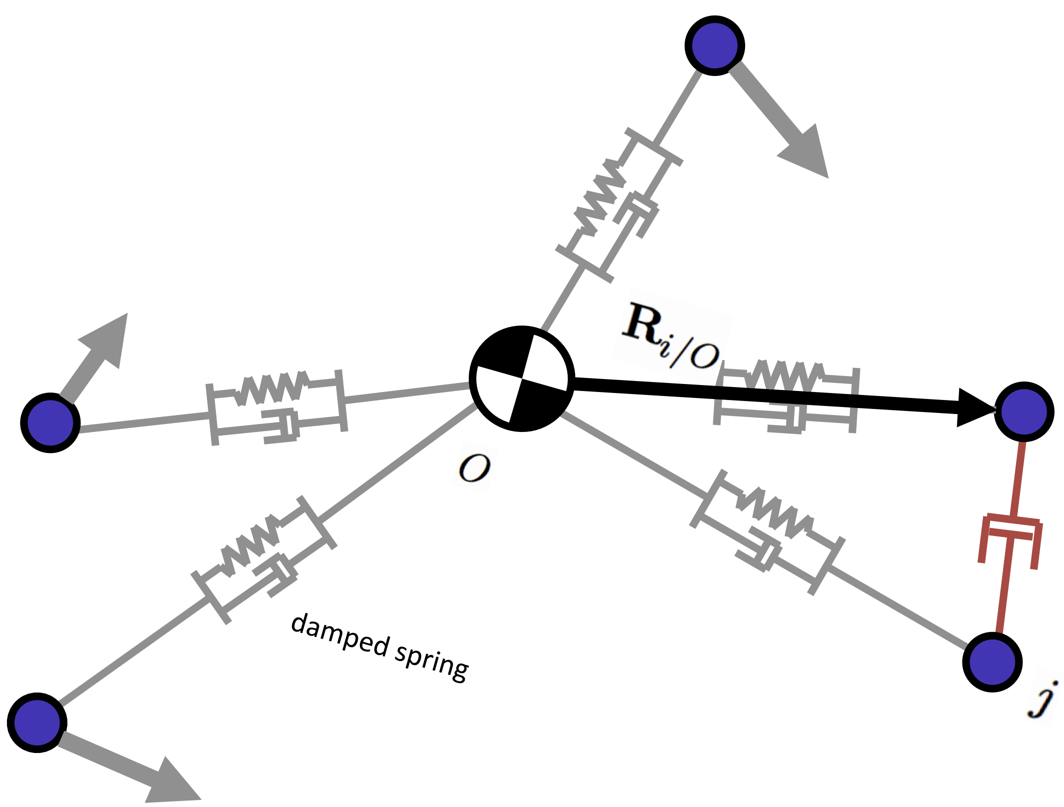


- Males form synchronized subgroupscwhose size and members change dynamically in time (real data)
- Link arrows indicate presence of uni- and bi-directional interactions



Interactive swarm model

- Swarming model *without* interaction: damped spring between each insect and swarm centroid
- Swarming model *with* interaction: include velocity damper between interacting insects

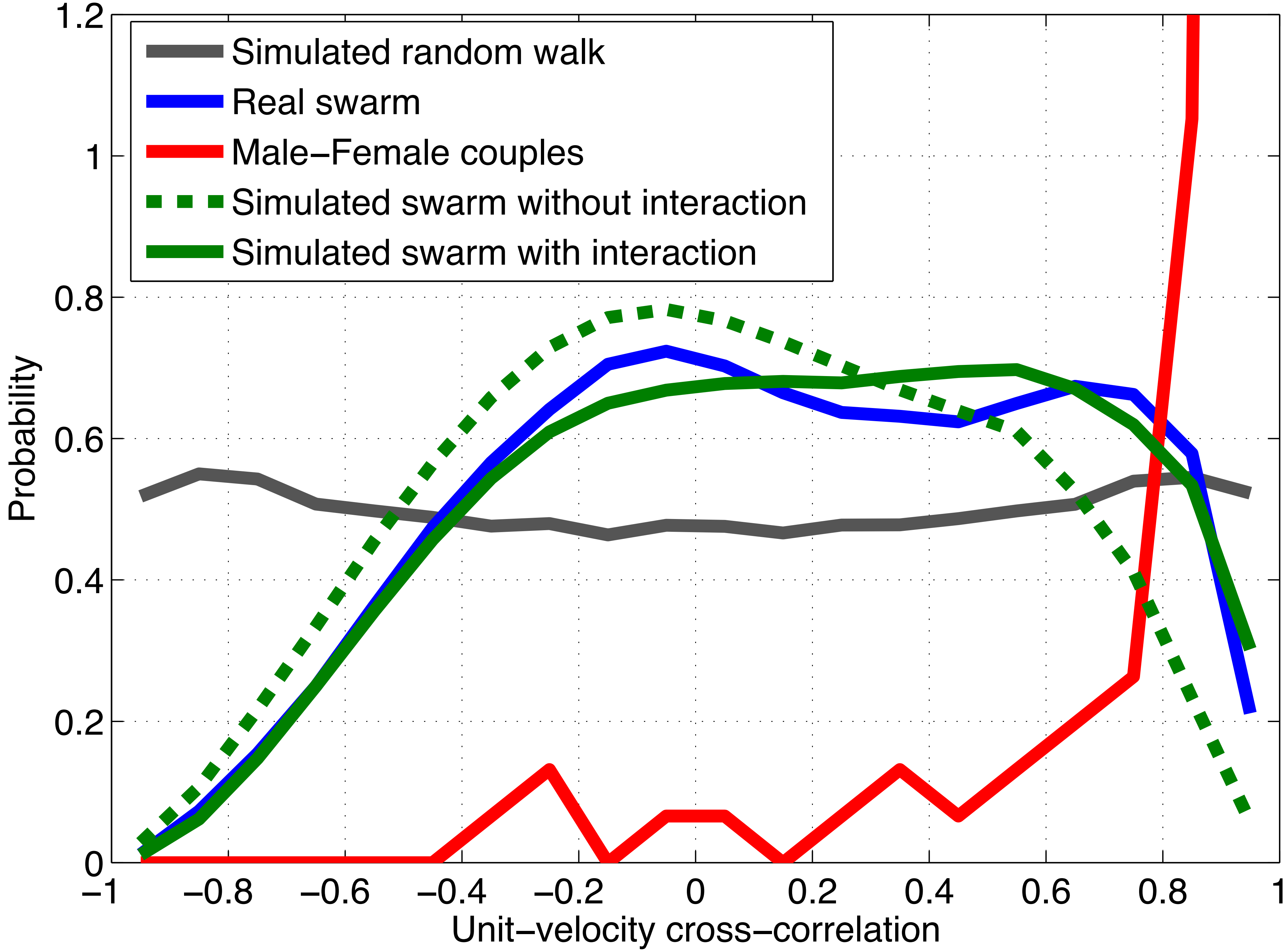


$$m\ddot{\mathbf{R}}_{i/O} = \mathbf{F}_i^{(ext)} + \mathbf{F}_i^{(drag)} + \mathbf{F}_i^{(int)}$$

$$\mathbf{F}_i^{ext} + \mathbf{F}^{drag} = -k\mathbf{R}_{i/O} - b\left(\dot{\mathbf{R}}_{i/O} \cdot \mathbf{r}_i\right)\mathbf{r}_i$$

