Swansea University
Prifysgol Abertawe

Animal groups into the Swarm-Verse:

understanding collective motion across species & ecological contexts

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SHOAL

Andrew King
Ines Fürtbauer

universiteit groningen

Charlotte K. Hemelrijk
Hanno Hildenbrandt

Jens Krause
David Bierbach

Collective behavior in animals

- Across species & ecological contexts
- Serving a function or side-effect
- With underlying **involved cognition**


How do spatio-temporal patterns of collective behaviour emerge?

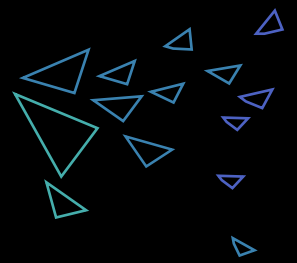
“The zoologist is delighted by the differences between animals, whereas the physiologist would like all animals to work in fundamentally the same way.”

-Alan Lloyd Hodgkin (1914 - 1998)

"The biologist is delighted by the differences between groups animal, whereas the theoretician would like all

~~animals~~ collectives to work in fundamentally the same way."

-Alan Lloyd Hodgkin (1914 - 1998)



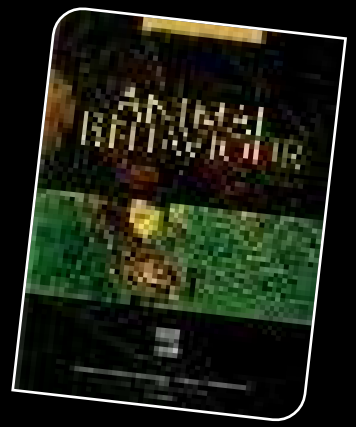
*Collective motion dynamics

Collective motion
Animals & Robots

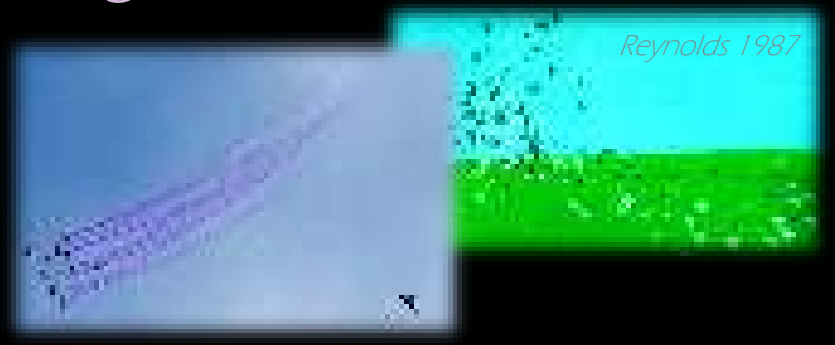
Species-specific dynamics

Animals

Bio-hybrid methods & systems



Behavioural algorithms *



Models

Bio-mimetic

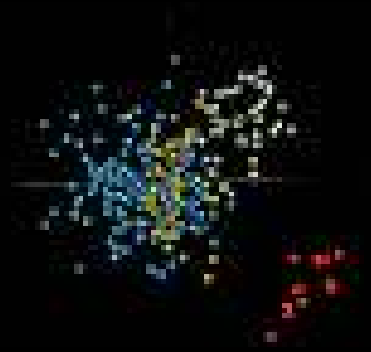
Bio-inspiration

(Swarm) Robotics

Carrillo-Zapata et al. 2020

[1]
The Swarm-Verse

Understanding collective behaviour across species and ecological contexts



[2]
Individual heterogeneity

Morphology, Personality & Social networks

[3]
Collective escape in bird flocks

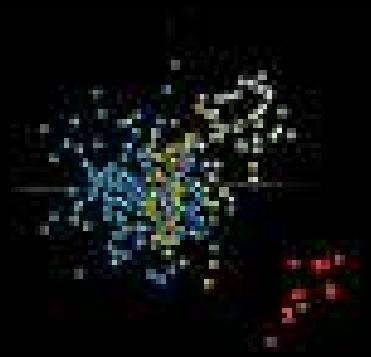
Insights from data-inspired agent-based models

[4]
Coda

In progress, future aims & applications

[1]
The Swarm-Verse

Understanding collective behaviour across species and ecological contexts



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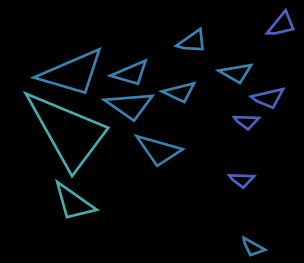
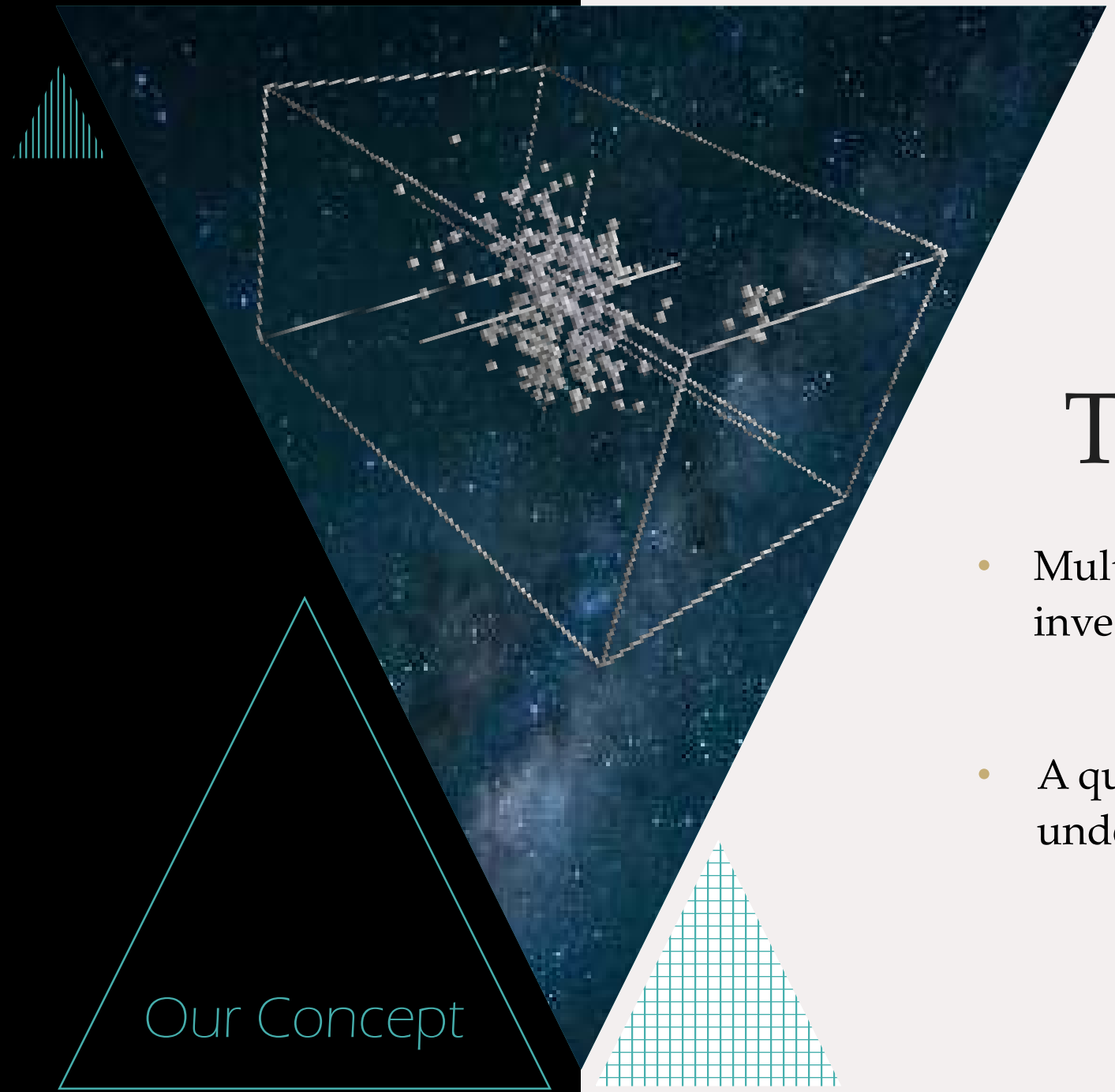
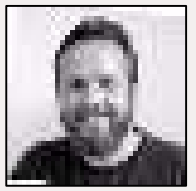






Andrew King

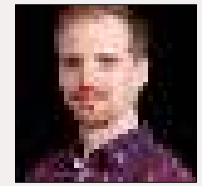
The Swarm-Verse

- Multidimensional spaces for comparative investigation of collective motion
- A quantifiable & predictive framework to understand intra- and interspecific variation

Our Concept

Papadopoulou M., Garnier S., King A.J. (In prep.)

Our Concept



Simon Garnier
NJIT

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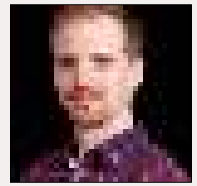
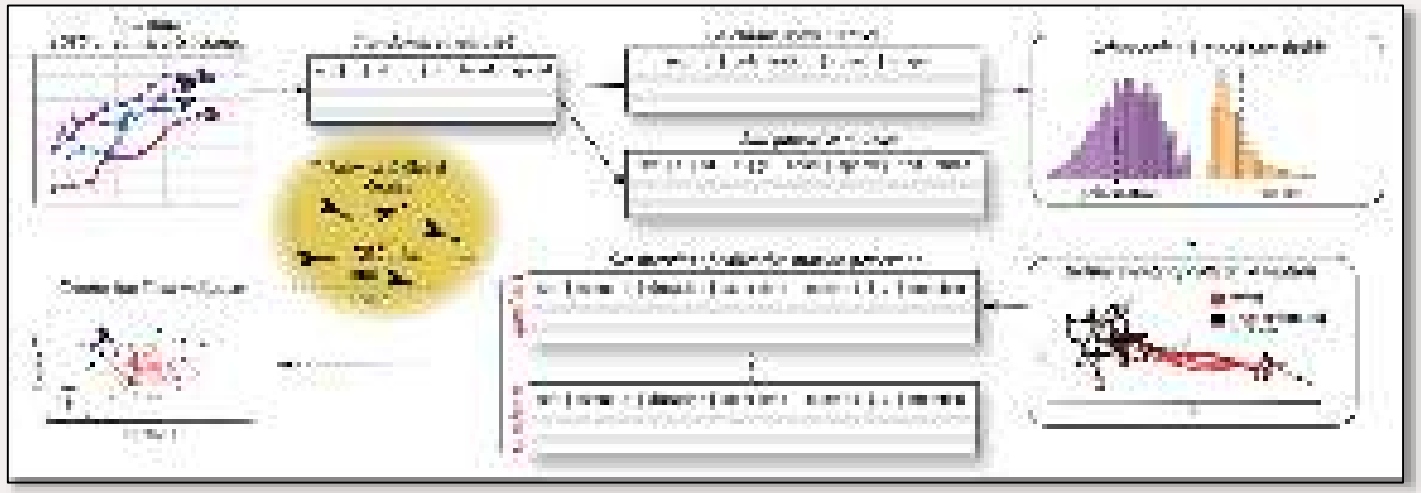


Simon Garnier
NYU

The Swarm-Verse



Papadopoulou M., Garnier S., King A.J. (In prep.)

Pilot Datasets

Stickleback fish
(Gasterosteus aculeatus)

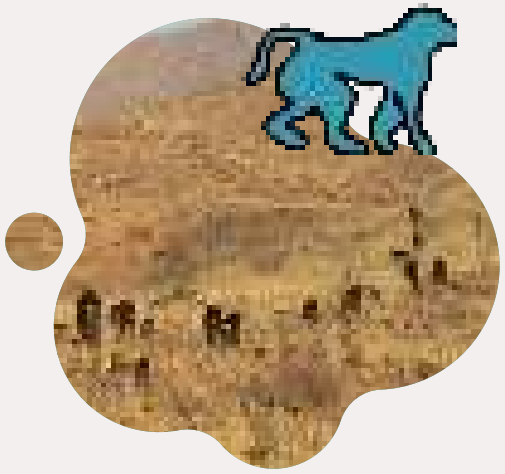
Lab experiments *[1]

Homing pigeons
(Columba livia)

Field experiments *[2]

Goats
(Capra aegagrus hircus)

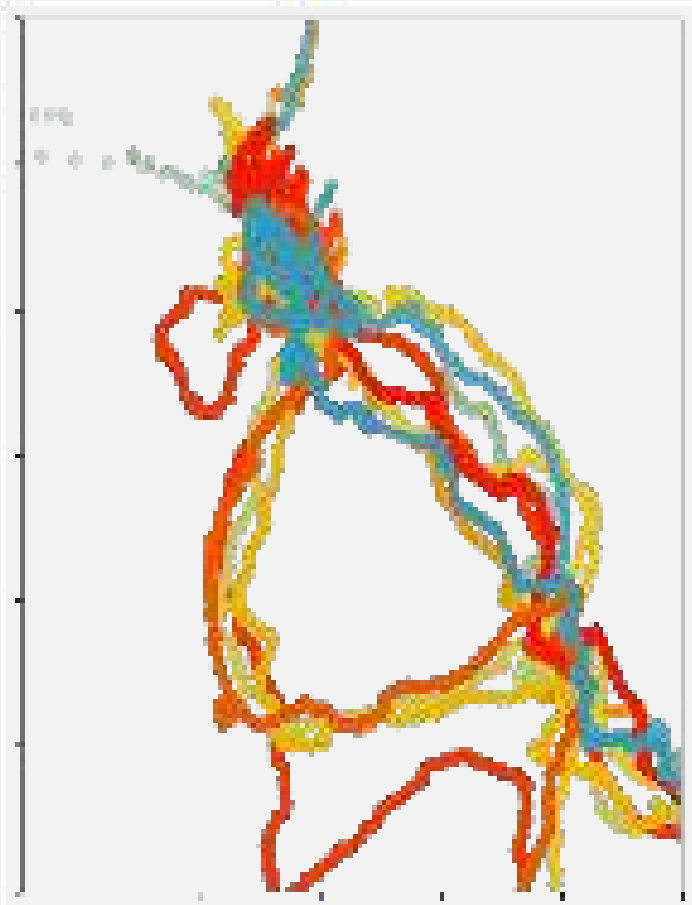
Free ranging *[3]



Chacma baboons
(Papio ursinus)

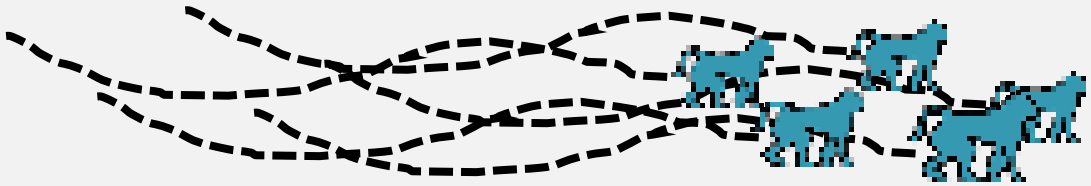
Foraging *[4]

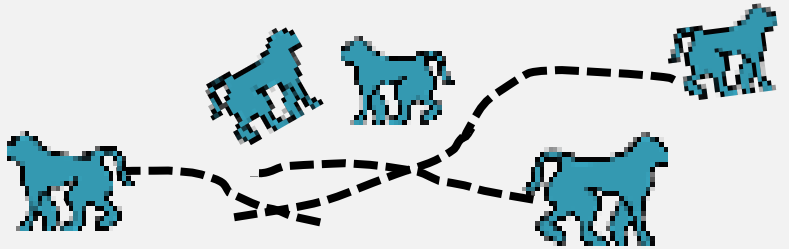
*[1] Georgopoulou DG et al. (2022) Behav. Ecol.
*[2] Sankey DWE et al (2021) Curr. Biol.
*[3] O'Bryan LR, (2019) Front. Ecol. Evol.
*[4] Bracken AM et al (2022) Proc. R. Soc. B



Step 1.
Events of collective motion

Coordinated motion ≠ **Disorder**





Papadopoulou et al. (2023) Philos. Trans. R. Soc. B

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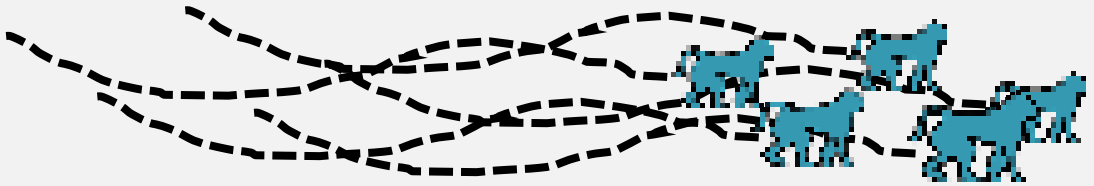
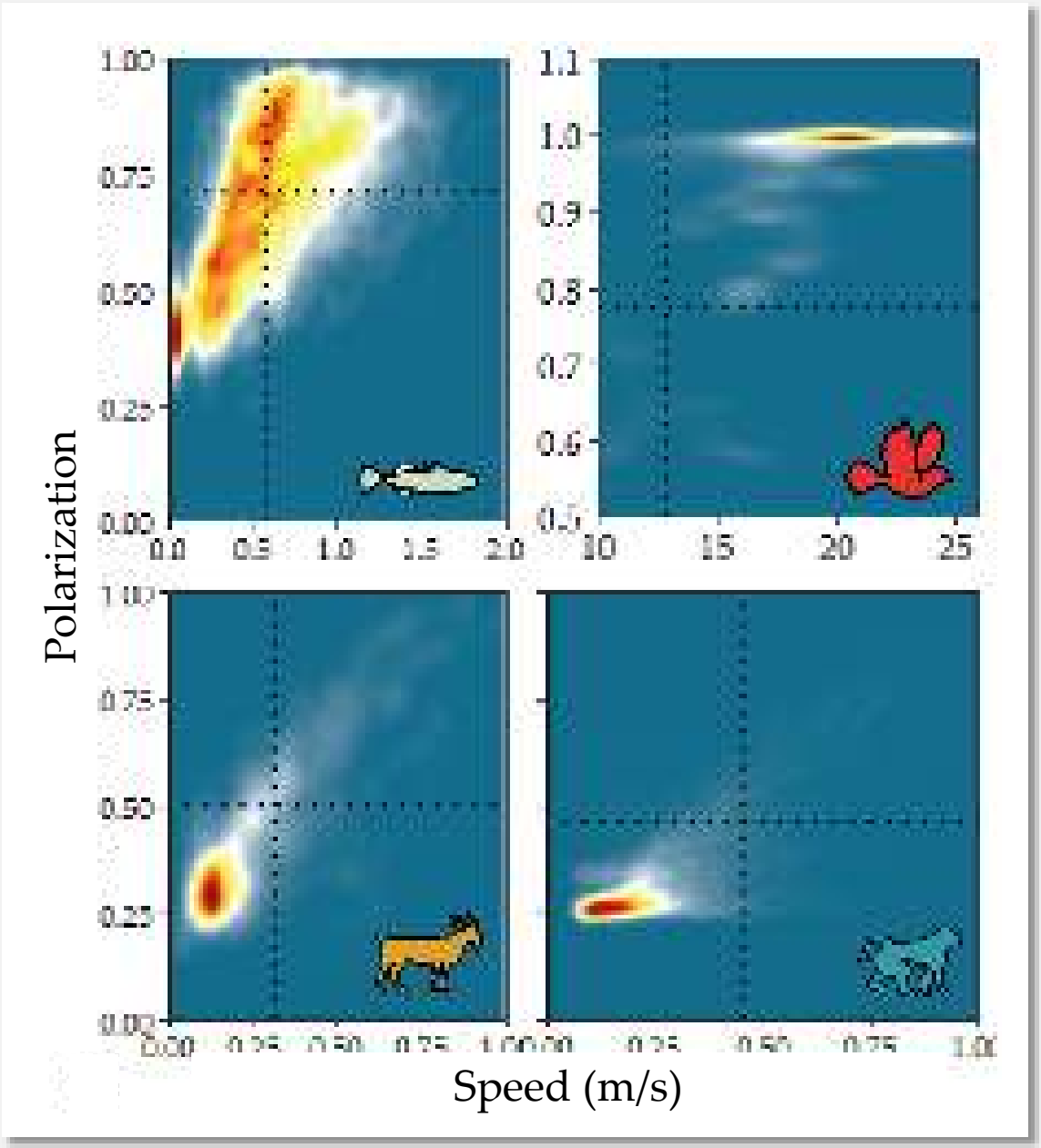
Coordinated motion