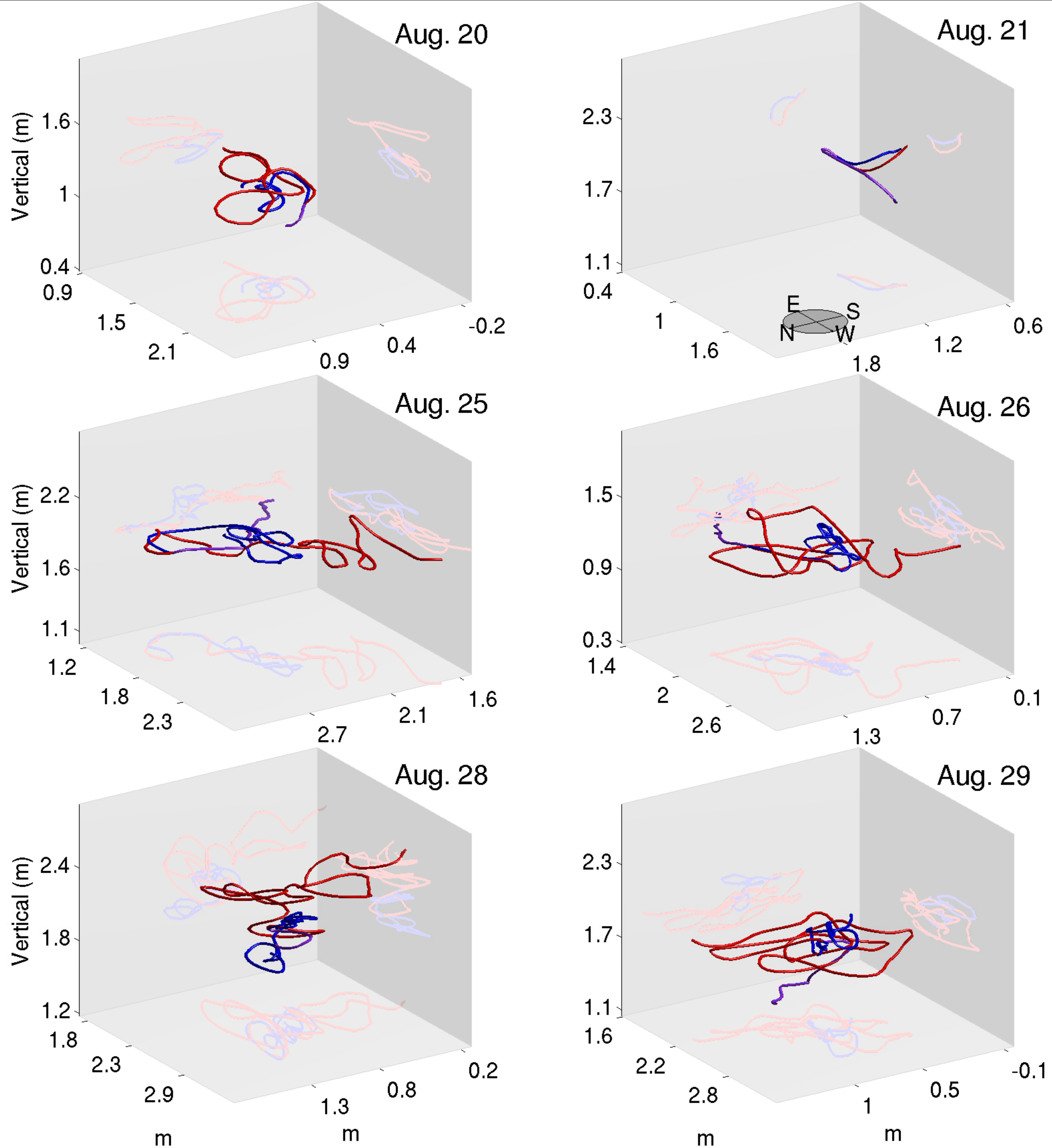
$$\mathbf{F}_i^{(int)} = \begin{cases} \text{White Noise} & \text{(if in non-interacting state)} \\ \sum_{j \in \mathcal{A}} b_{int}\left(\dot{\mathbf{R}}_{j/i} \cdot \mathbf{r}_{j/i}\right)\mathbf{r}_{j/i} & \text{(if in interacting state)} \end{cases}$$