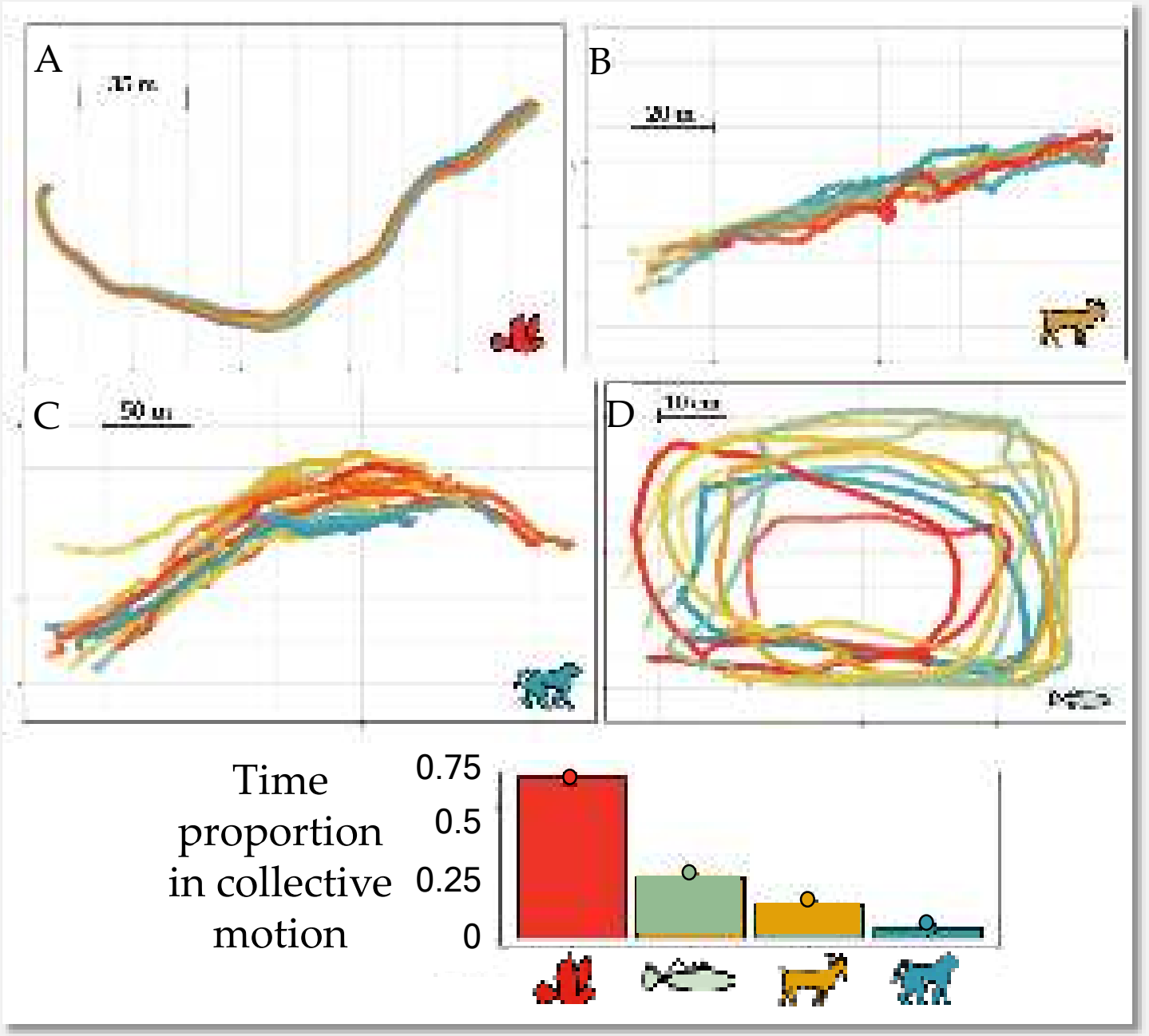




Papadopoulou et al. (2023) Philos. Trans. R. Soc. B

Step 1.
Events of collective motion

~ 300 events across species

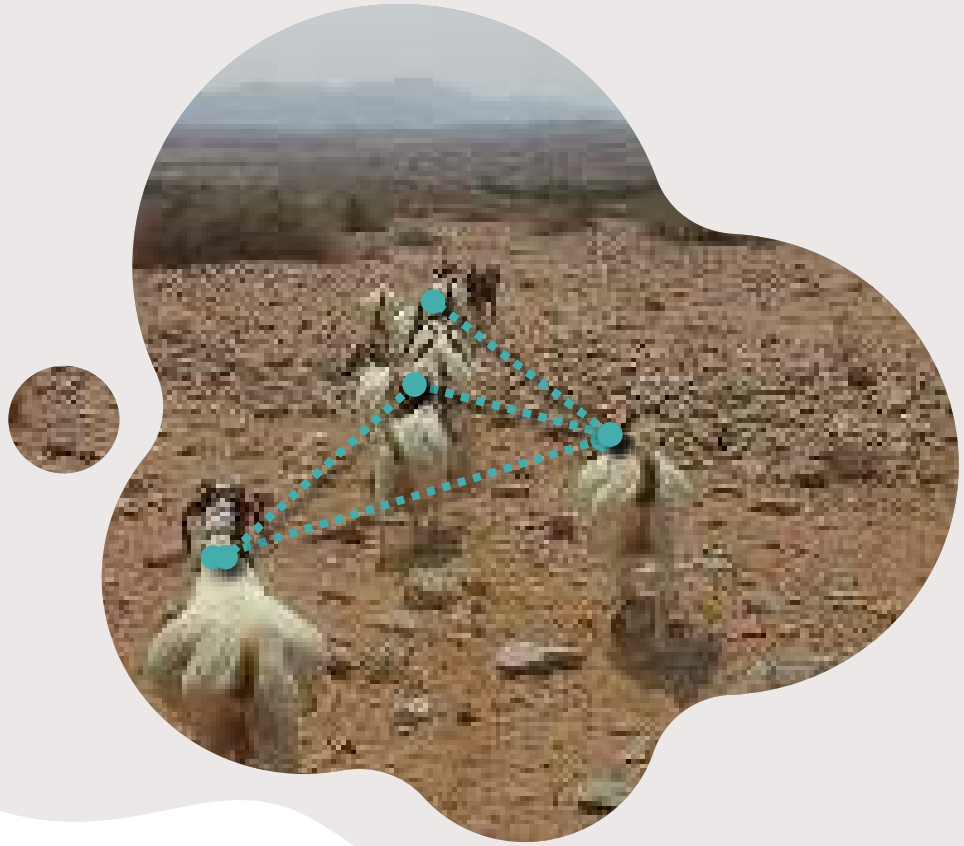


Papadopoulou et al. (2023) Philos. Trans. R. Soc. B

Step 2.
Collective motion properties

- Group level Speed, Polarization, Shape
(*average + temporal variation*)

Papadopoulou et al. (2023) Philos. Trans. R. Soc. B



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Collective motion properties

- **Group level** Speed, Polarization, Shape
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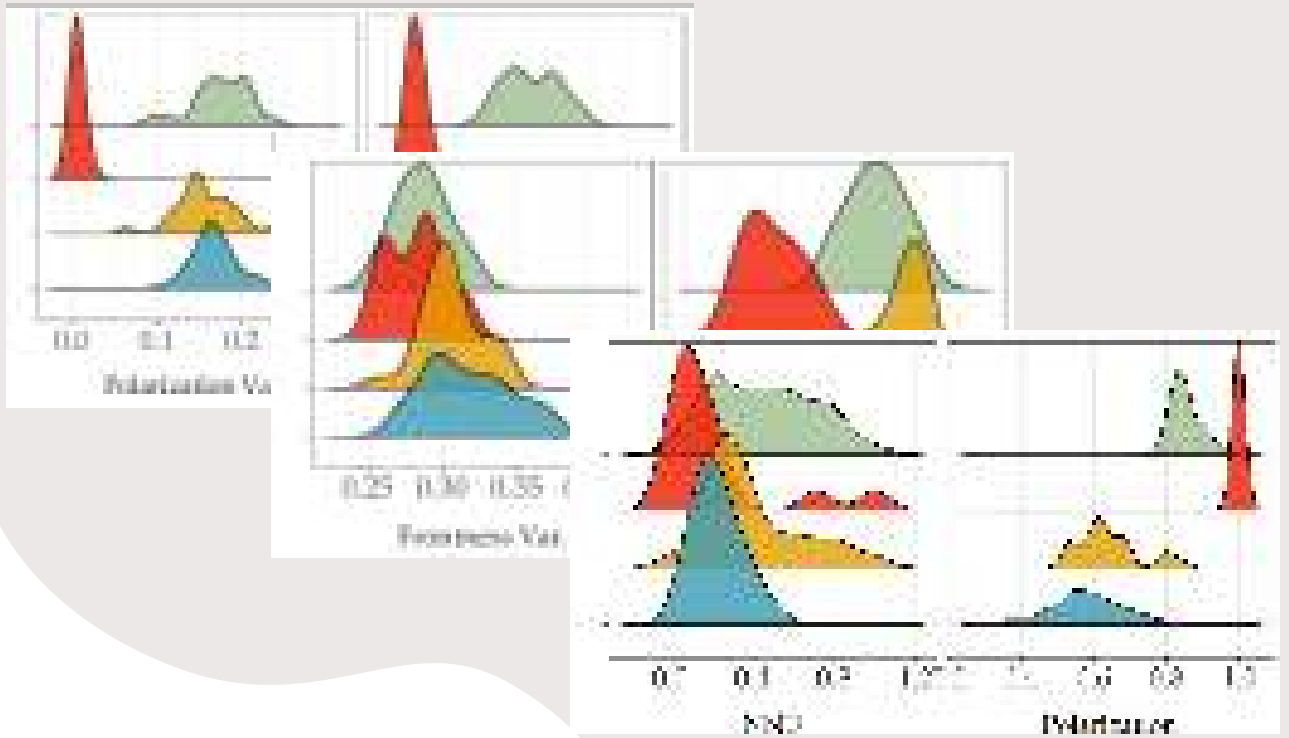
- **Pairwise** NND, bearing angles, frontness
  (*group average, within-group variation, temporal variation of group average)*

Papadopoulou et al. (2023) Philos. Trans. R. Soc. B

10 metrics that describe the collective motion of an event



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Papadopoulou et al. (2023) Philos. Trans. R. Soc. B

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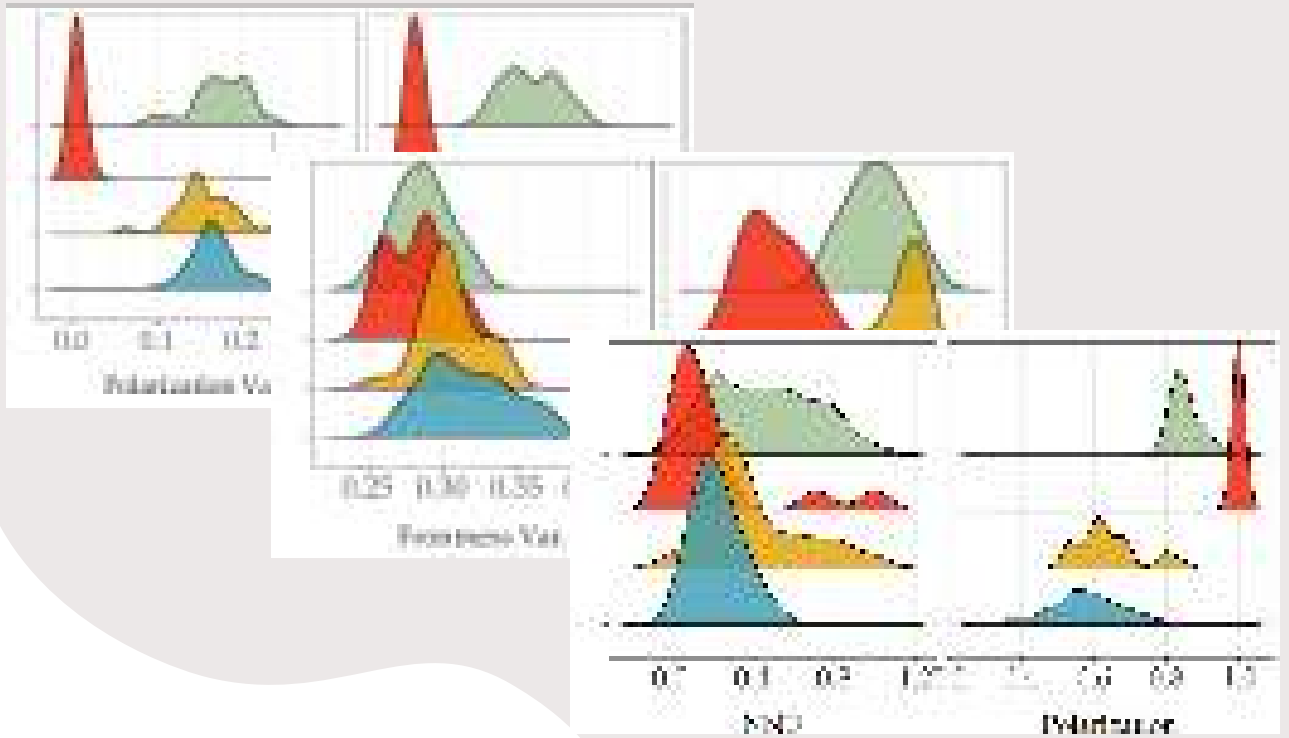
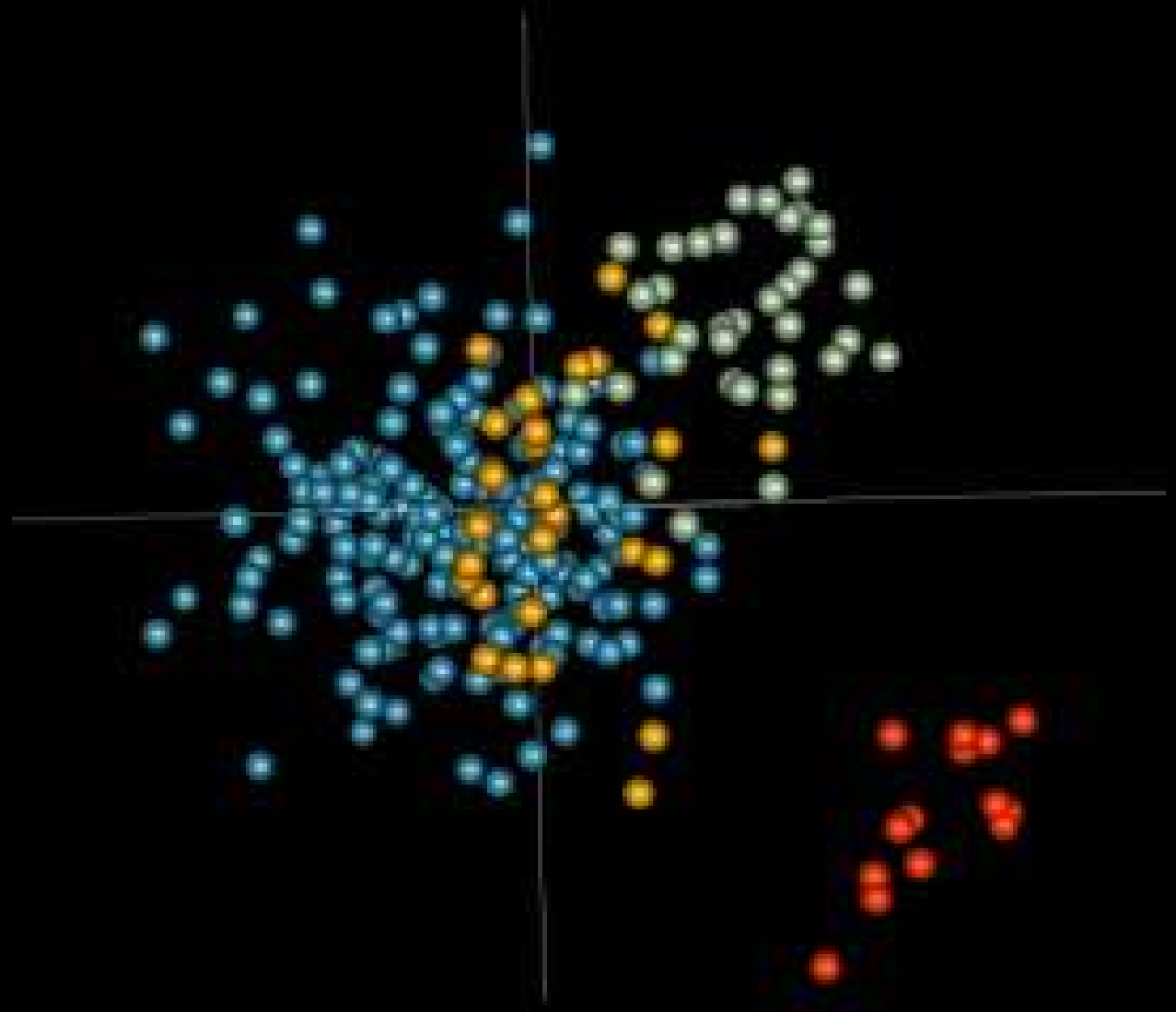


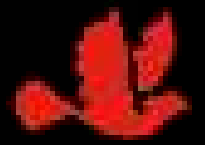
Step 3.
Dimensionality reduction

- Principal Component Analysis
- t-distributed stochastic neighbour embedding (t-SNE)

Papadopoulou et al. (2023) Philos. Trans. R. Soc. B

The Swarm-Space

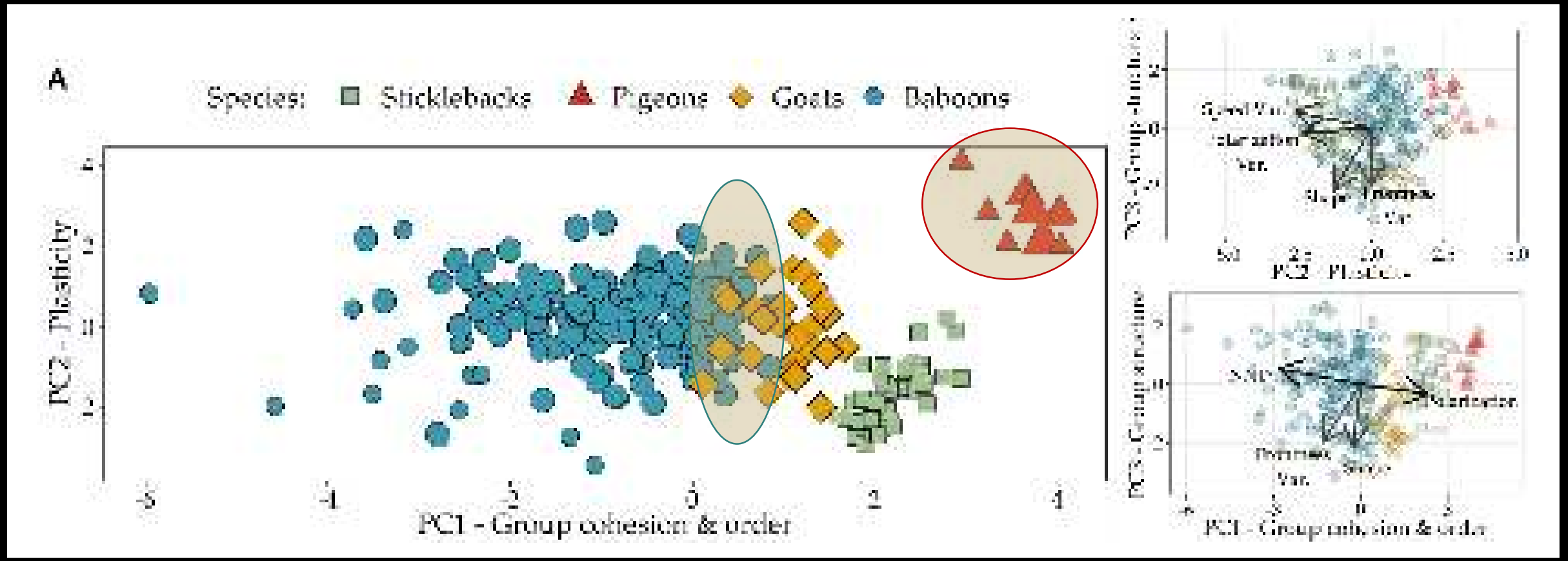




Papadopoulou et al. (2023) Philos. Trans. R. Soc. B

Swarm Space (PCA)

Variation between and within species



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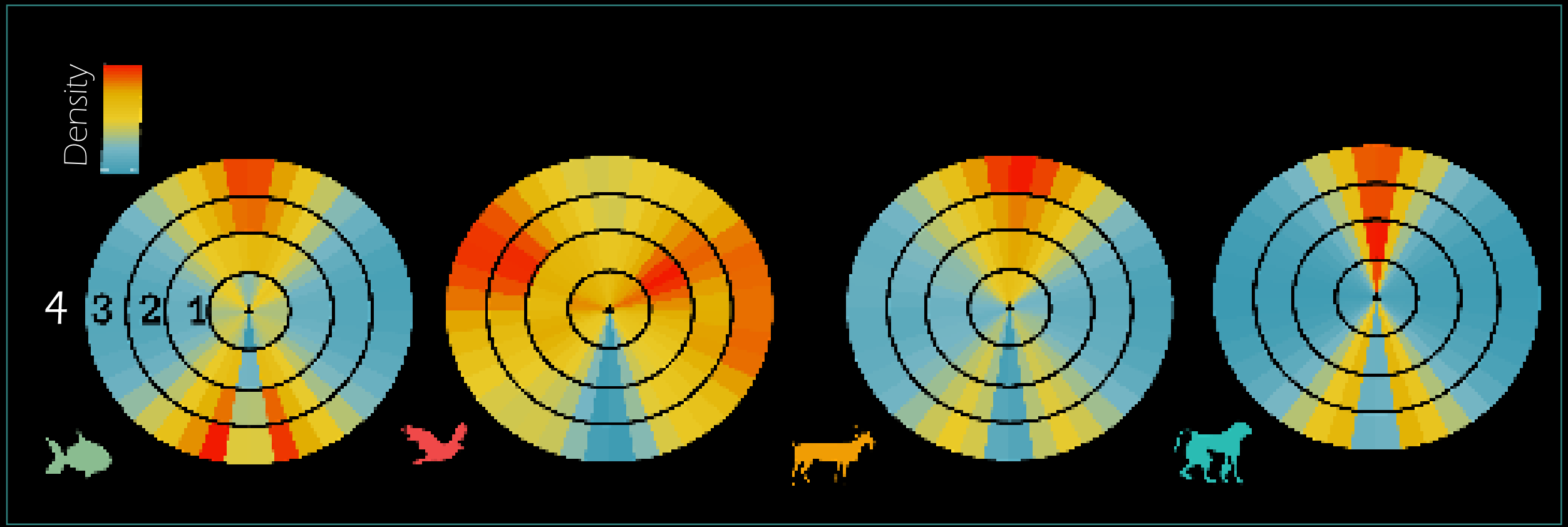
Swarm Space (PCA)

Variation between and within species

Internal structure

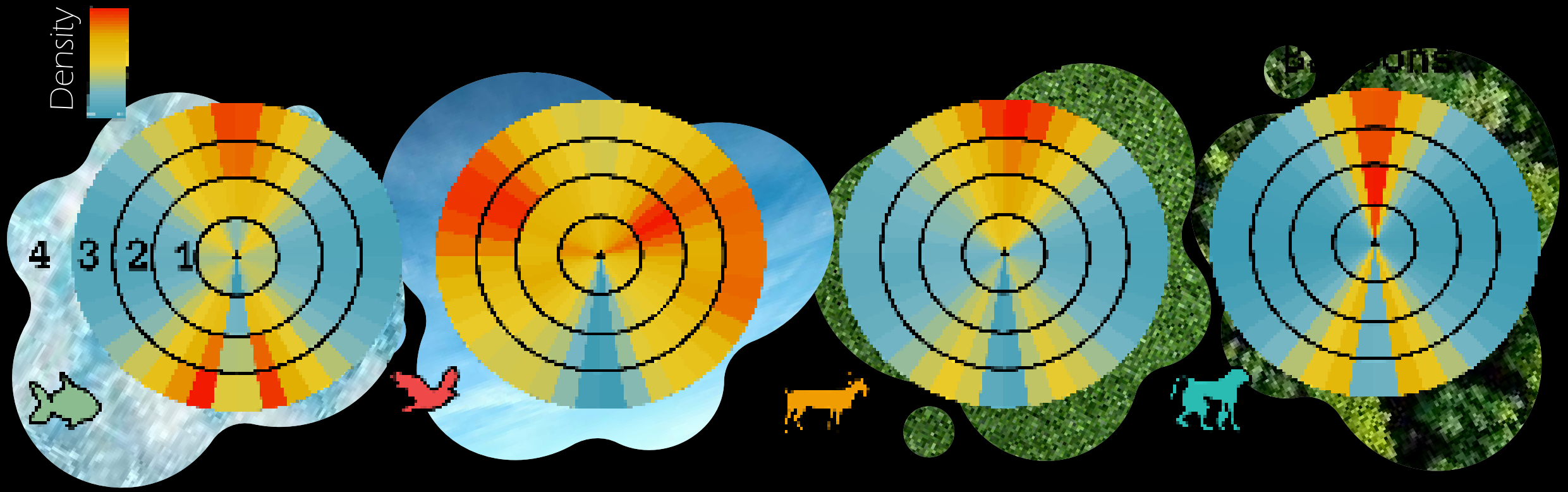


Papadopoulou et al. (2023) Philos. Trans. R. Soc. B

Swarm Space (PCA)

Variation between and within species

Self-organized effects (e.g. locomotion) *Related to ecological context*



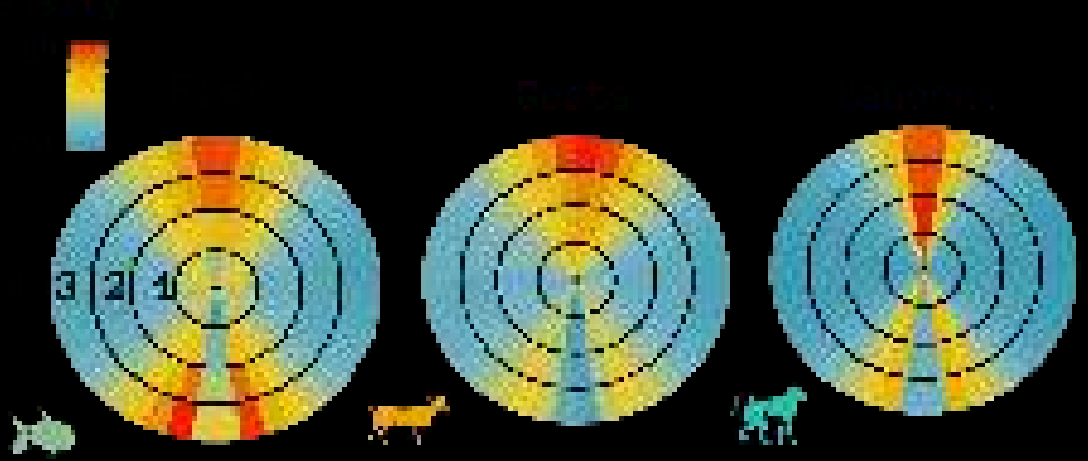
Papadopoulou et al. (2023) Philos. Trans. R. Soc. B

Swarm Space (PCA)

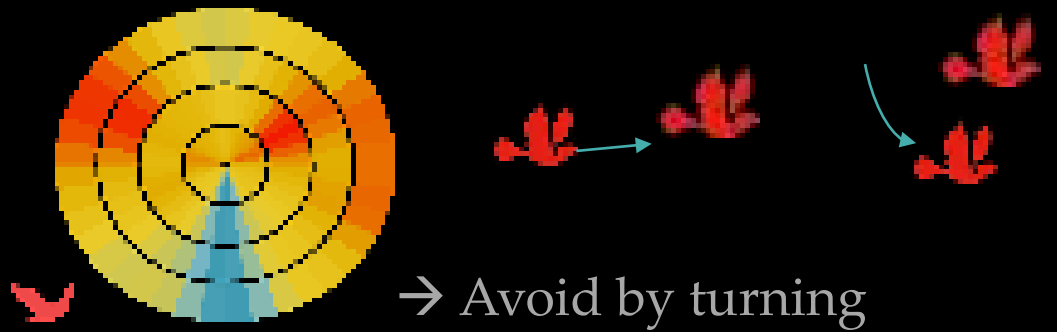
Variation between and within species

Self-organized effects (e.g., locomotion)

Stop & Go Motion



Continuous Motion

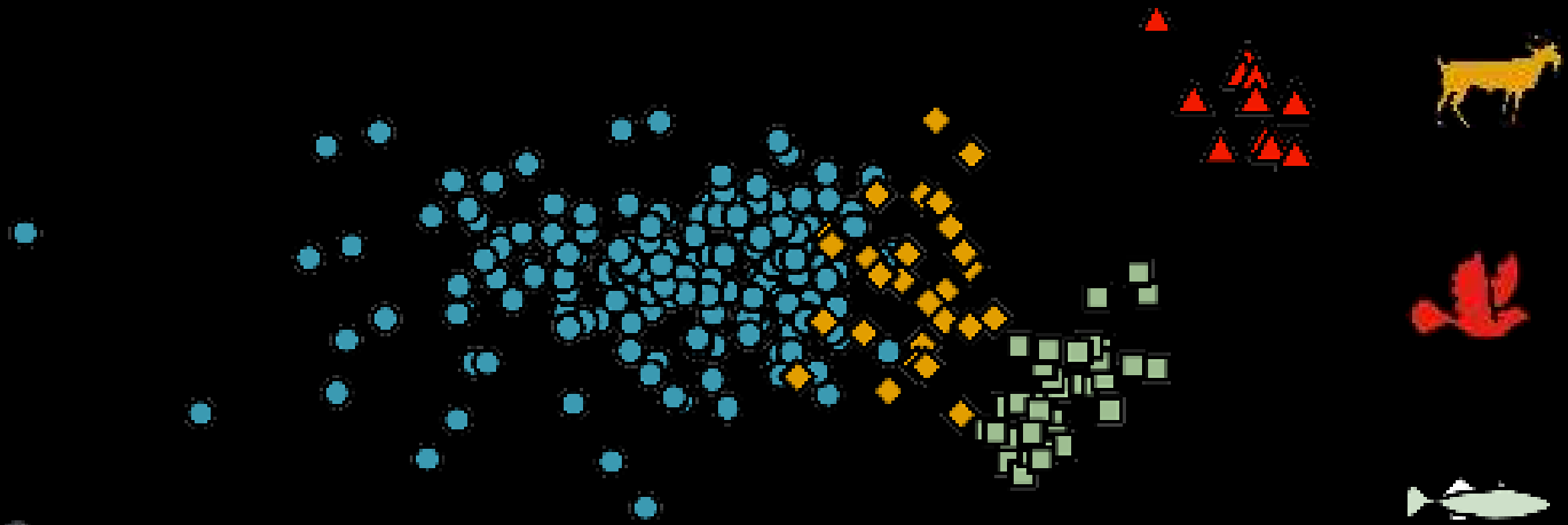


→ Avoid by turning

Papadopoulou et al. (2023) Philos. Trans. R. Soc. B

The Swarm-Space

for the comparative investigation of collective motion



1. Individual level differences

2. Emergence

[1]
The Swarm-Verse

Understanding collective behaviour across species and ecological contexts

[2]
Individual heterogeneity

Morphology, Personality & Social networks

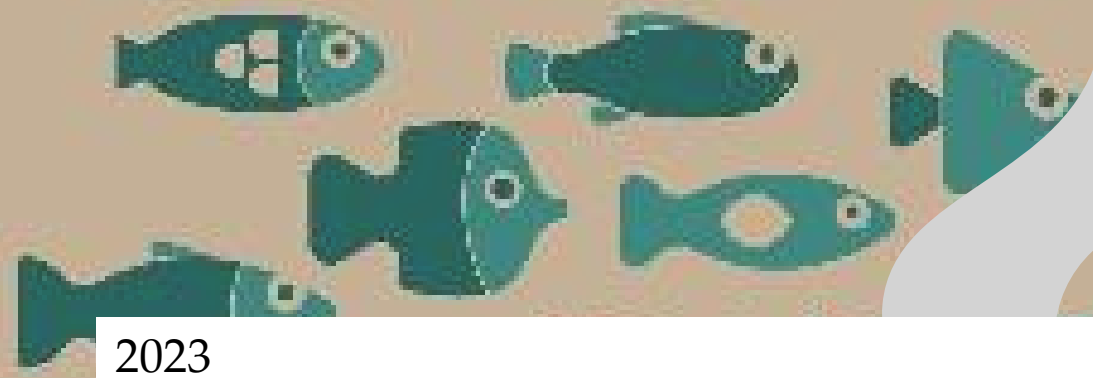
[3]
Collective escape in bird flocks

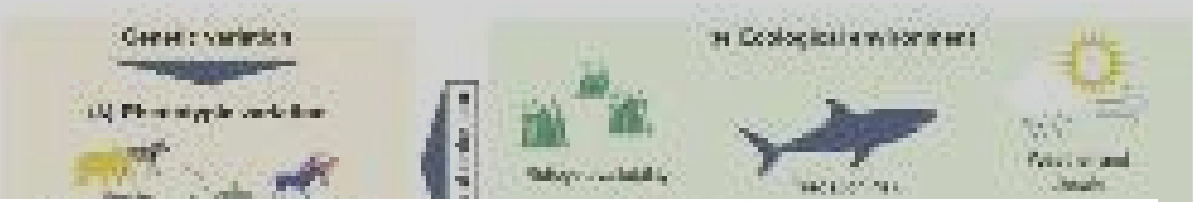
Insights from data-inspired agent-based models

[4]
Outlook

future aims & applications

Individual Heterogeneity



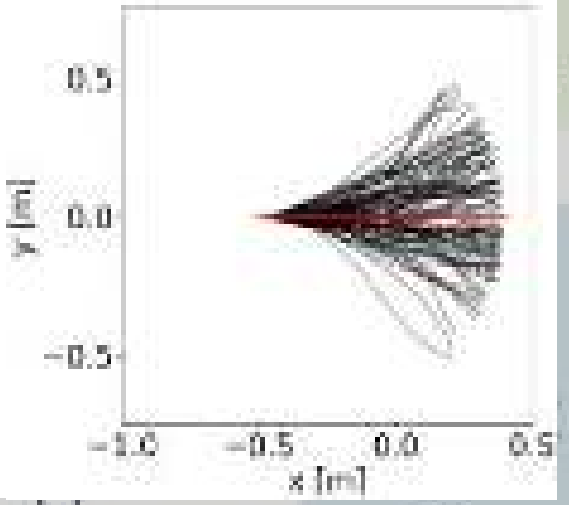


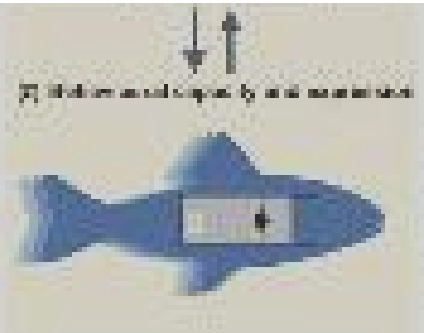
2023

Individuality in Swarm Robots with the Case Study of Kilobots: Noise, Bug, or Feature?

Mohsen Raoufi[1,2,3], Pawel Romanczuk[1,2] and Heiko Hamann[3,4]

[1]Science of Intelligence, Research Cluster of Excellence, 10587 Berlin, Germany
[2]Institute for Theoretical Biology, Department of Biology, Humboldt Universität zu Berlin, Berlin, Germany
[3]Department of Electrical Engineering and Computer Science, Technical University of Berlin, Berlin, Germany
[4]Department of Computer and Information Science, University of Konstanz, Konstanz
mohsenraoufi@icloud.com