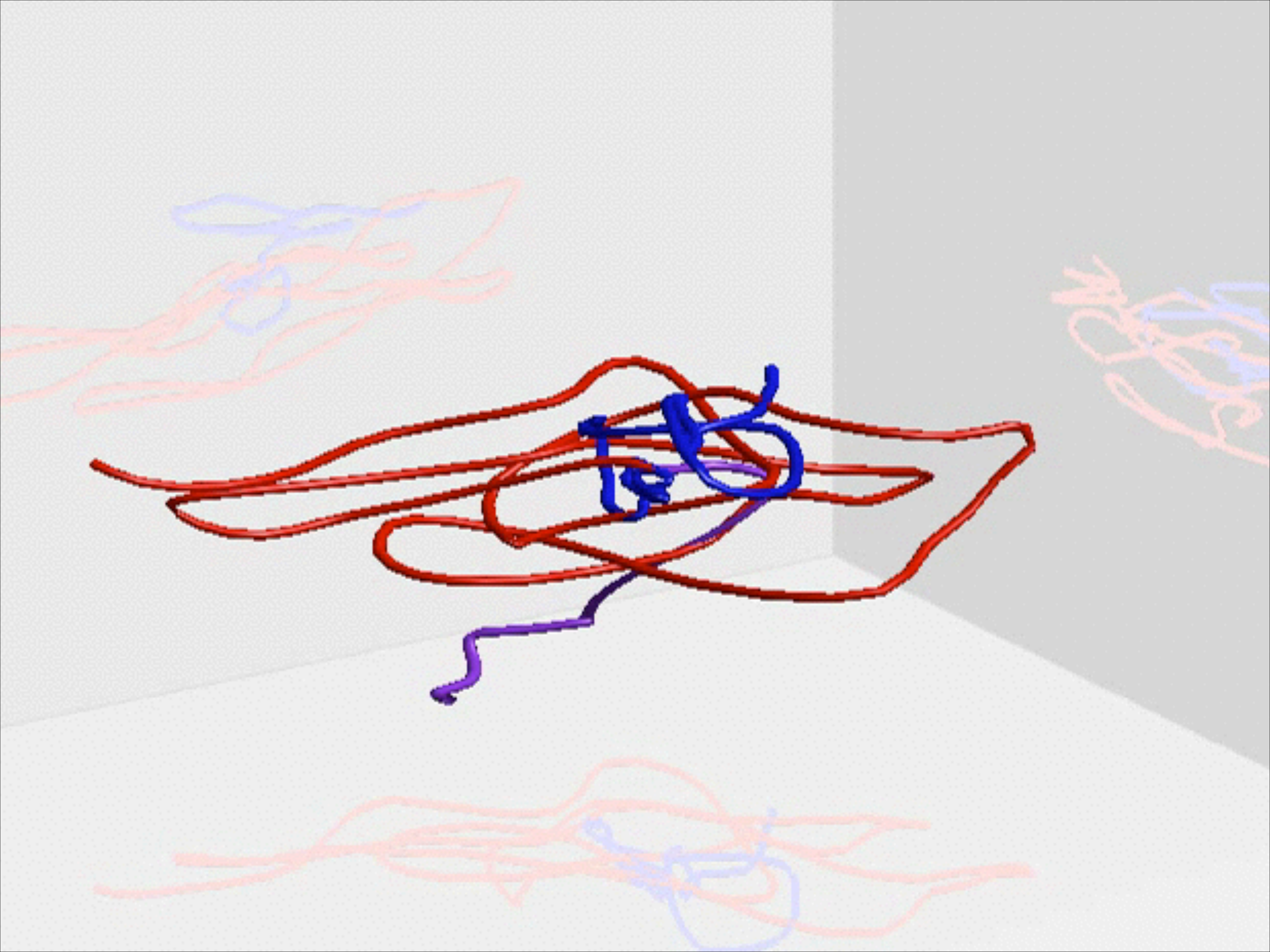
Swarming model with local interaction fits data better