Trends in Ecology & Evolution

CellPress

Review

The Role of Individual Heterogeneity in Collective Animal Behaviour

Jolle W. Jolles, Andrew J. King and Sharon S. Killen

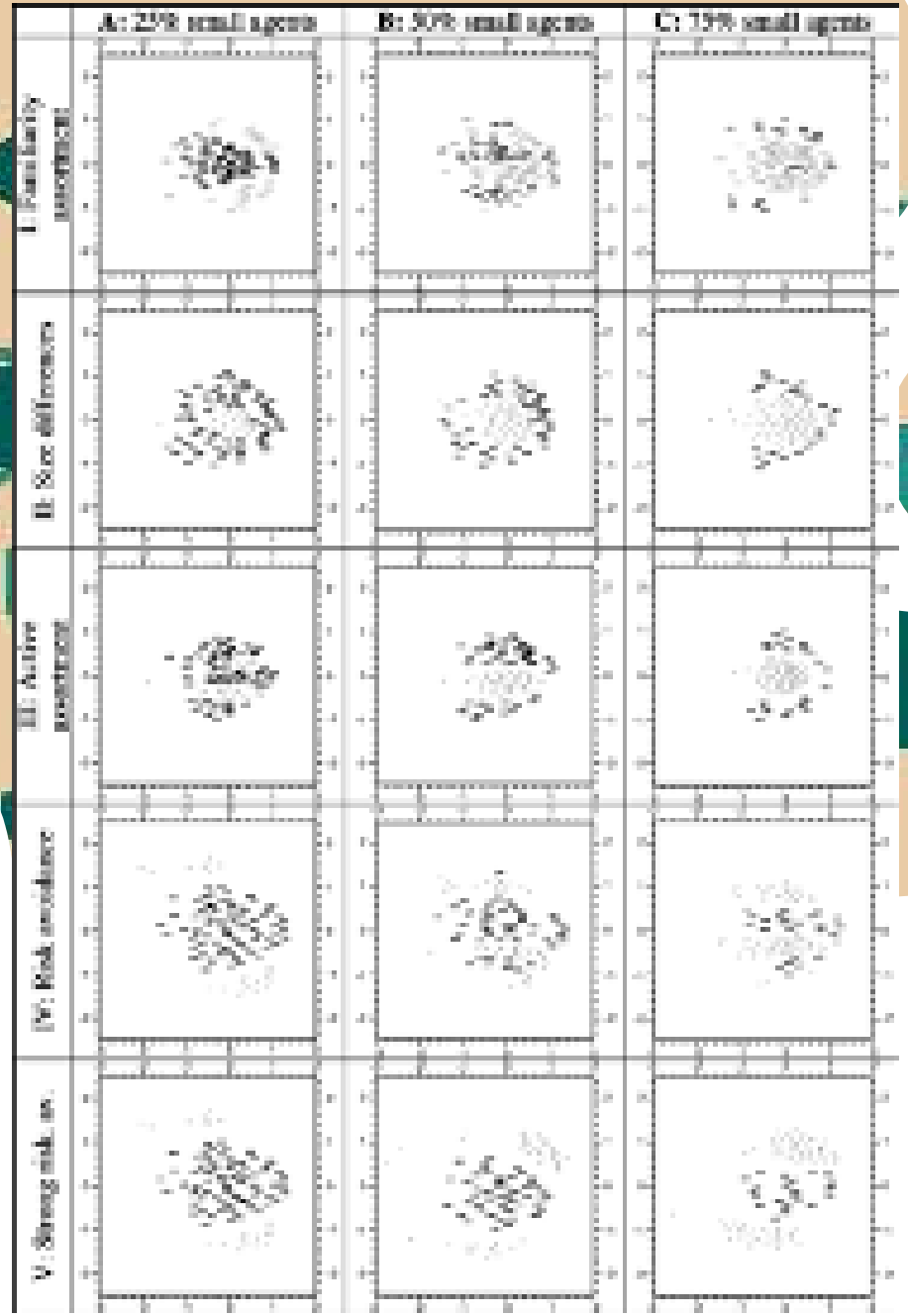
Individual Heterogeneity

+ MORPHOLOGY

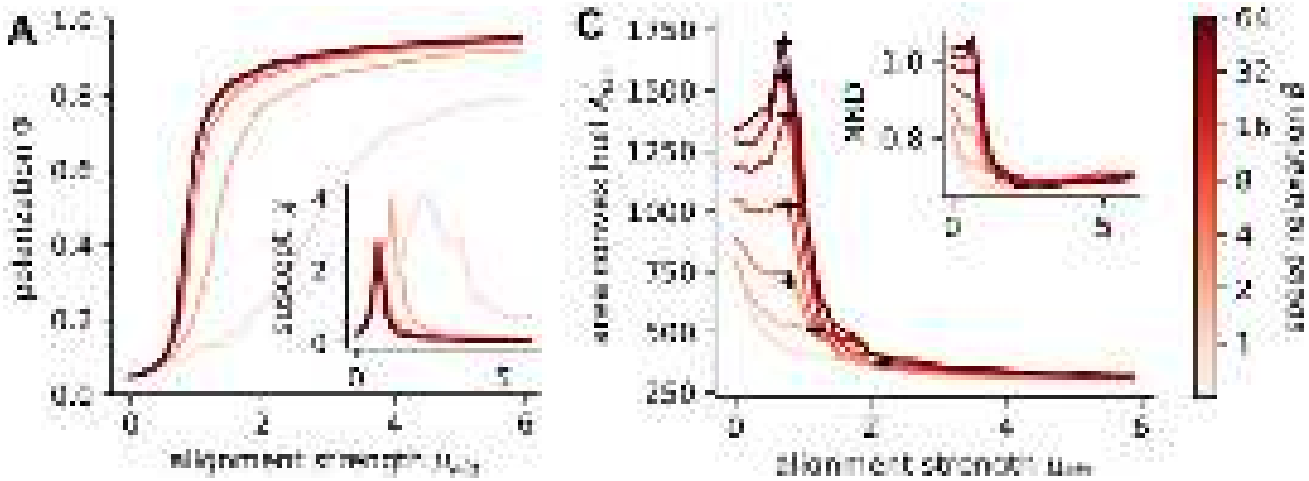
- Body size
- Preferred speed

→ *Size compositions & internal structure*

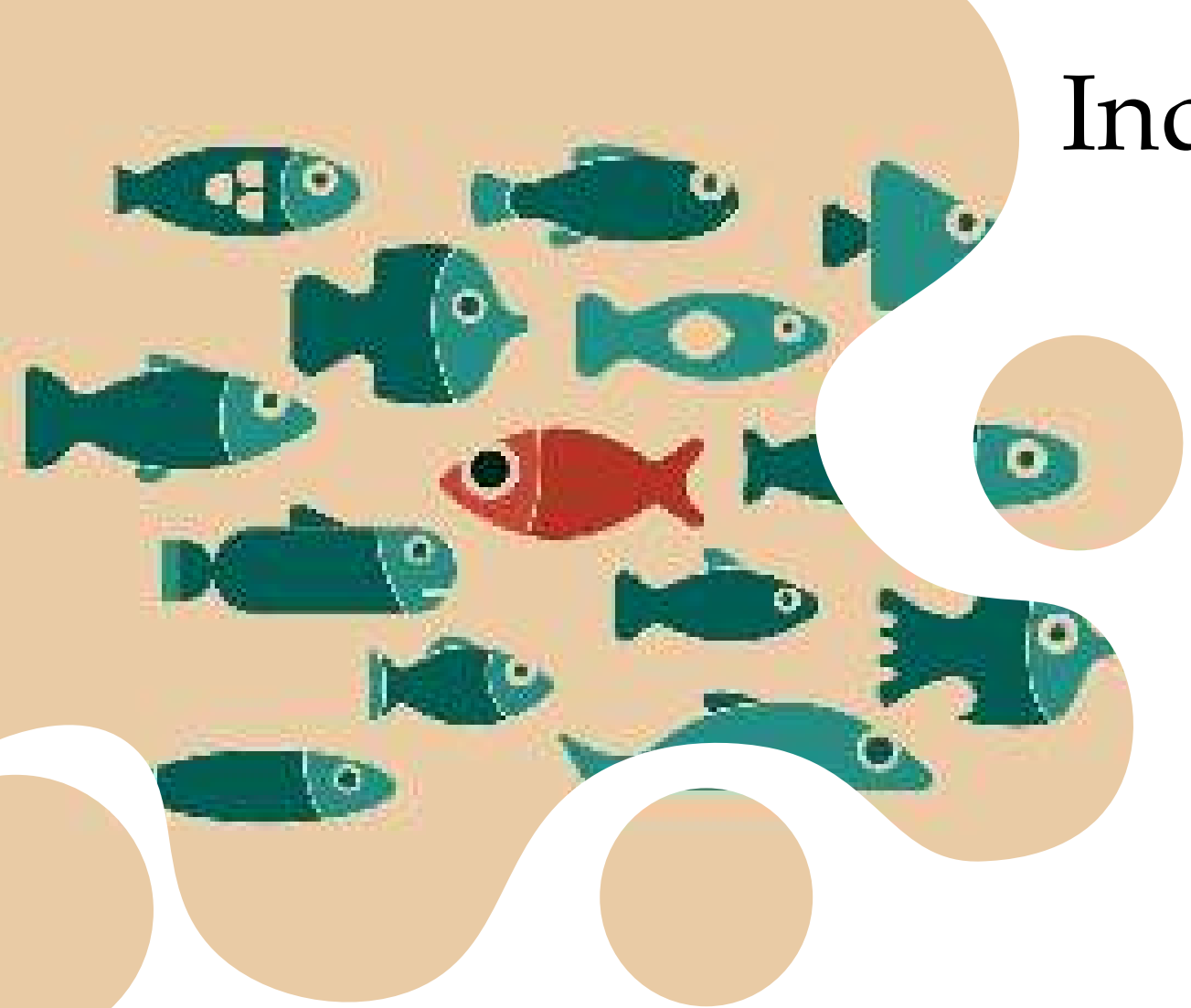
→ *Speed variations & collective dynamics*



Hemelrijk & Kunz (2005) Behav.Eco.



Klamser et al. (2021) Front.Eco.Evol.



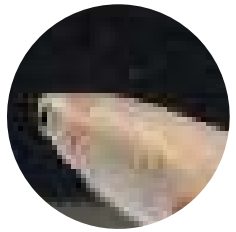
Individual Heterogeneity

+ **MORPHOLOGY**

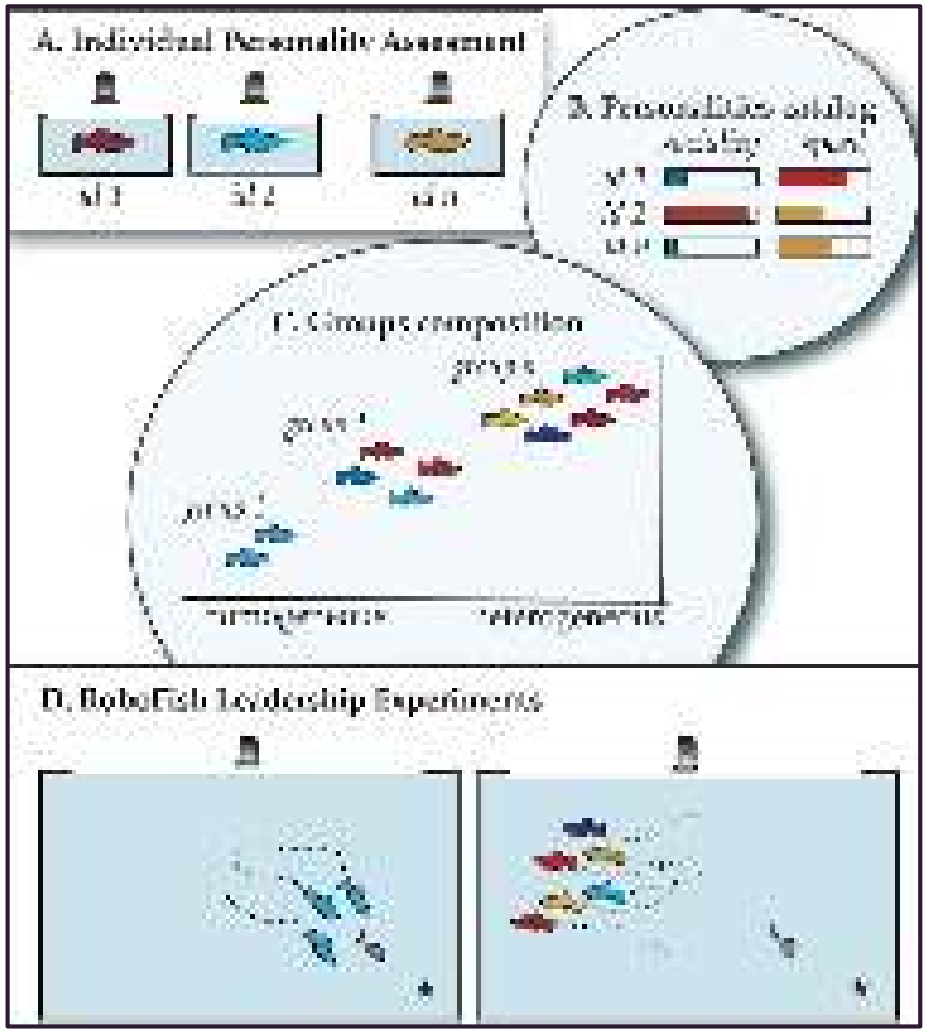
+ **PERSONALITY**

- Activity level
- Boldness
- Sociability

Personality composition & Collective motion



Influence of group composition on information transfer and leadership

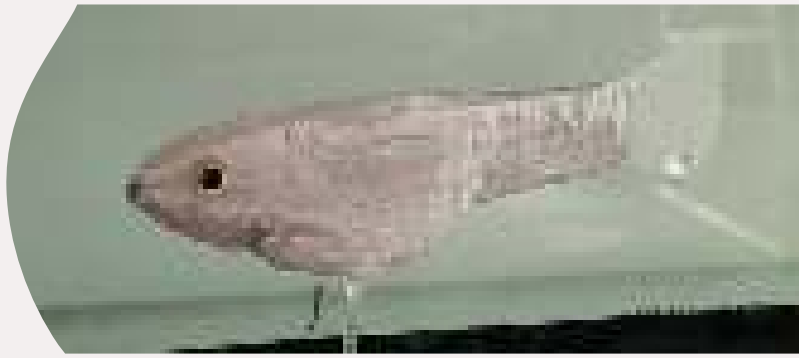


Jens Krause

David Bierbach

Papadopoulou et al. In prep.

Case study -
Swimming with the RoboFish



- Shoals of **Amazon mollies** (*Poecilia formosa*): genetically identical sisters

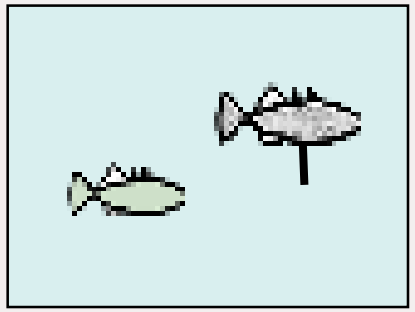
- **Robin the Robofish:**
  - Resembling body shape/size of mollies
  - Pre-programmed

Bierbach et al. (2017) Nat Commun | Bierbach et al. (2018) R Soc Open Sci

Papadopoulou et al. In prep.

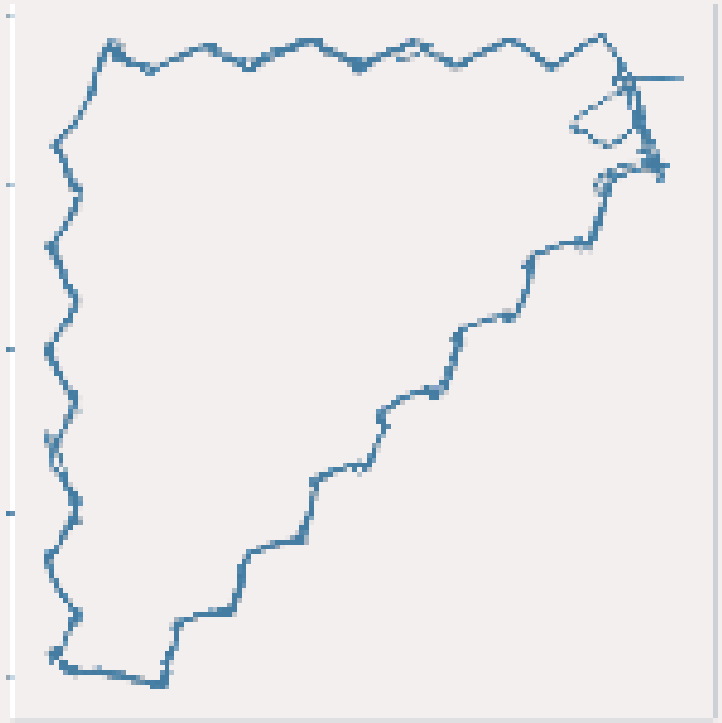
Experiments

(24 individuals)



Phase 1:
Robofish + 1 molly

Sociability Assessment



Papadopoulou M et al. (In prep)

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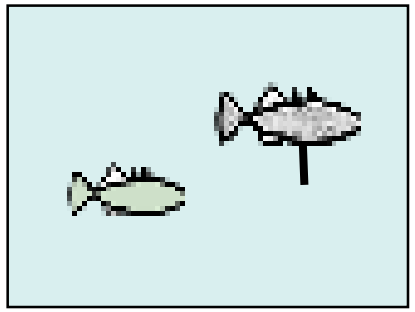

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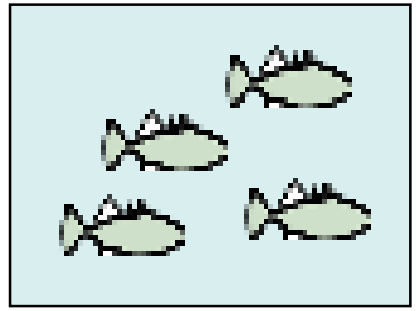


Phase 2:
Homogeneous groups of 3-8 mollies

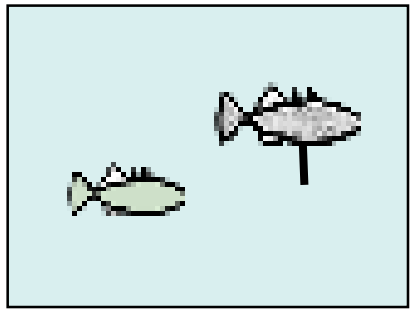
Collective Motion

Papadopoulou M et al. (In prep)

Papadopoulou et al. In prep.

Experiments

(24 individuals)



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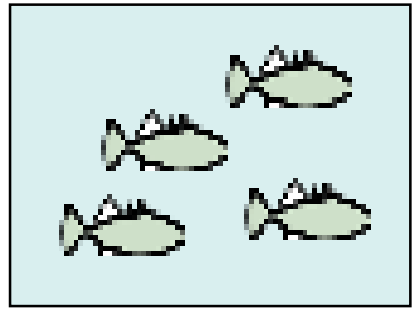
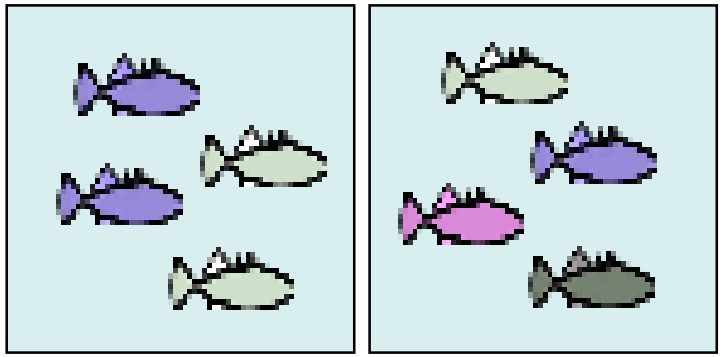


Phase 2:
Homogeneous groups of 3-8 mollies

Collective Motion

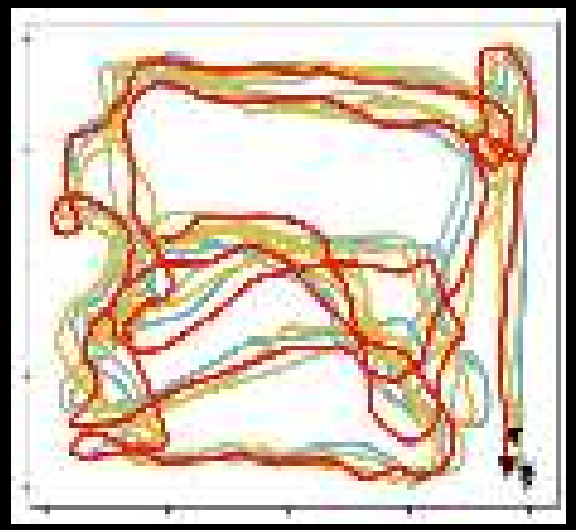


Phase 3:
Heterogeneous groups of 3-8 mollies

Collective Motion

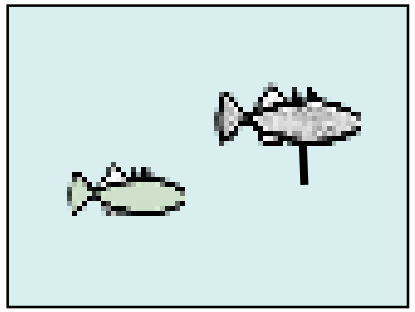
Papadopoulou M et al. (In prep)

Papadopoulou et al. In prep.



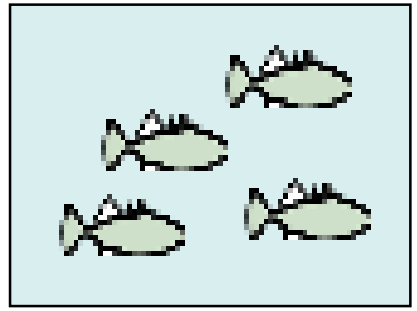
Experiments

(24 individuals)



Phase 1:
Robofish + 1 molly

Sociability Assessment



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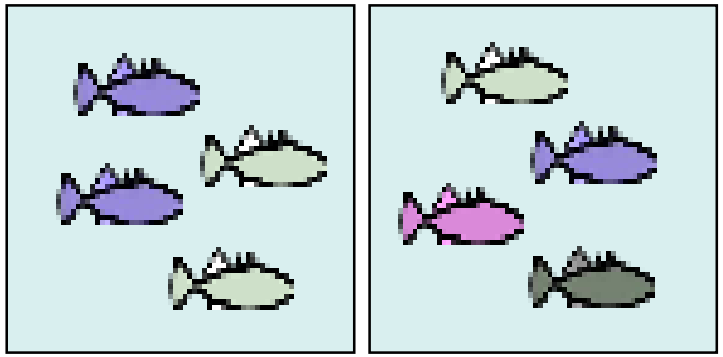
Collective Motion



Phase 3:
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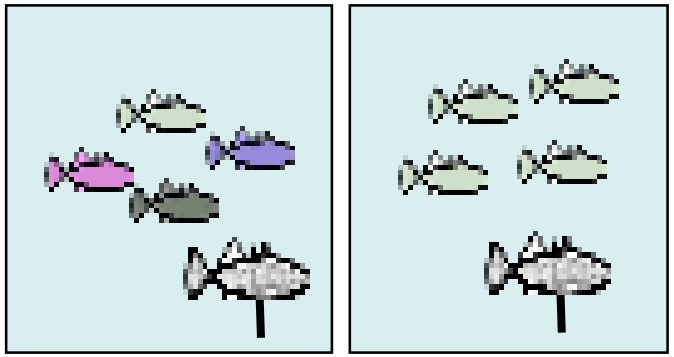
Collective Motion

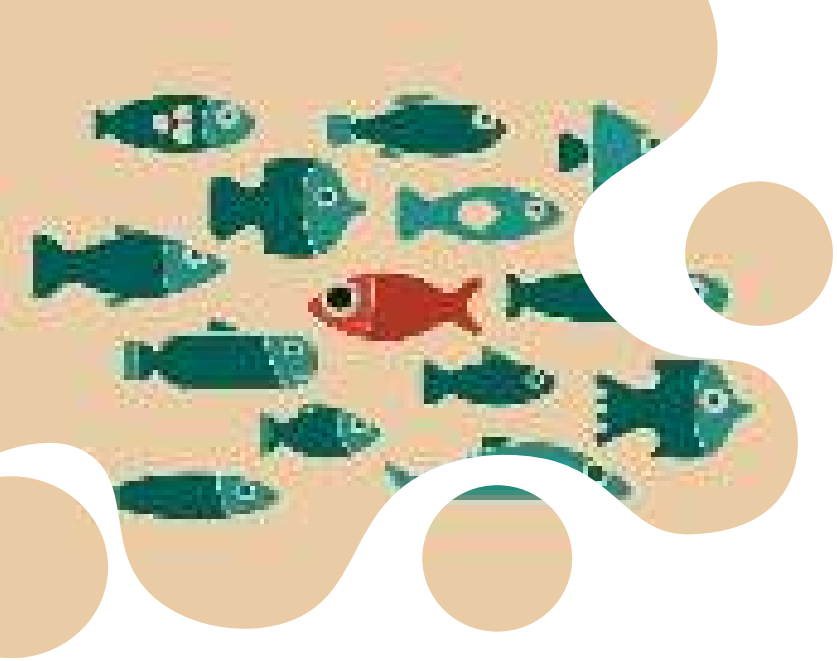


Phase 4:
Robofish + Groups

Social influence assessment

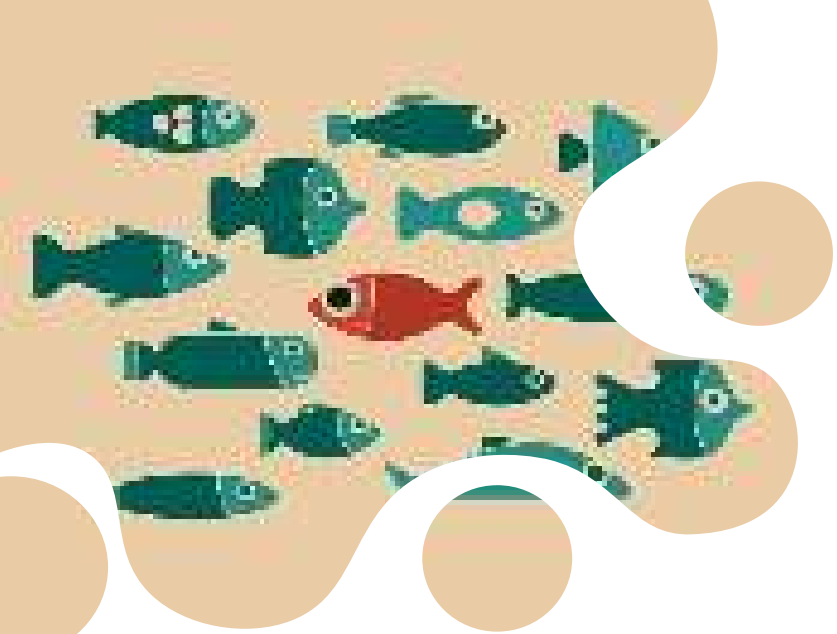
Papadopoulou et al. In prep.