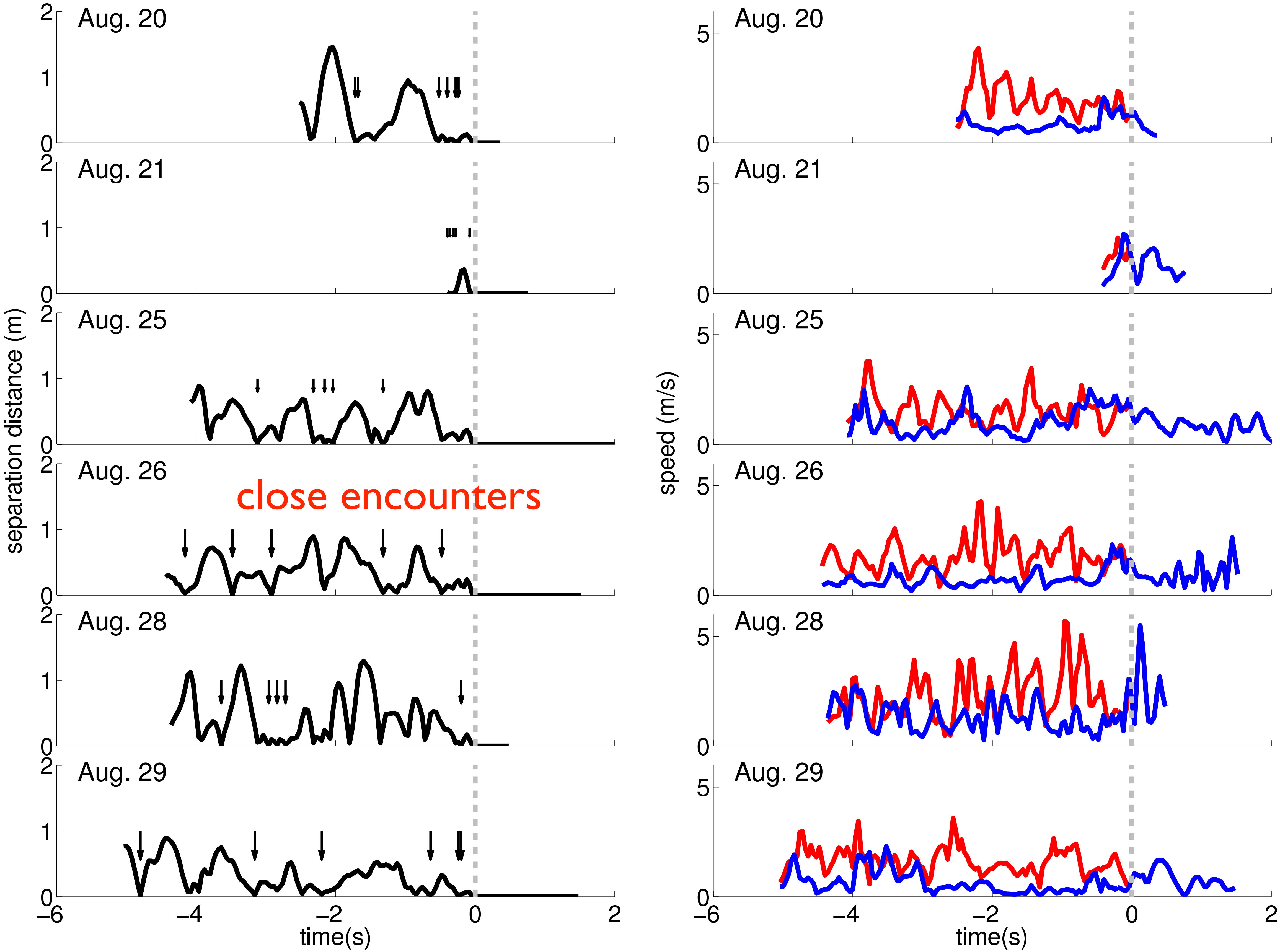
Six mating events

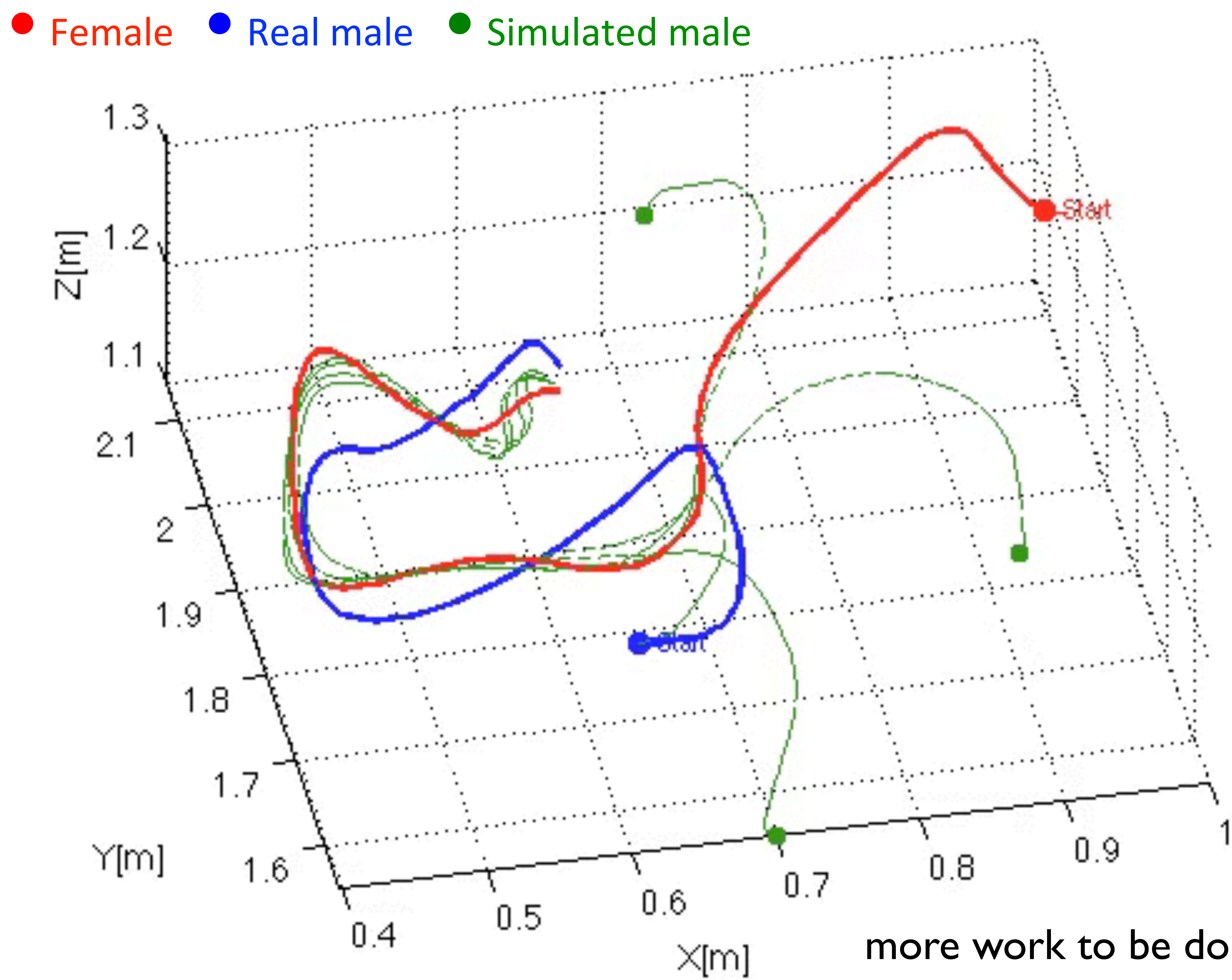
blue = male red = female purple = couple





Six mating events





more work to be done…

Collective behavior in bio-groups

Summary: Tools from computer vision and nonlinear estimation have yielded 3D kinematics of

-schooling fish (up to eight)

-swarming mosquitoes (more than fifty)

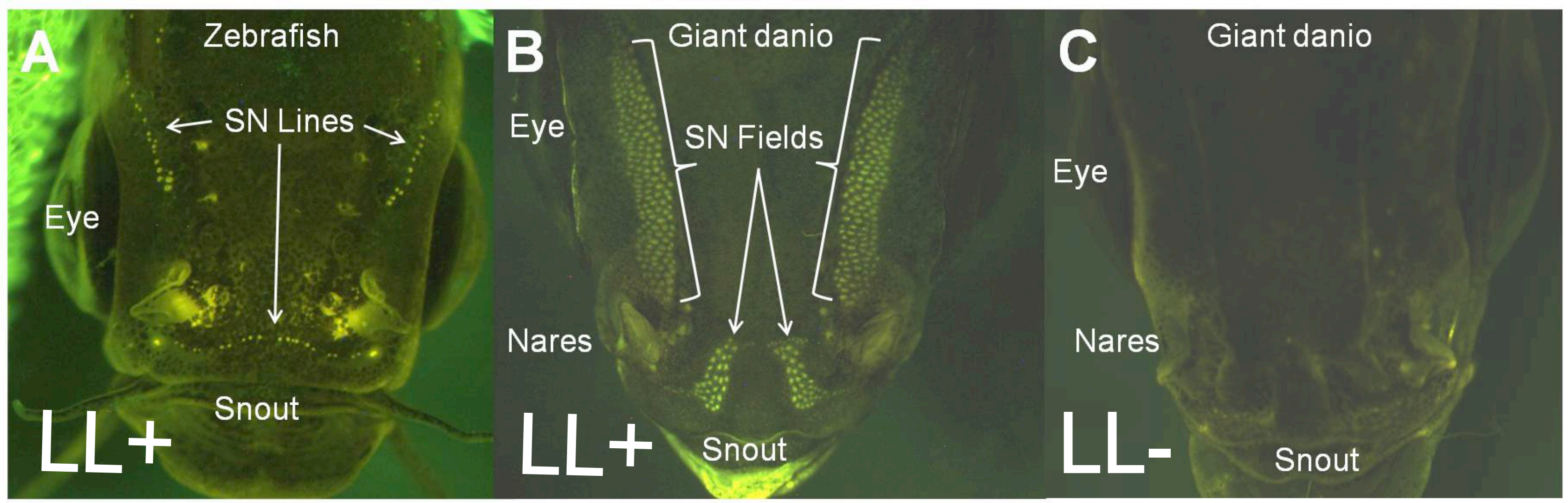
Ongoing work: Analysis of trajectory data is yielding insights via