Papadopoulou M et al. (In prep)



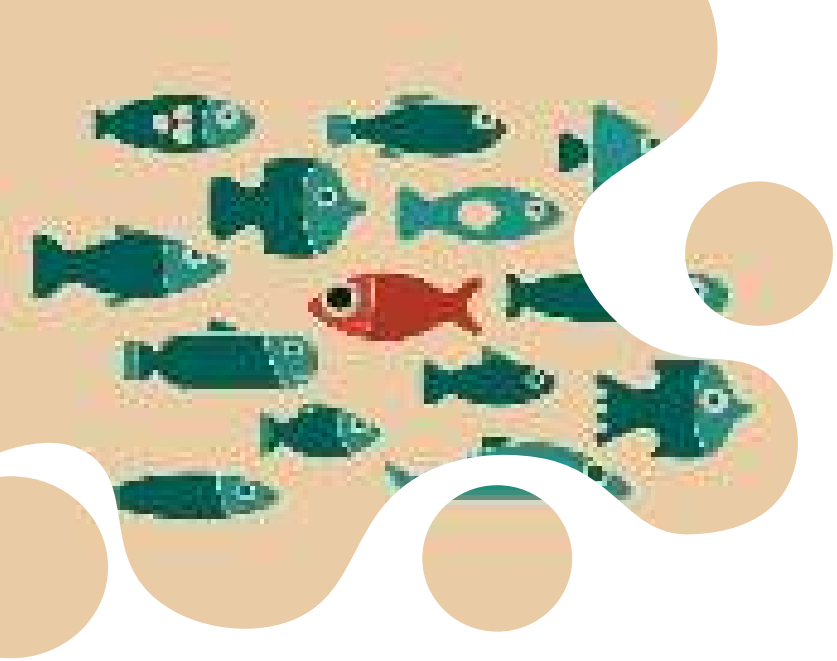
Group composition & Dynamics of collective motion

How do the levels of heterogeneity and sociability affect the characteristics of collective motion?



Group composition & Dynamics of collective motion

The Fish Space



Group composition & Leadership

Can individual sociability explain group attraction to the Robofish?

High ⟷ Low

[redacted]

Individual Heterogeneity

+ **MORPHOLOGY**

+ **PERSONALITY**

+ **SOCIAL STRUCTURE**

- *Preferred associations*
- *Dominance hierarchies*

Case study-
Decision making in baboons

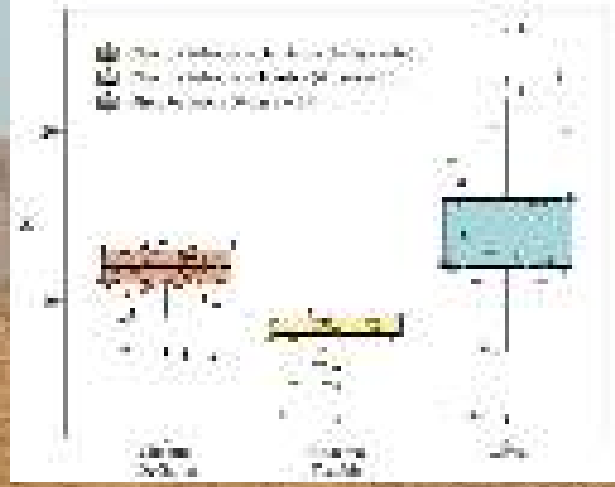
- Chacma baboons (*Papio ursinus*):

1. De Gama troop in South Africa*[1]
2. Tsaobis troop in Namibia
   (Lisa O'Bryan, Tsaobis Baboon Project)

- Olive baboons (*Papio anubis*)

3. Mpala Research Centre in Kenya*[2]

What is the effect of the underlying social structure on the dynamics of collective motion and decision-making?

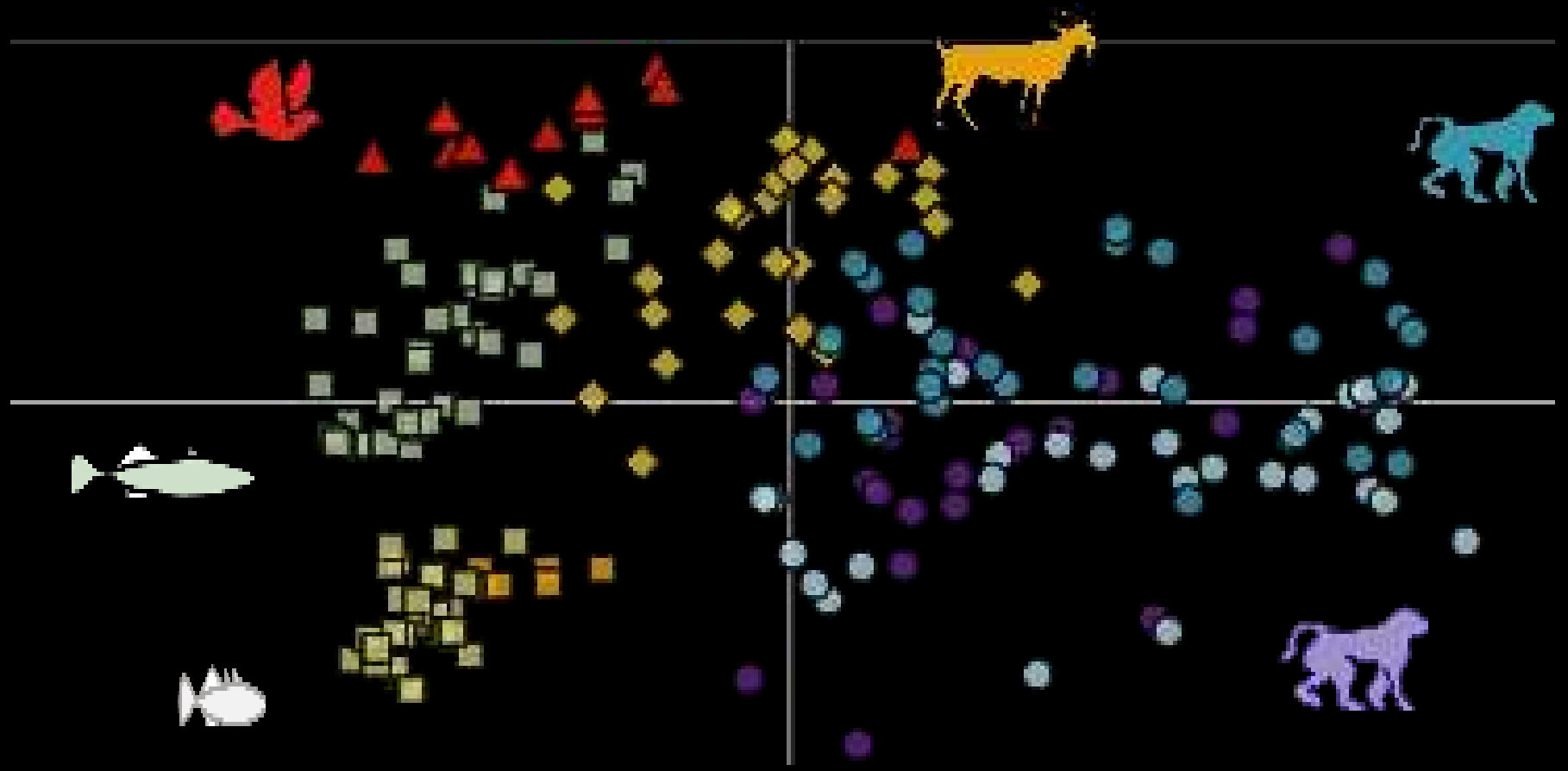


Papadopoulou et al. In prep.

*[1] *Bracken* et al. (*2021*) *Int J Primatol* | *[2] Strandburg-Peshkin et al. (2015), Science

Expanding the Swarm-Space

New baboon & fish species



Mechanisms to link individual variation to emergent collective behaviour

[1]
The Swarm-Verse

Understanding collective behaviour across species and ecological contexts

[2]
Individual heterogeneity

Morphology, Personality & Social networks

[3]
Collective escape in bird flocks

Insights from data-inspired agent-based models

[4]
Coda

future aims & applications


Kastberger et al. (2008) PLoS One


NATIONAL

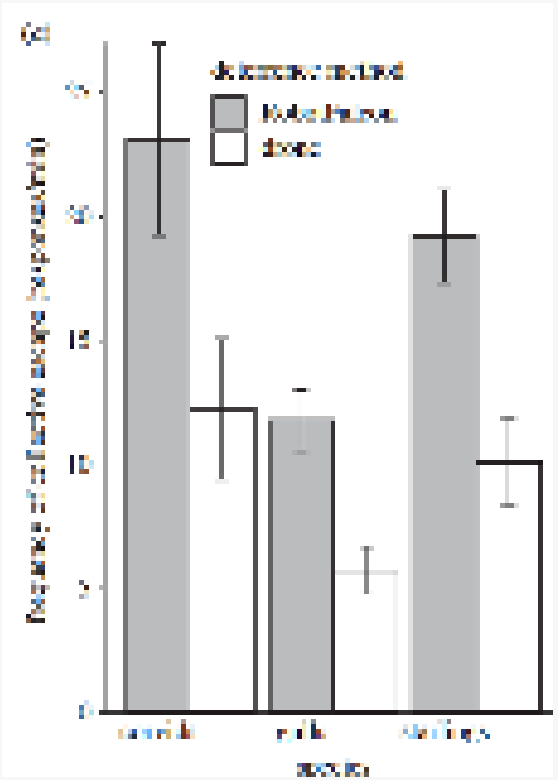

Sulphur mollies (*Poecilia sulphuraria*) attacked by a great kiskadee
Duran et al. (2022) Curr. Biol.


Ray Hamlyn (2013)
"Dance of the Dunlins"

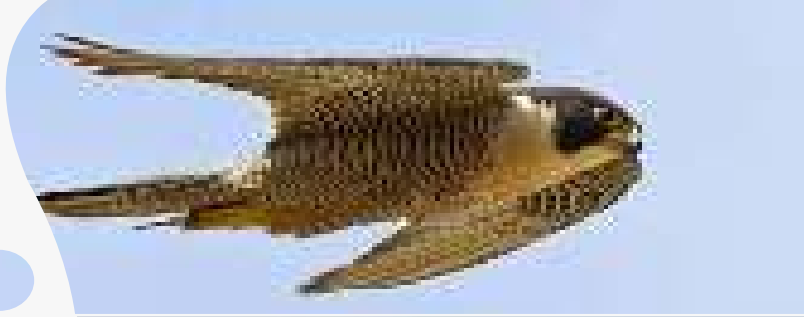
Collective escape in bird flocks

~ *the RobotFalcon*

A robotic falcon induces similar collective escape responses in different bird species



Storms et al. 2022 J. R. Soc. Interface



Robert Musters (Roflight – avibird.com)

Rolf Storms

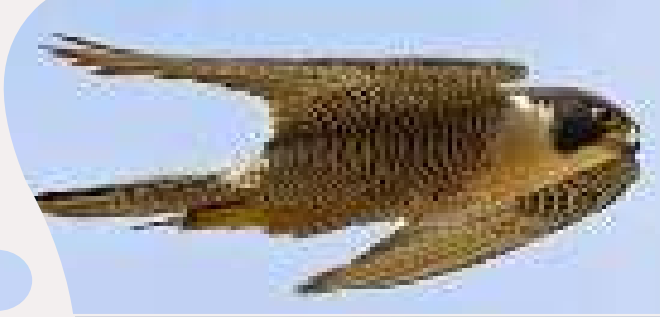
Case studies -

Escaping the RobotFalcon

- A. Pigeons

- B. Starlings

Charlotte K. Hemerlijk

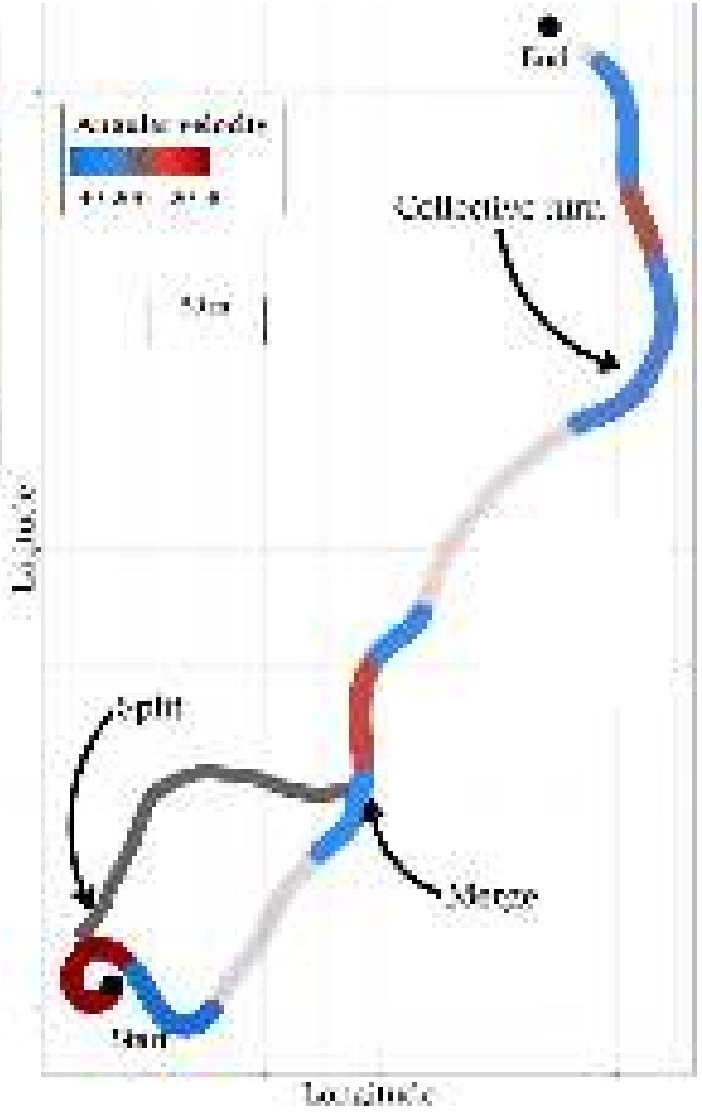


Robert Musters (Roflight – avibird.com)

Rolf Storms

Pigeon flocks

Trajectories of both predator and prey during airborne pursuit



Dan Sankey

Steve Portugal

Papadopoulou et al. 2022 R.Soc.Open Sci.

CellPress

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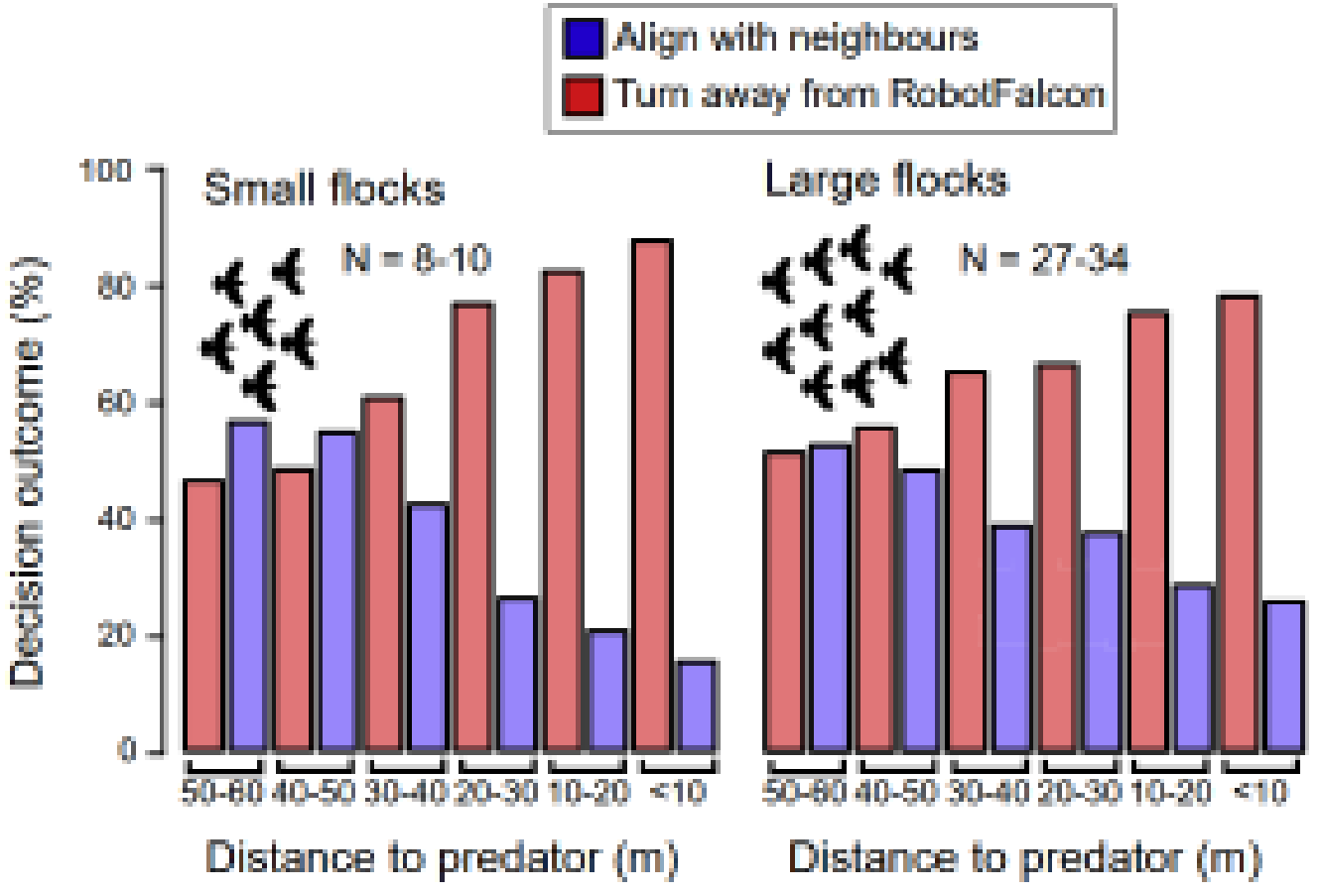
Absence of "selfish herd" dynamics in bird flocks under threat

Predator avoidance

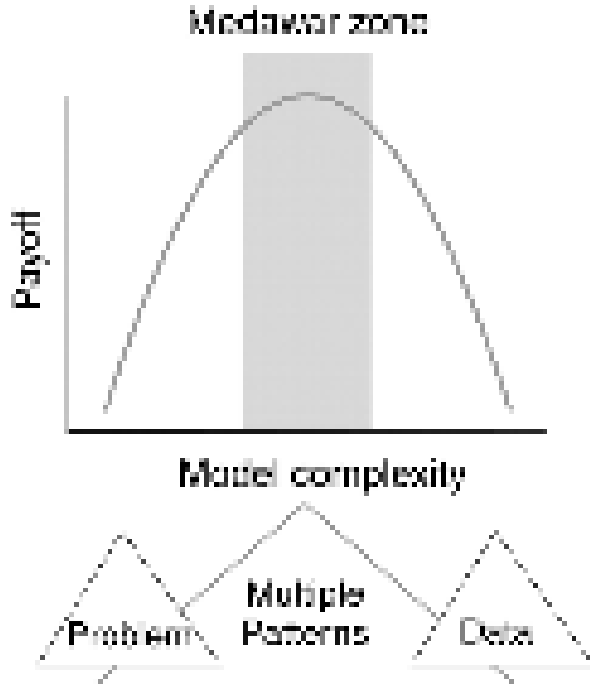
Emphasize predator avoidance rather than aligning when closer to the threat