-dynamic modeling of collective behavior

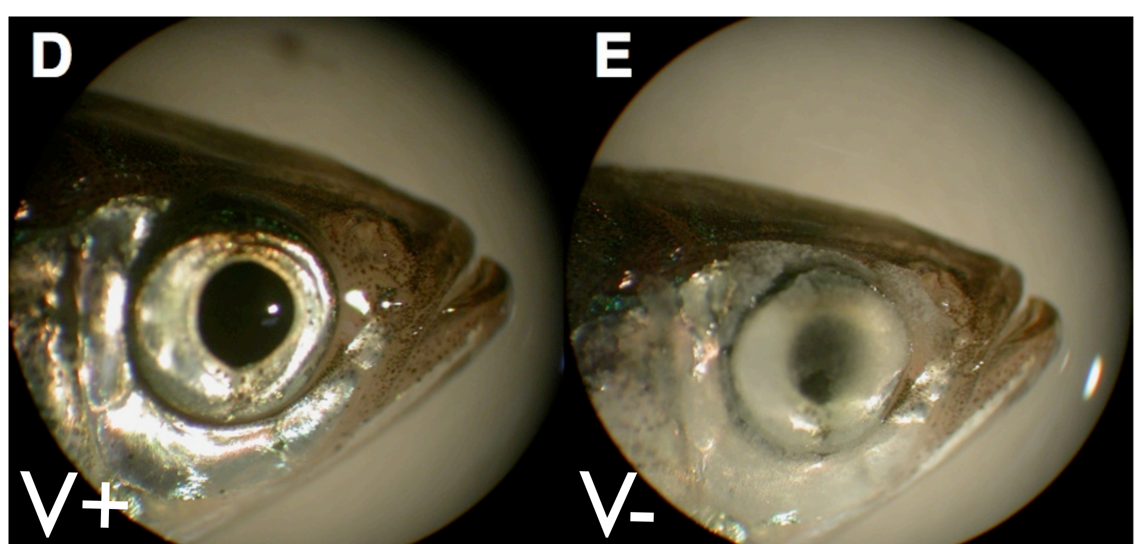
-manipulative experiments to validate models

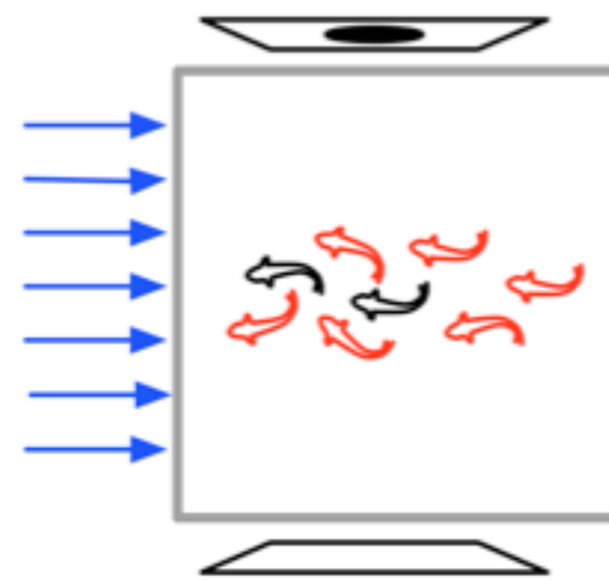
- **Manipulative experiments to** evaluate the sensory basis for how schooling fish transmit and receive social information
- **Approach**: Sensory deprivation experiments, robotic fish