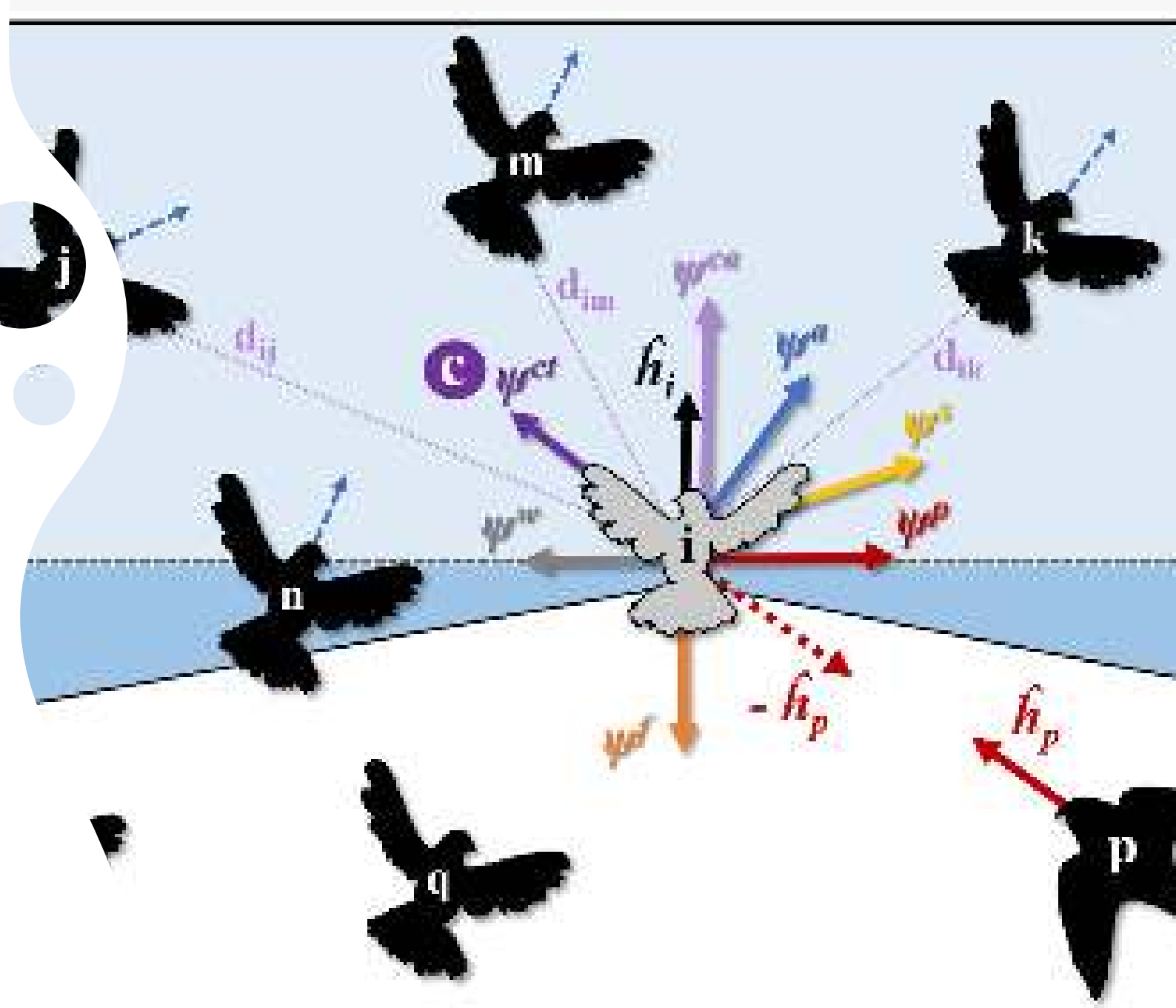
An agent based model of pigeons:

HoPE

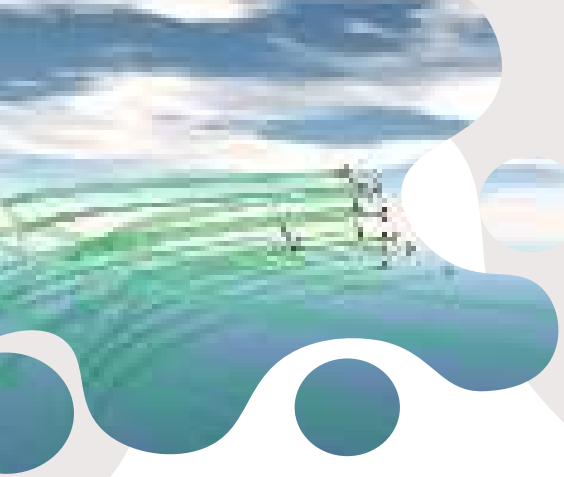
- *Pattern-oriented modelling:*



Grimm et al. (2005) Science

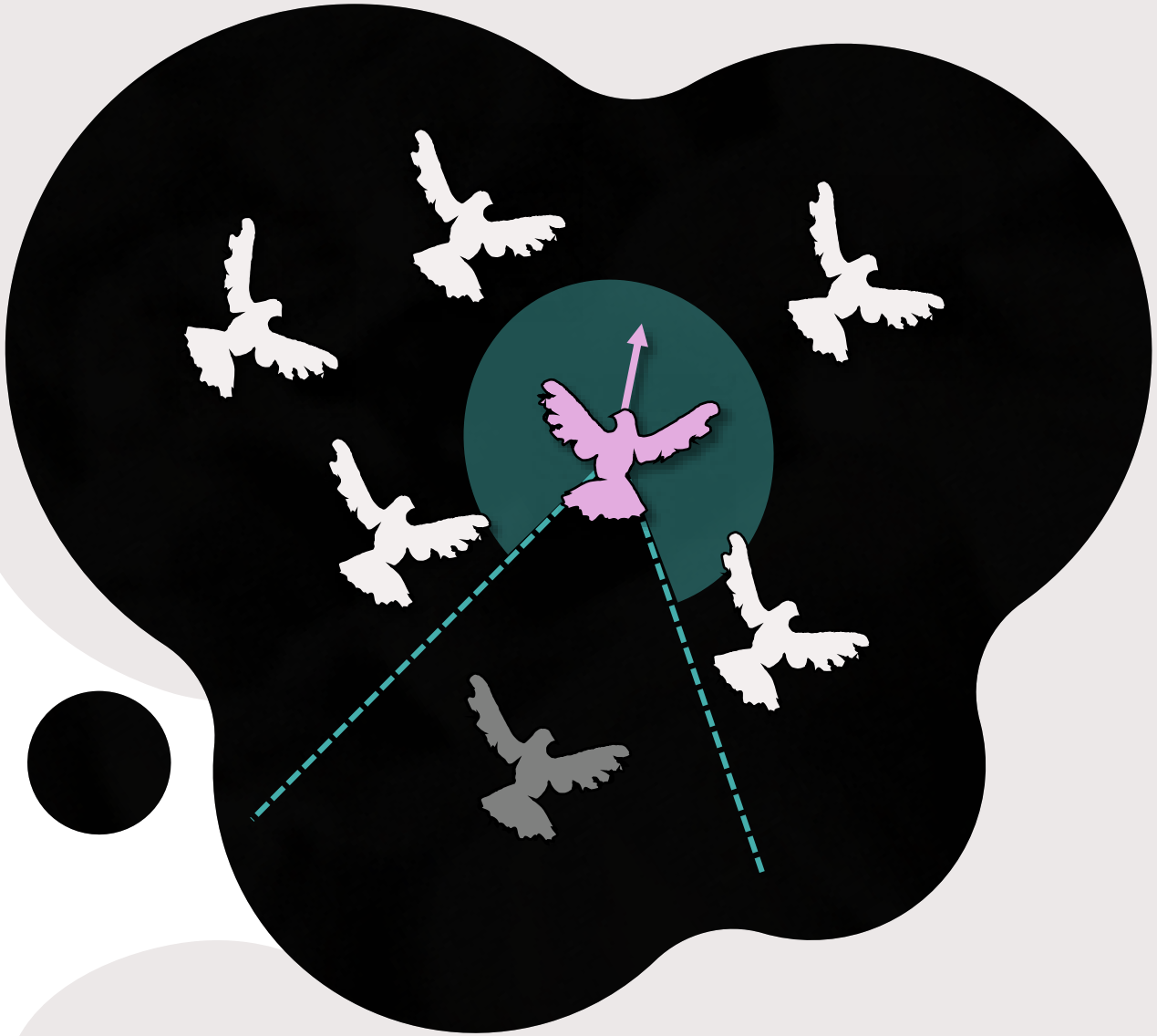


Papadopoulou et al. (2022) PLoS Comput. Biol.

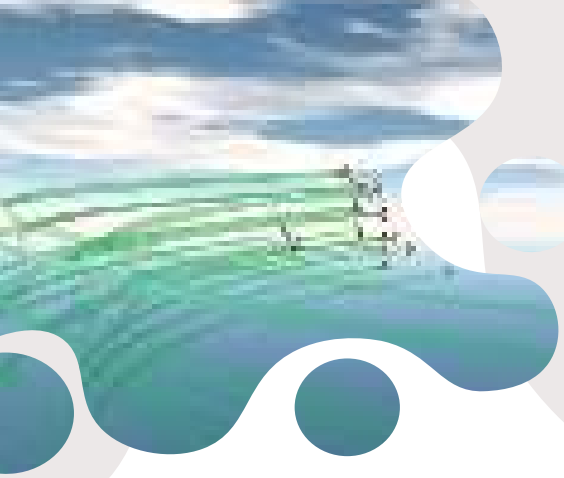


1. Social Influence

- Topological neighbours



Papadopoulou et al. (2022) PLoS Comput. Biol.



1. Social Influence

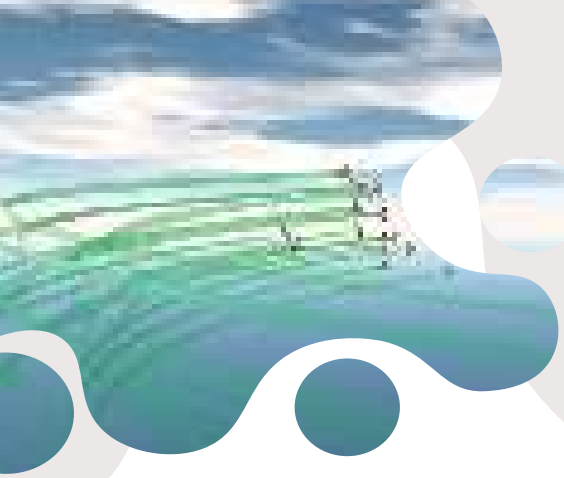
- Topological neighbours
- Interaction rules (pseudo-forces)

Attraction

Alignment

Avoidance

Papadopoulou et al. (2022) PLoS Comput. Biol.

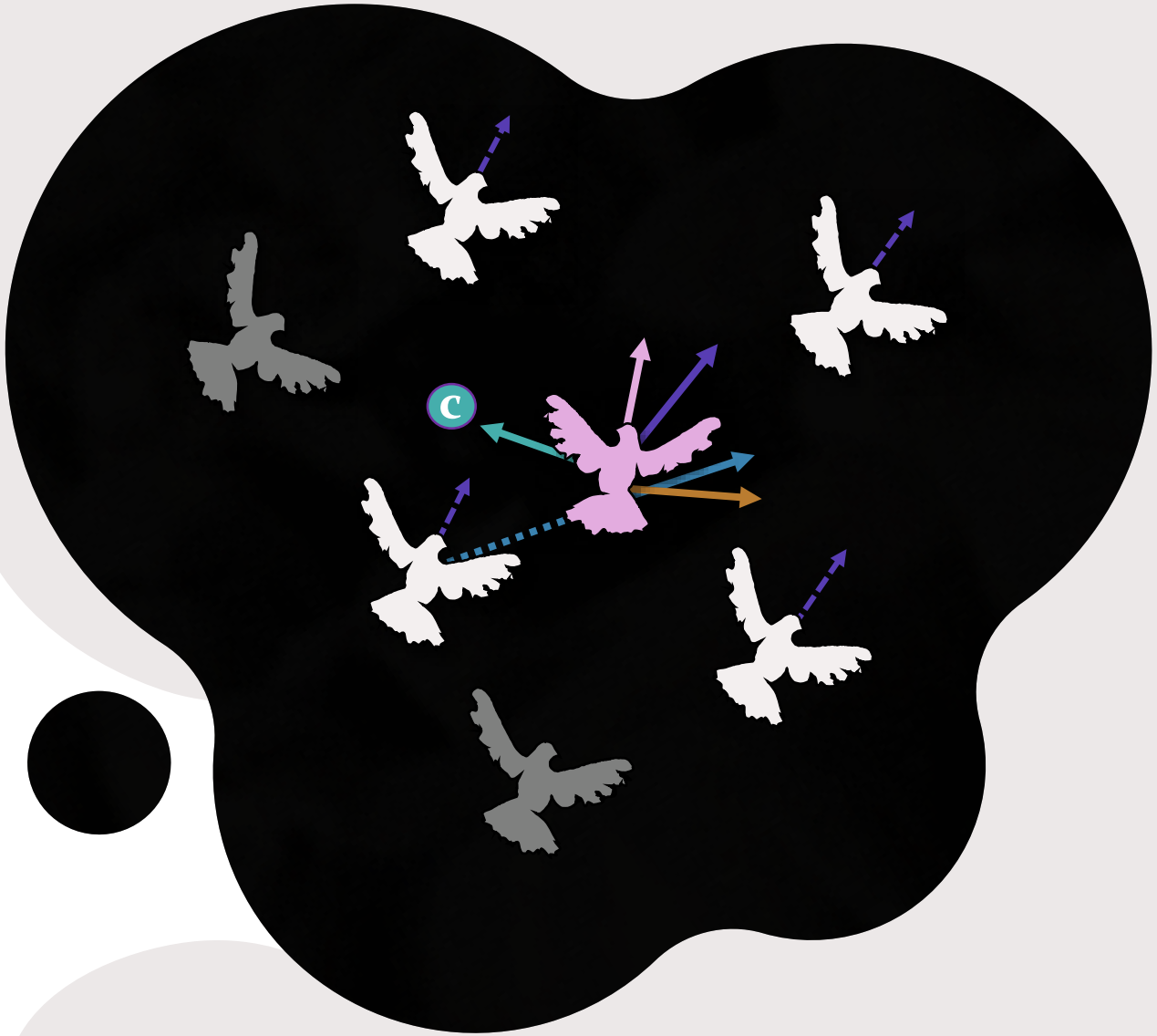


1. Social Influence

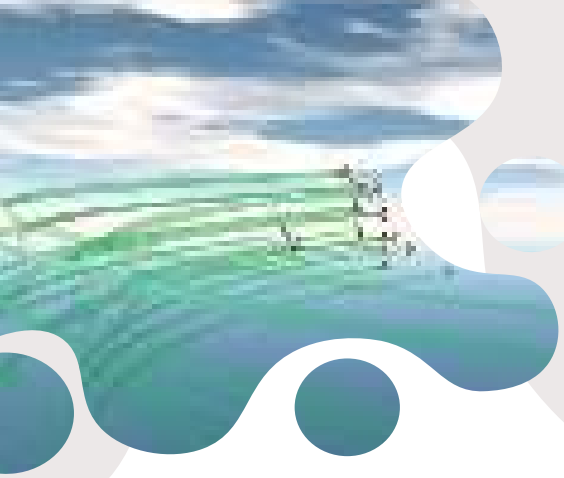
- Topological neighbours
- Interaction rules (pseudo-forces)

Attraction
Alignment
Avoidance
} **Coordination**

Noise



Papadopoulou et al. (2022) PLoS Comput. Biol.