Lateral line

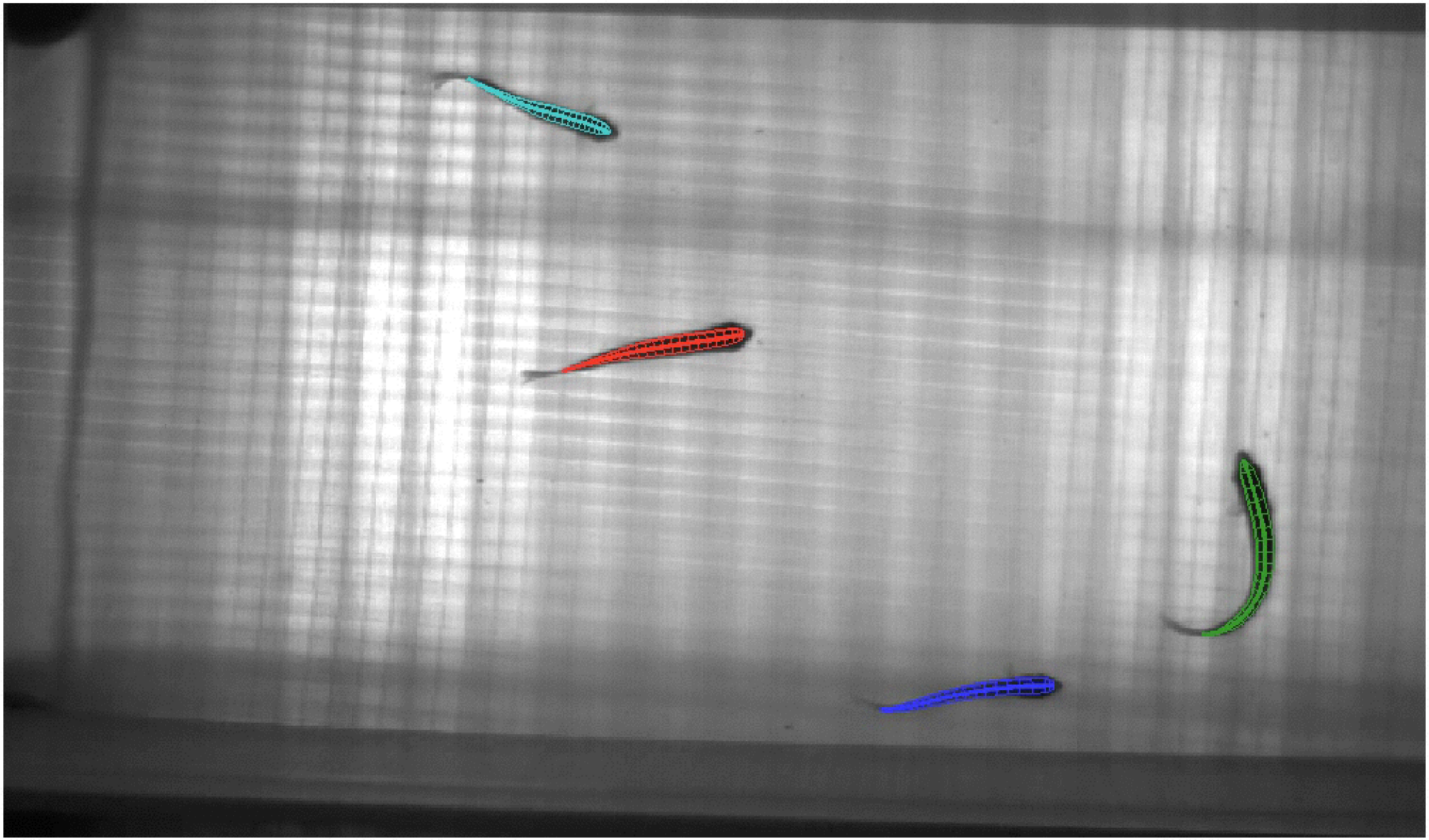


Visual



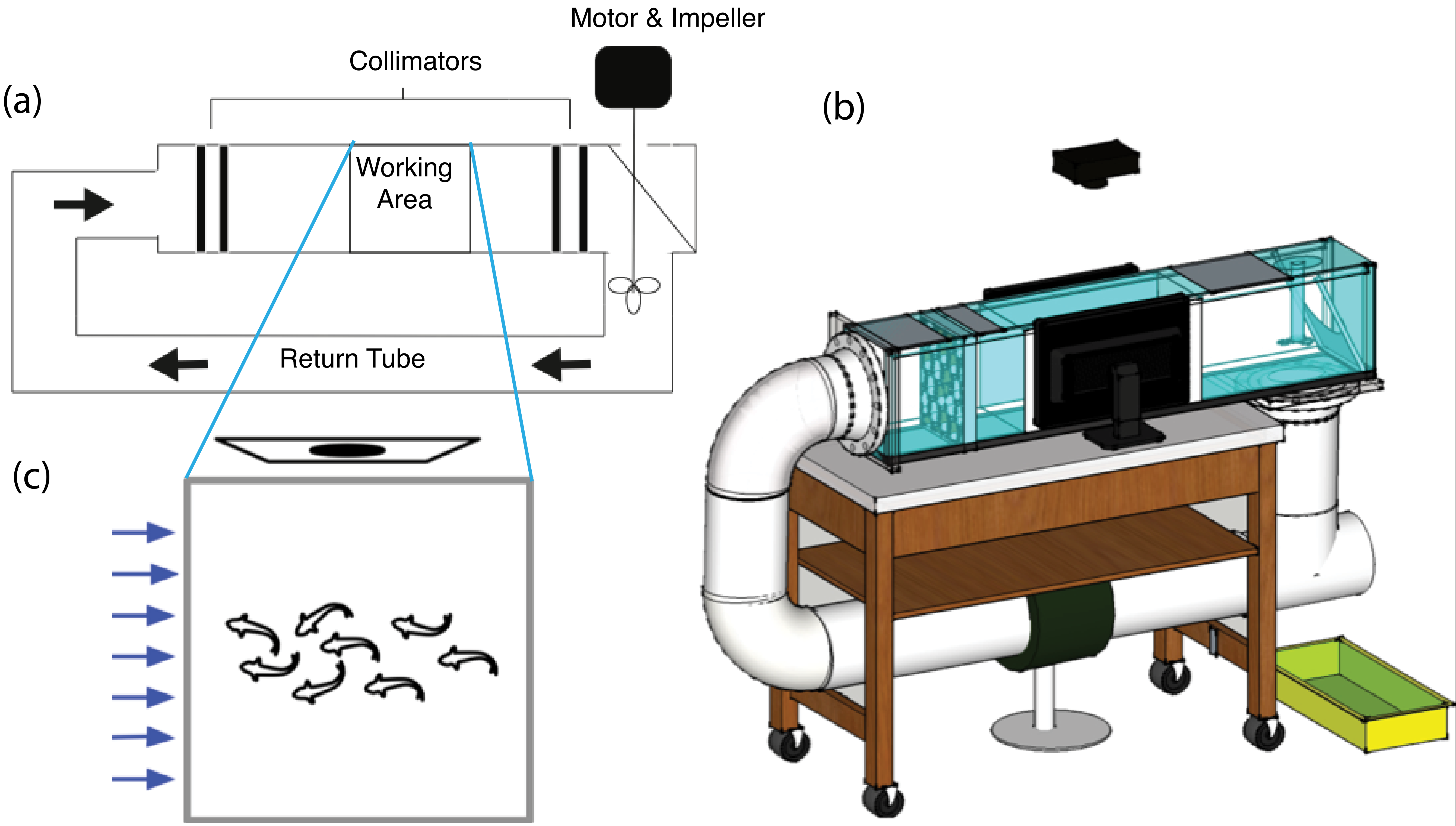


V+ school with one V- fish (red)