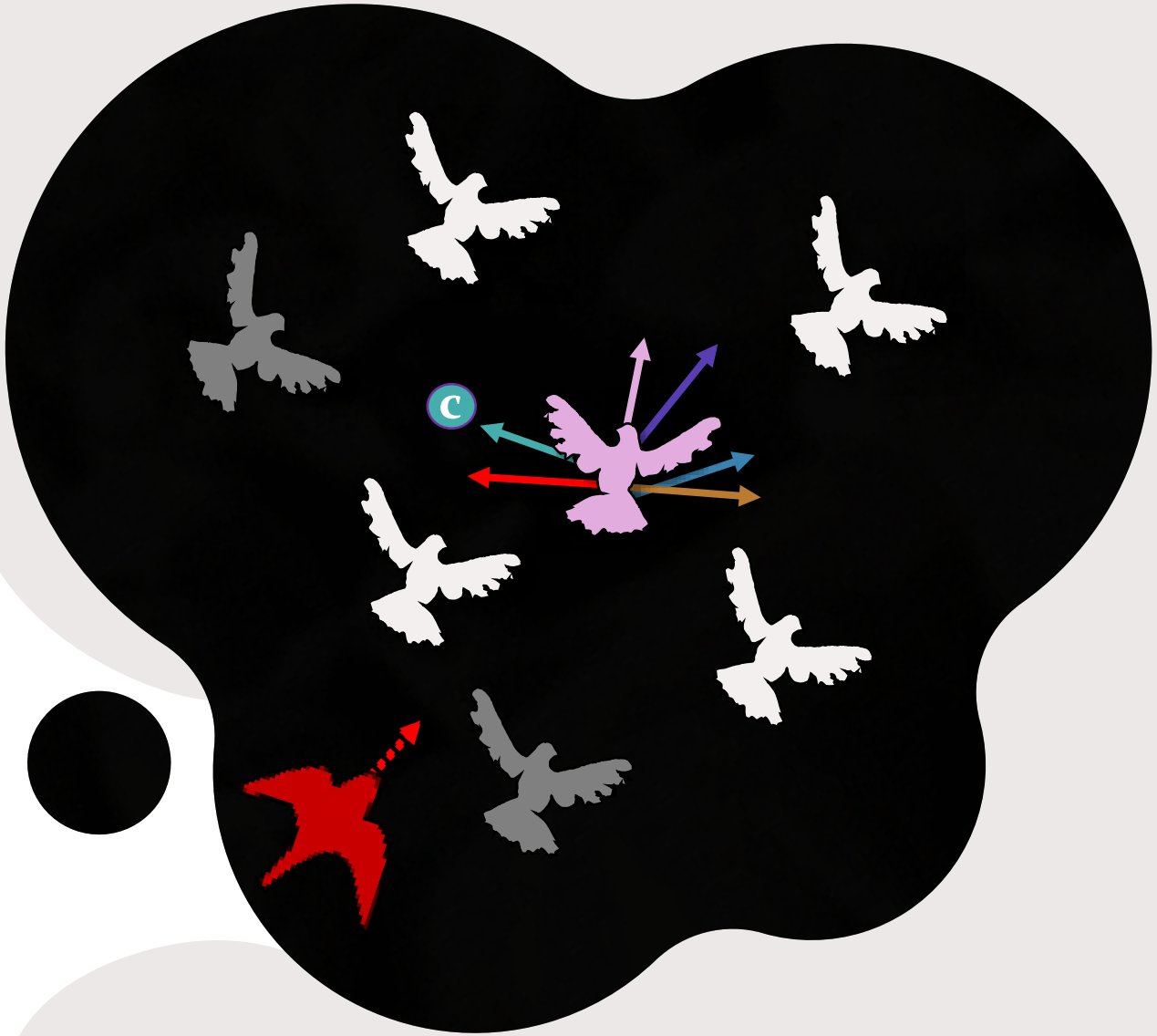


2. Escaping

- Predator avoidance

Attraction
Alignment
Avoidance

Escape
Coordination
Noise



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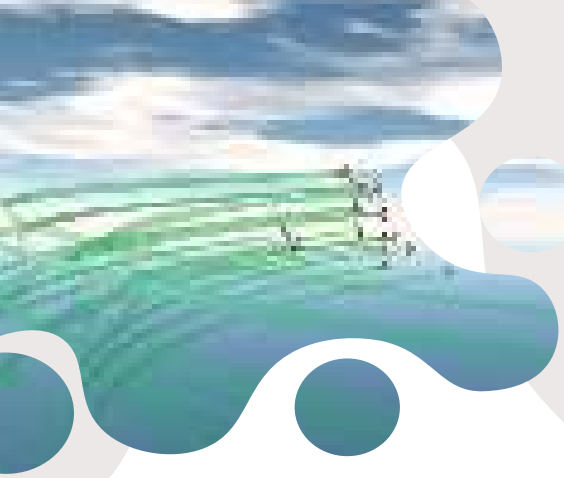
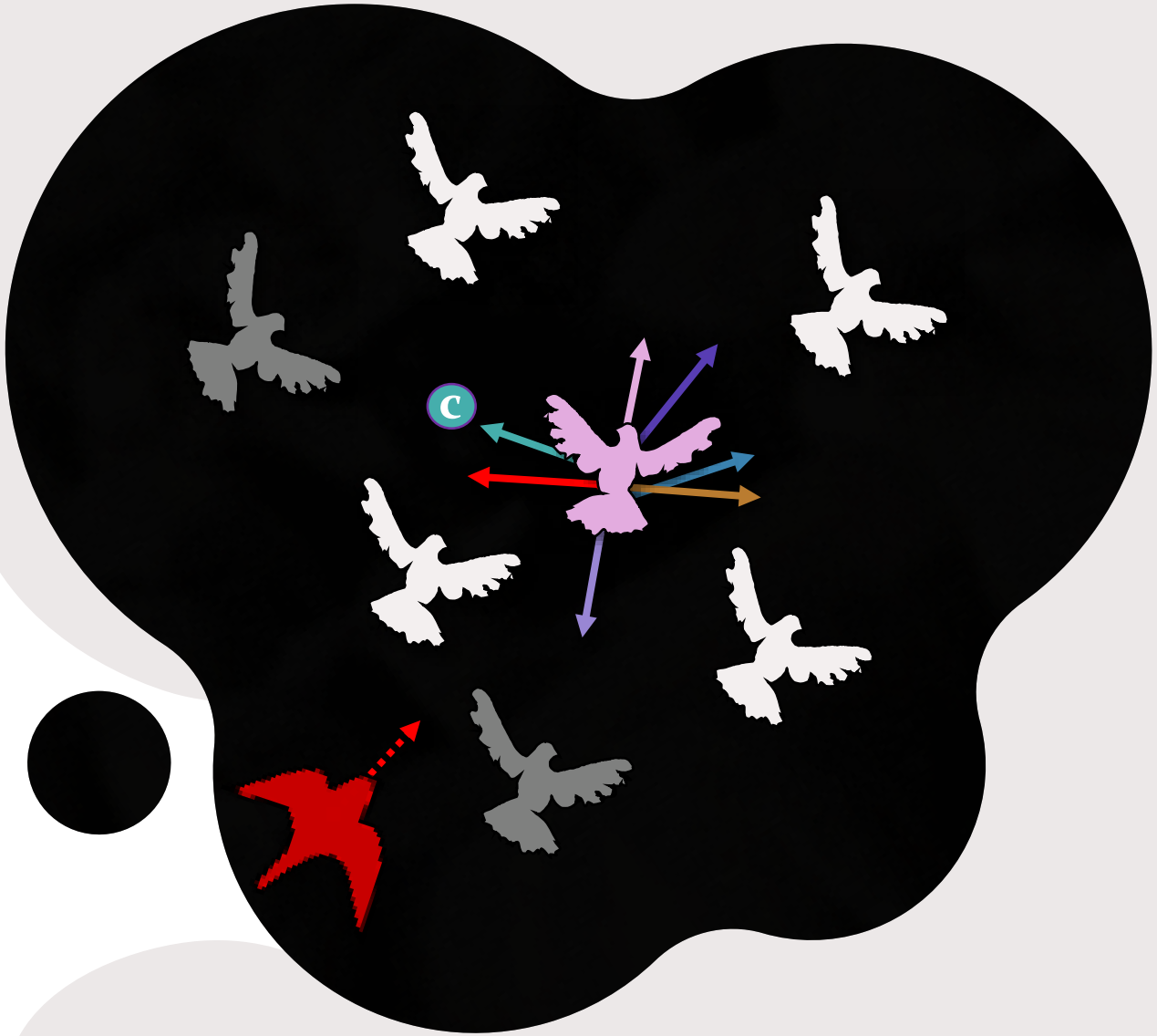


3. Locomotion

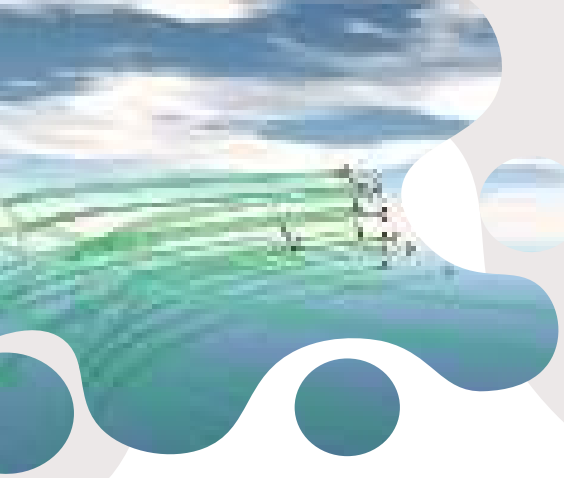
- Flight control

Attraction
Alignment
Avoidance

Escape
Coordination
Noise
Return to cruise speed



Sankey et al. (2019) Anim.Behav. | Papadopoulou et al. (2022) PLoS Comput. Biol.

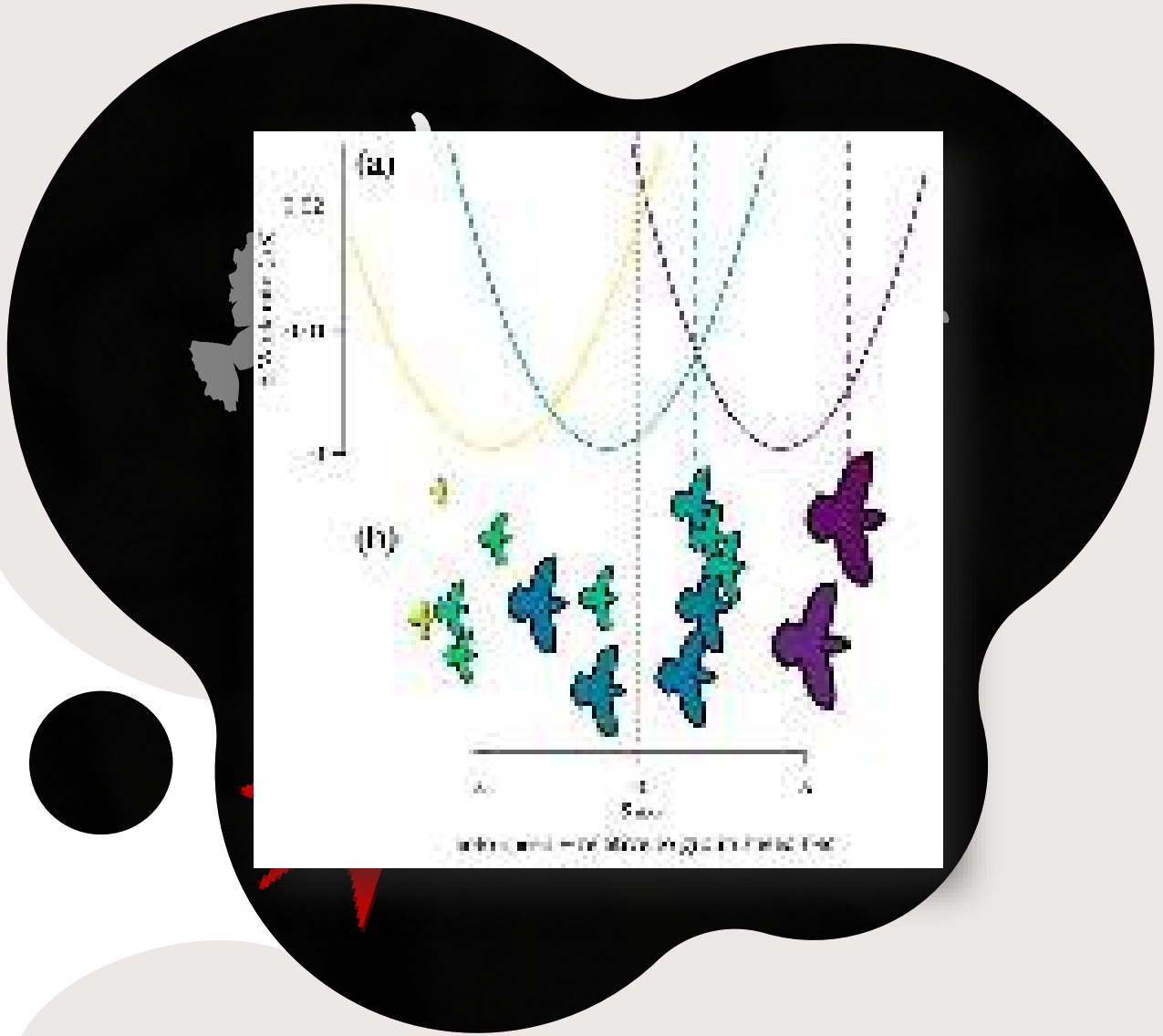


3. Locomotion

- Flight control
- Individual variation

Attraction
Alignment
Avoidance

Escape
Coordination
Noise
Return to cruise speed



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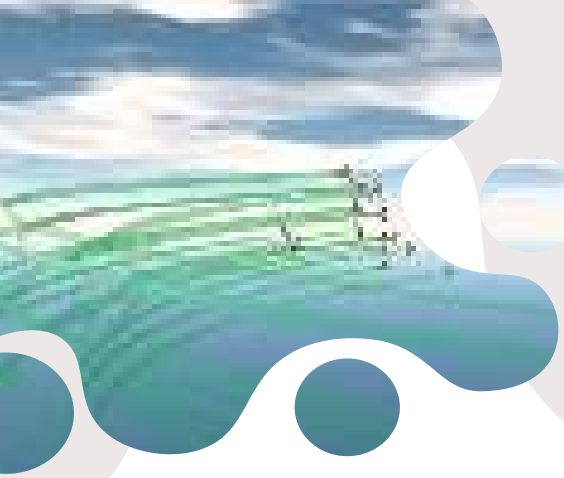

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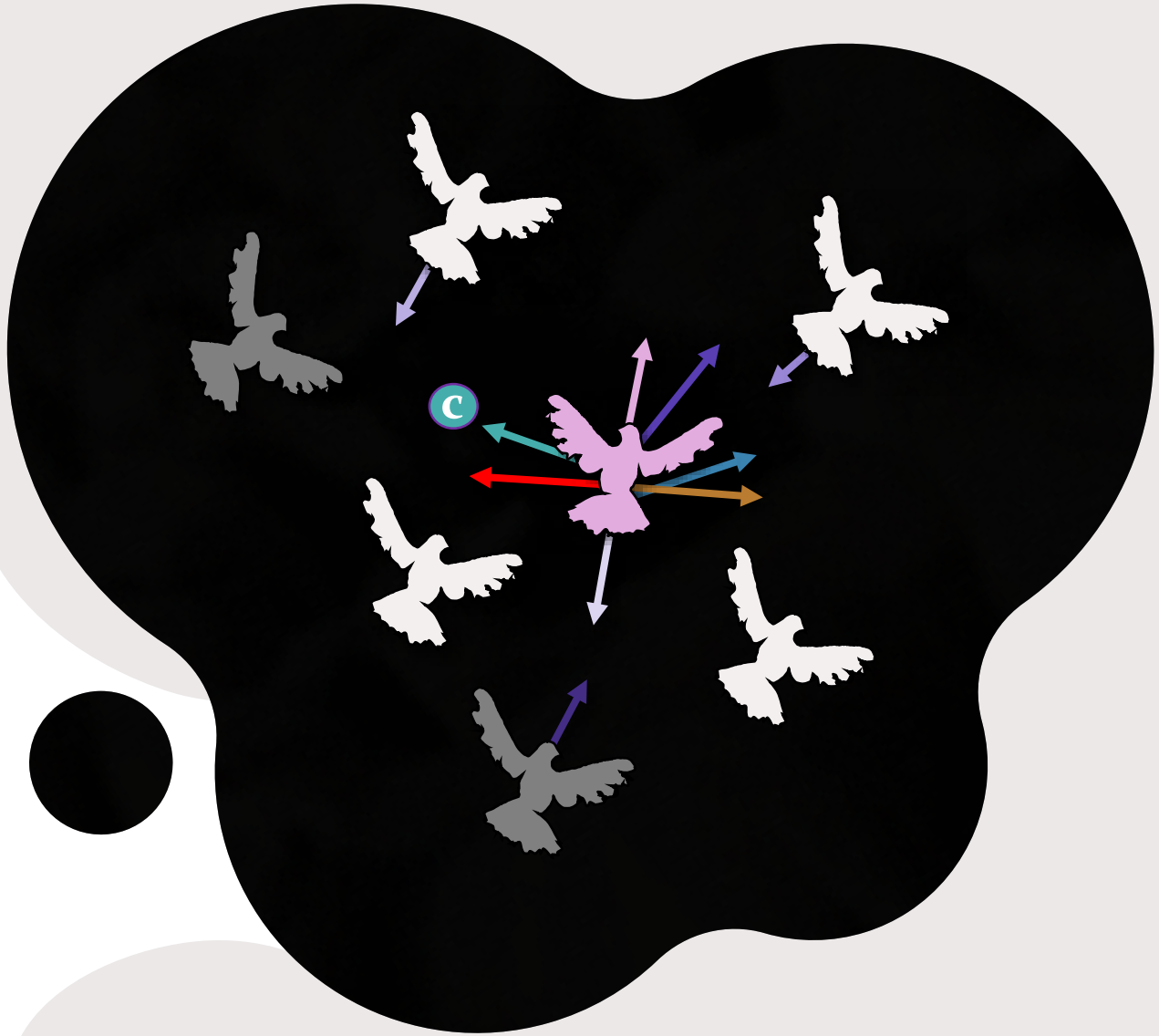
- Flight control
- Individual variation

Attraction
Alignment
Avoidance

Escape
Coordination
Noise
Return to cruise speed



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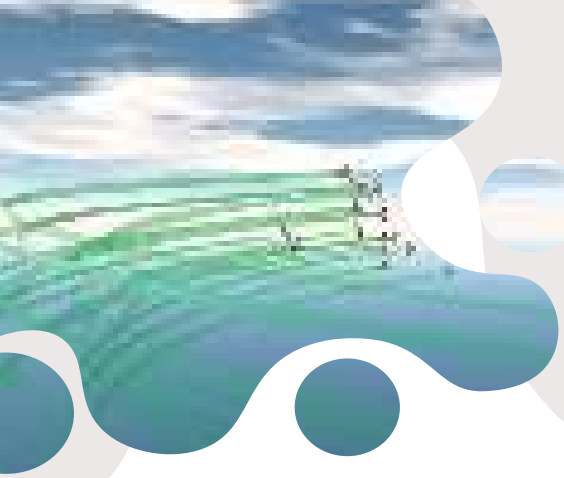
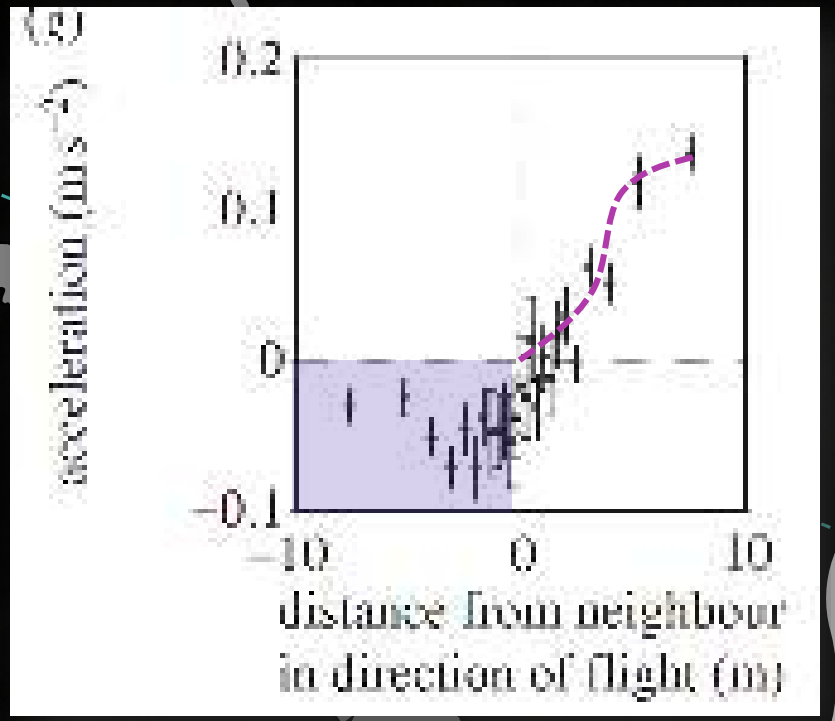


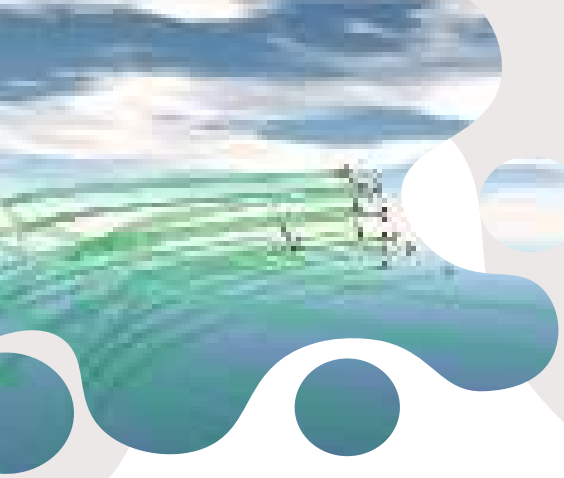
4. Species-specific rules

- According to inferred interaction rules from empirical data

  + **Acceleration-based attraction**



Pettit et al. (2013) J.R.Soc.Interface | Papadopoulou et al. (2022) PLoS Comput.Biol.