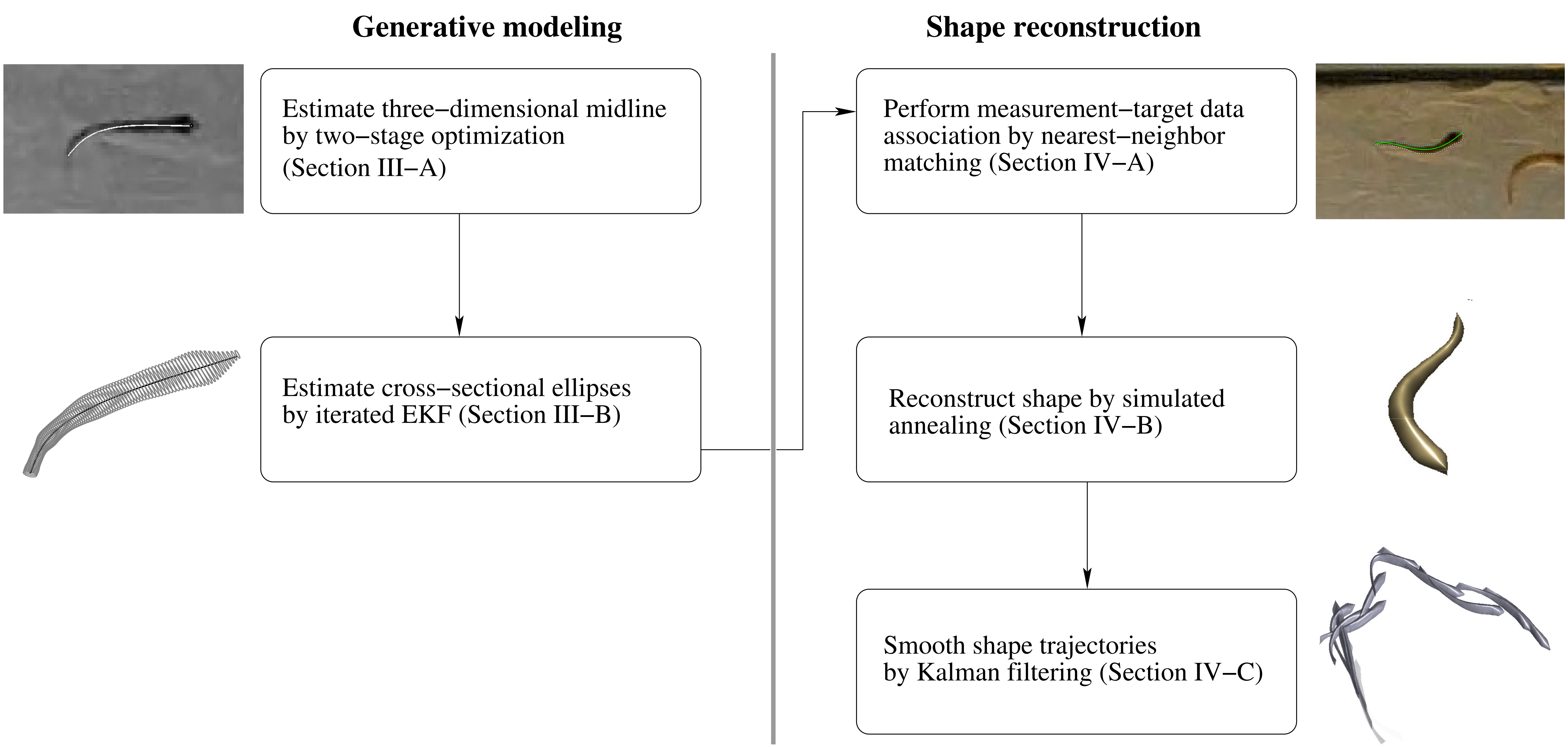


Pilot experiment: Manipulating wind speed (kind of works)

Experimental setup



3D fish-tracking system



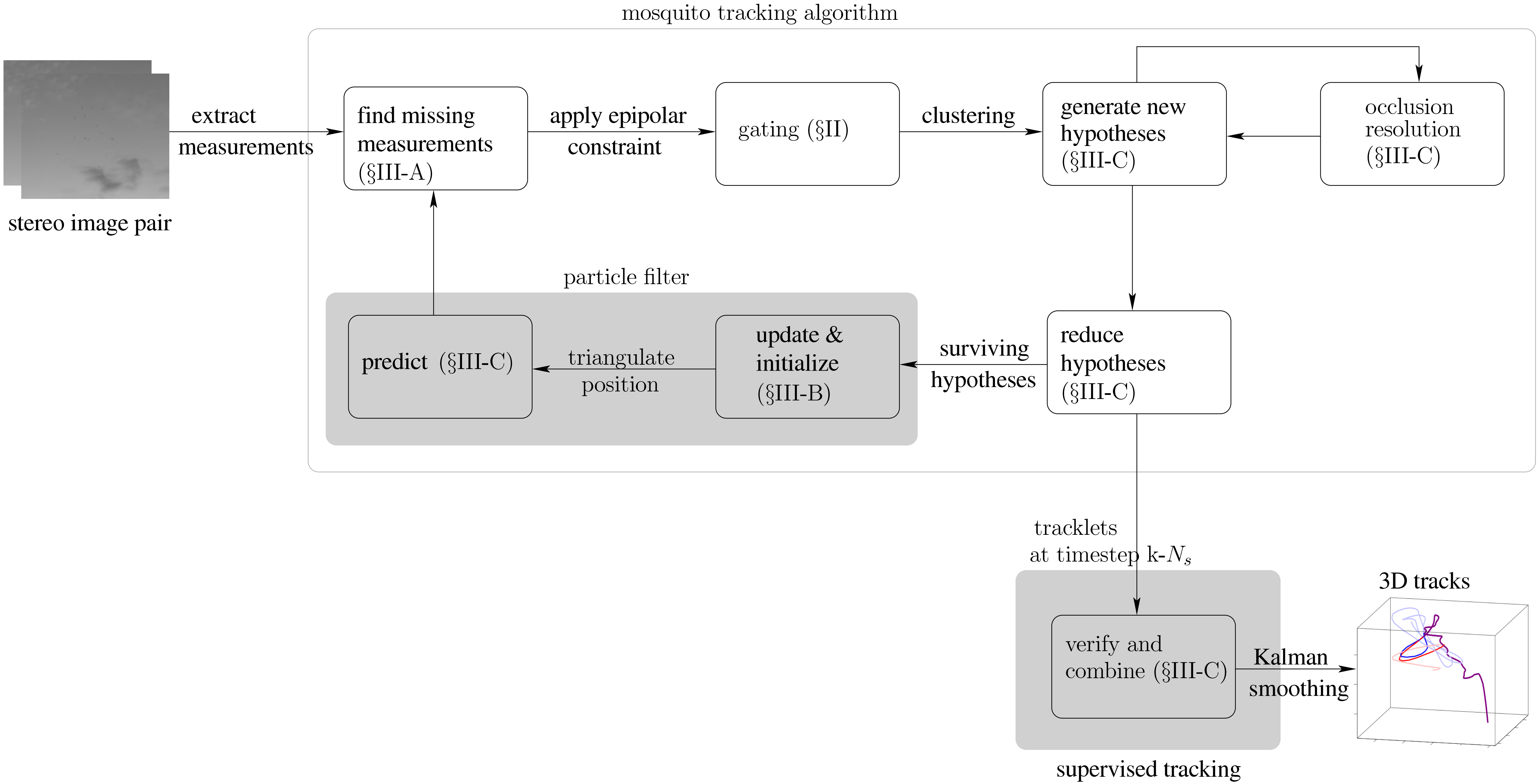
Swarming and mating in *An. gambiae*

Objective: To apply tools from engineering to study mating behavior in the field:

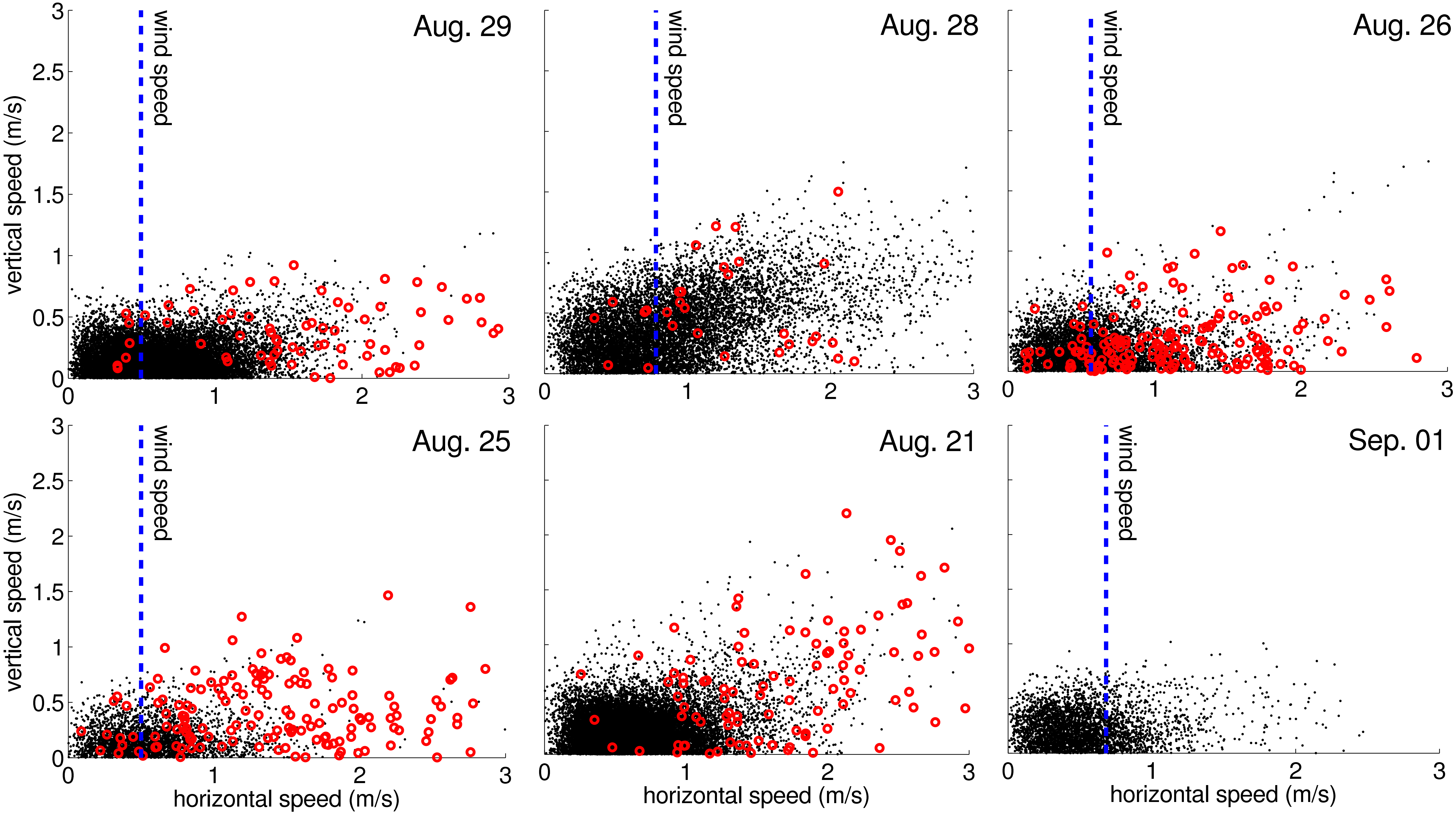
- What happens in swarms in populations of mosquitoes that are responsible for most of the human death caused by malaria?
- Female behavior in males swarms may not be random, but do they select mates?
- Do male flight patterns and/or position in the swarm relates to mating success?

Impact: Answers may influence vector control methods that rely on releases of sterile males

3D (mosquito) tracking system

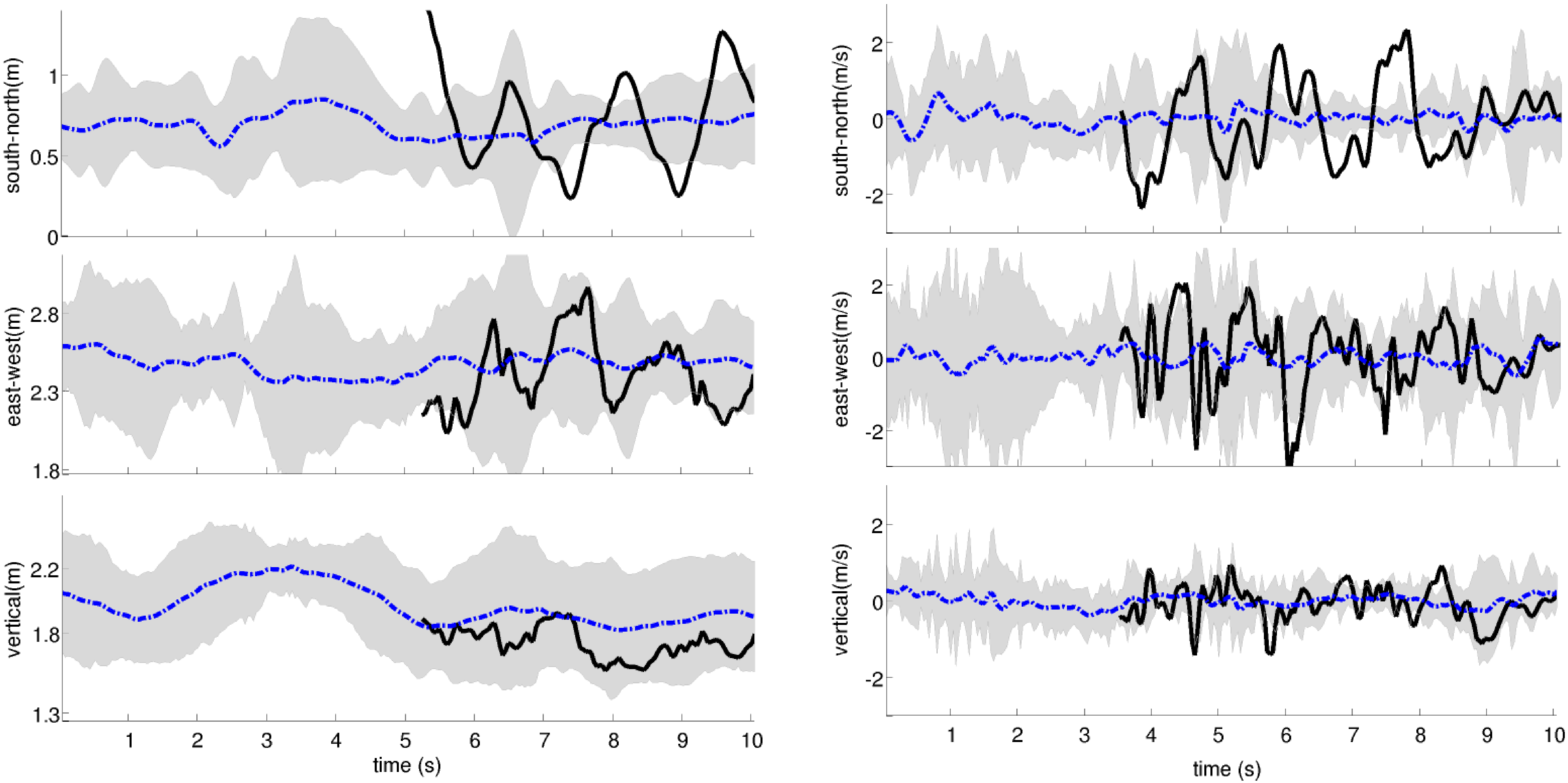


Horizontal vs. vertical speed



black = all males red = single female

But what about the female?



black = single female

blue = swarm centroid