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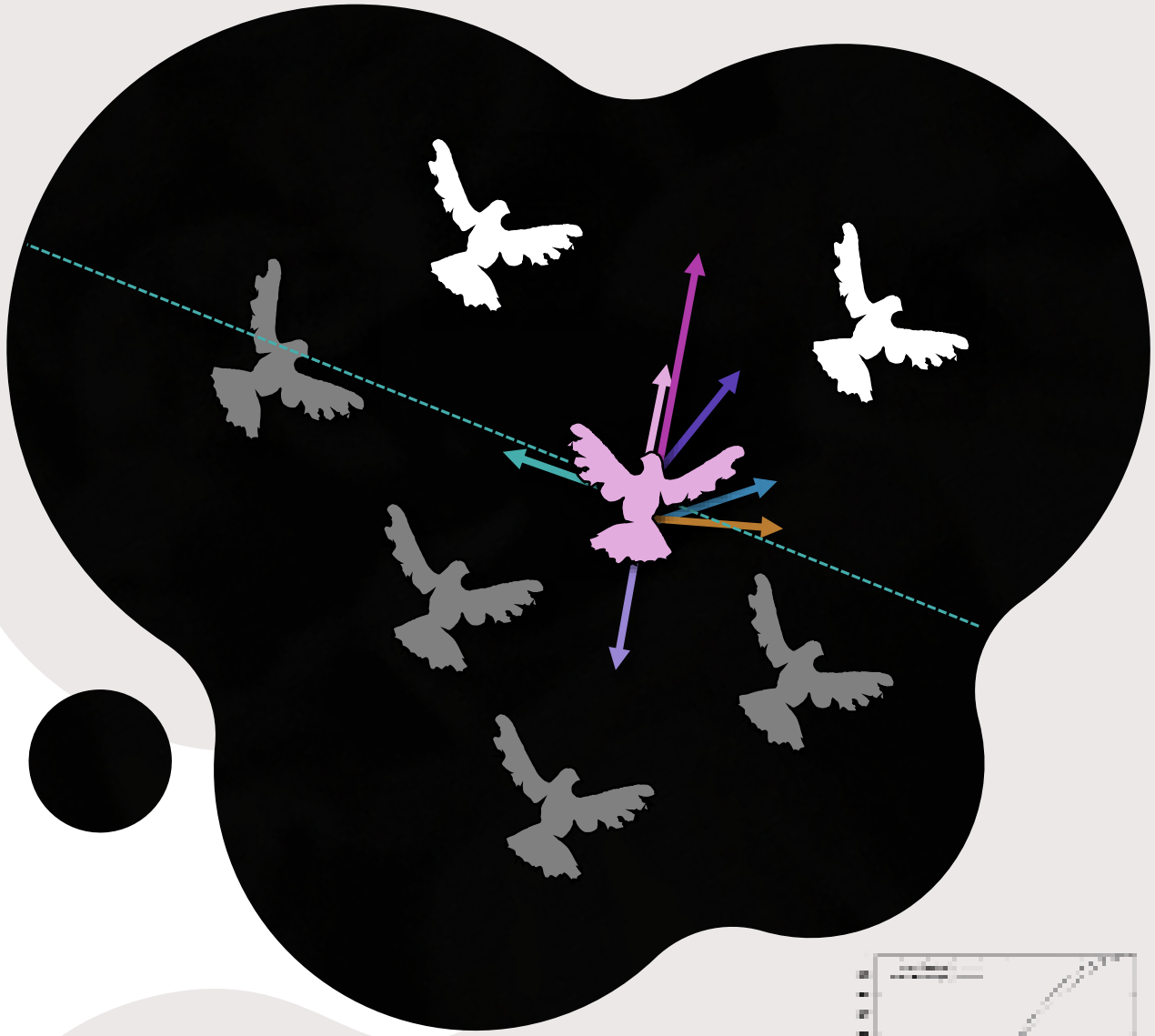

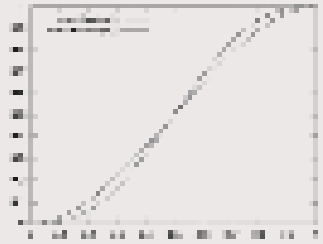

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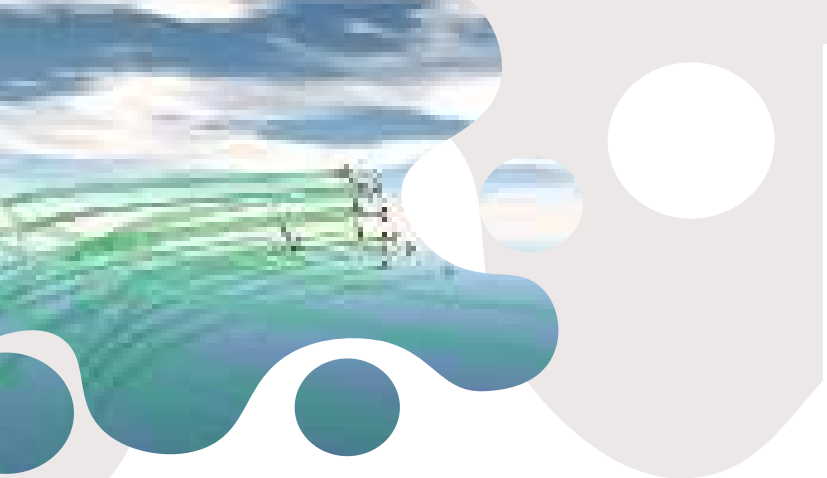
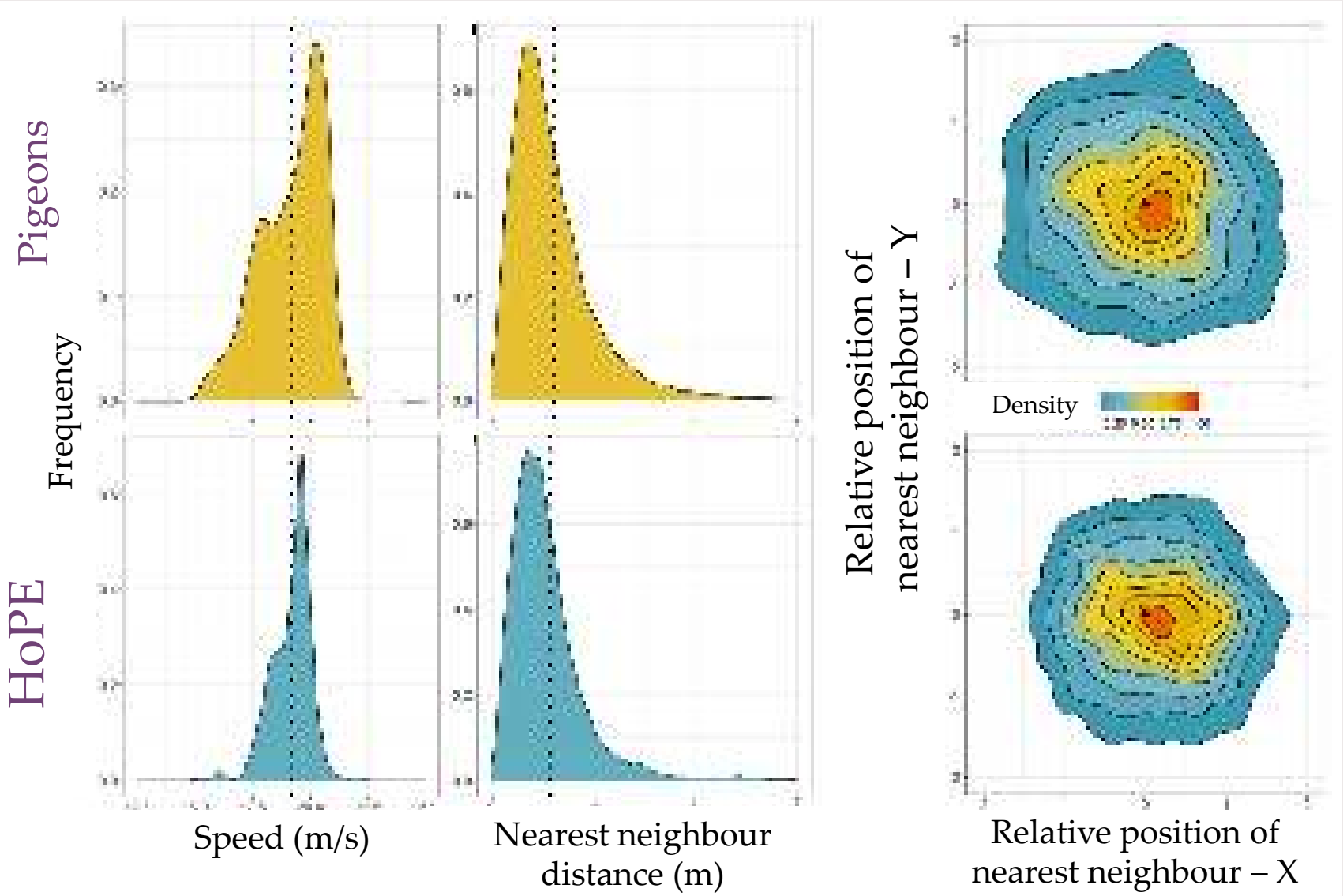


4. Model validation

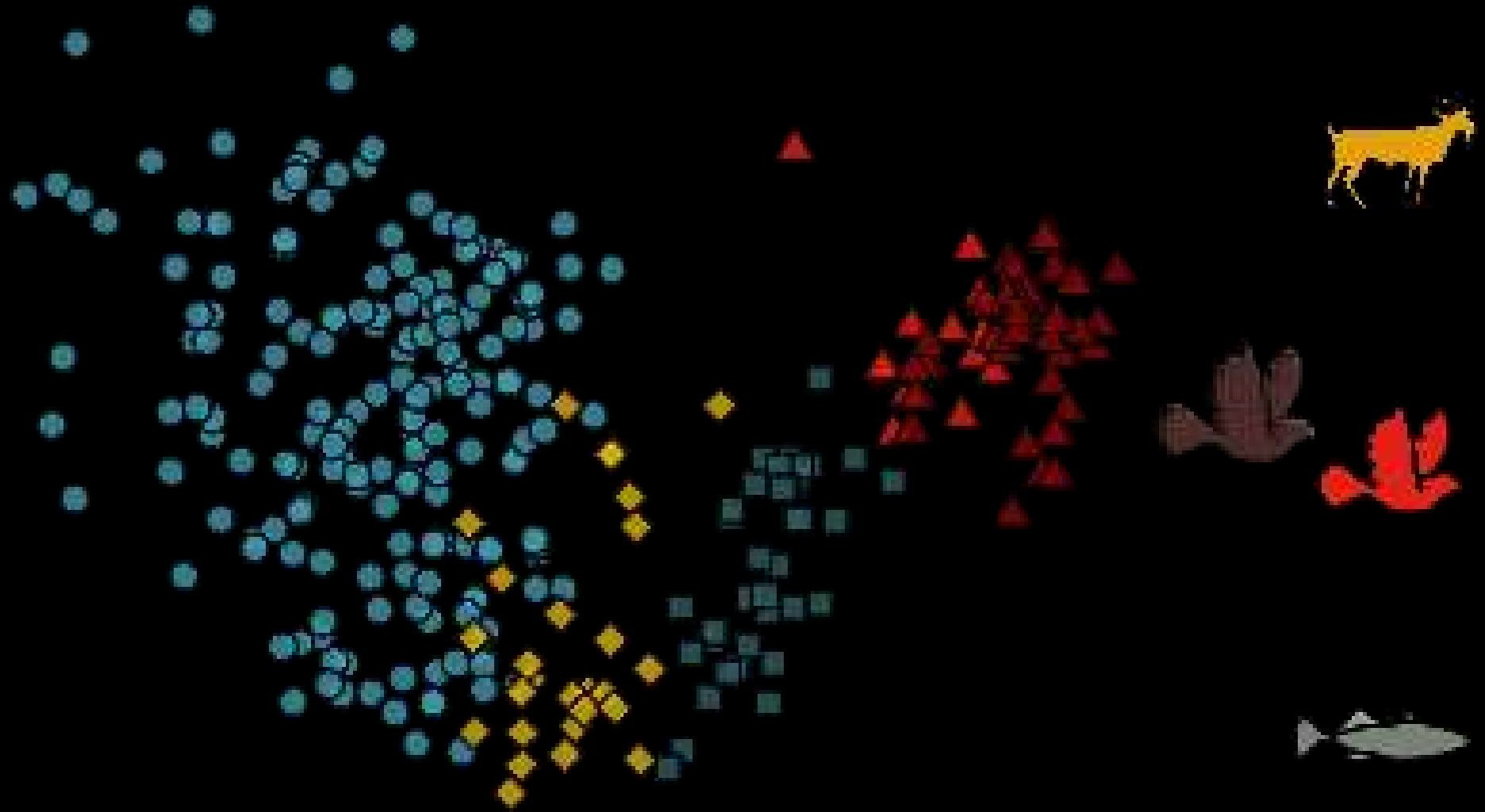
- Calibrate parameters based on 3 metrics



Grimm et al. (2005) Science | Papadopoulou et al. (2022) PLoS Comput.Biol.

Bio-hybrid Swarm Space

Simulated vs Empirical Data



Papadopoulou et al. In prep.

1. Predator avoidance

Emphasize predator avoidance rather than aligning when closer to the threat

Cell Press

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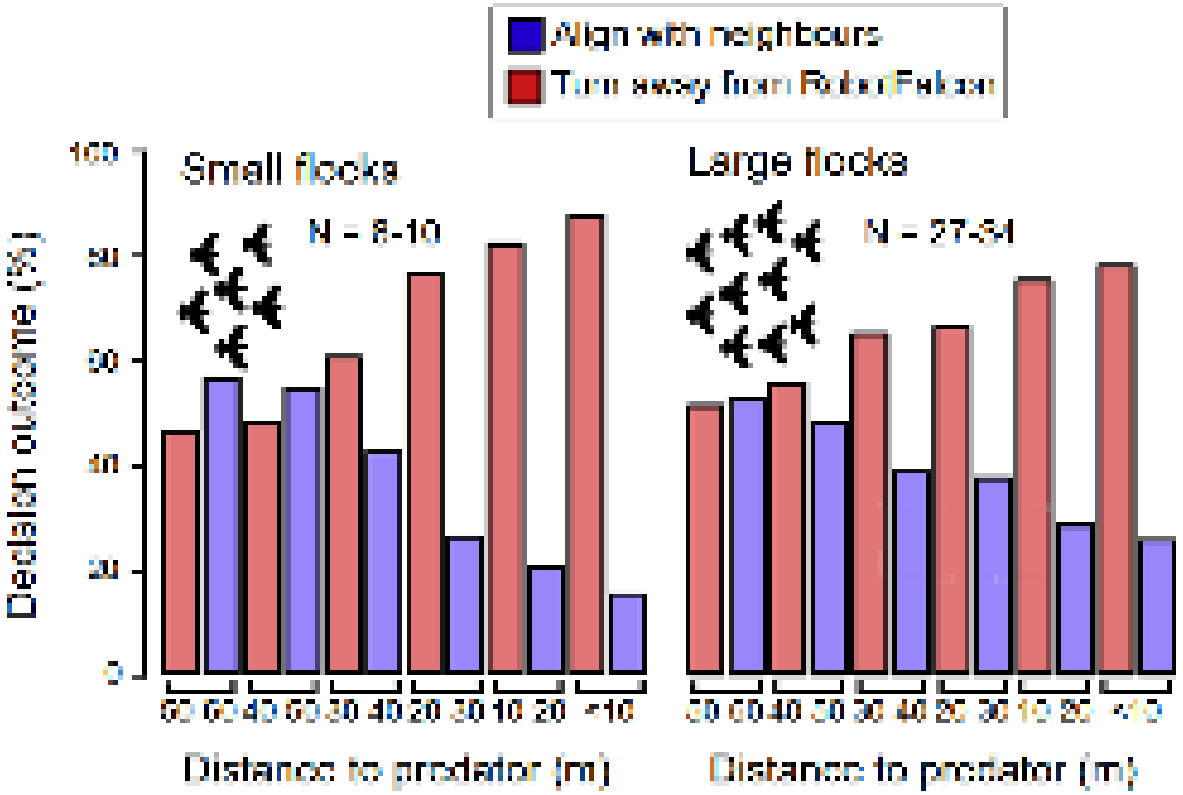
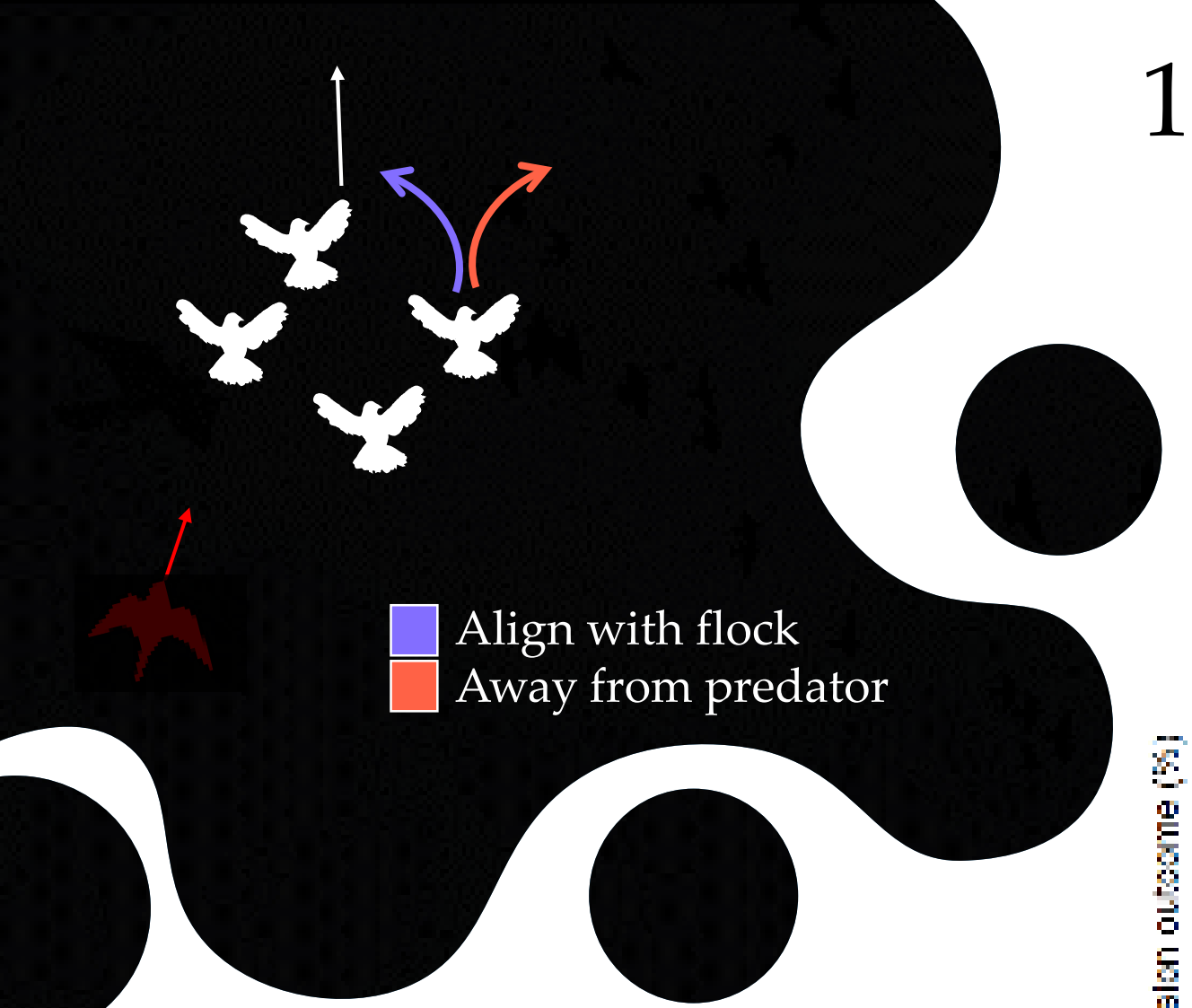
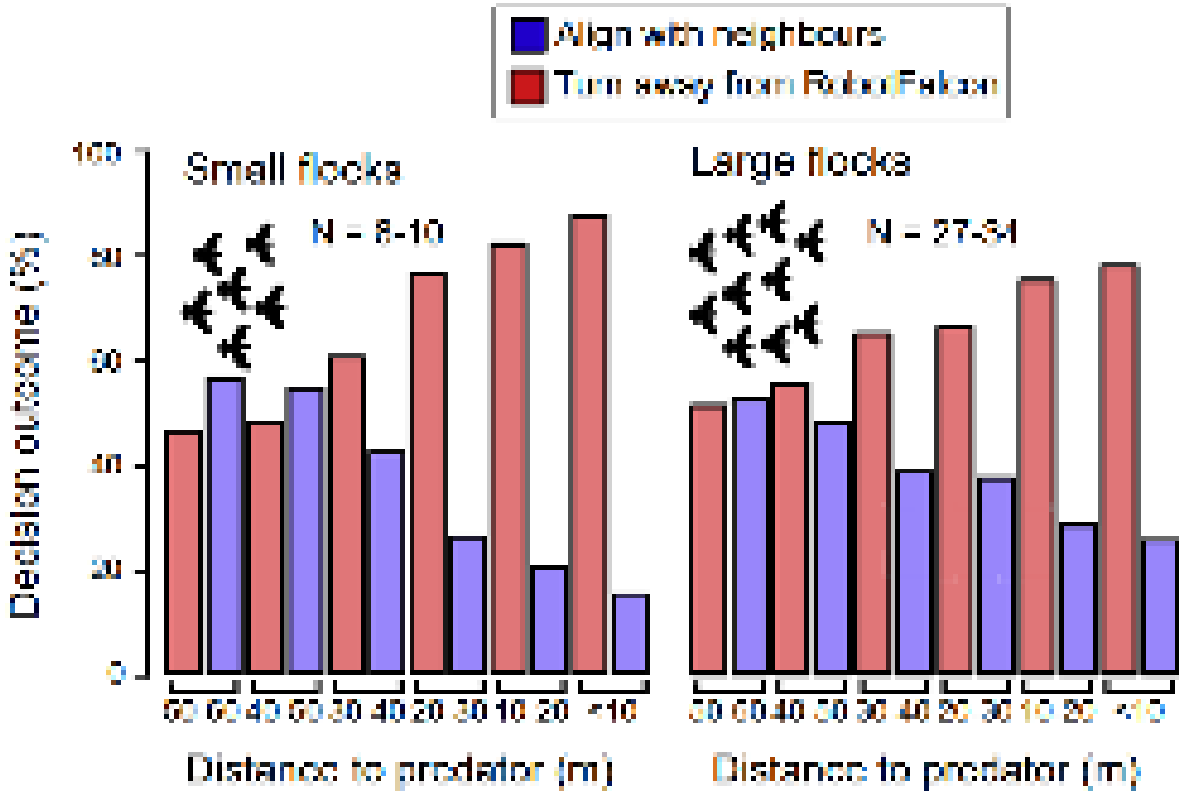
Absence of "selfish herd" dynamics in bird flocks under threat



1. Predator avoidance

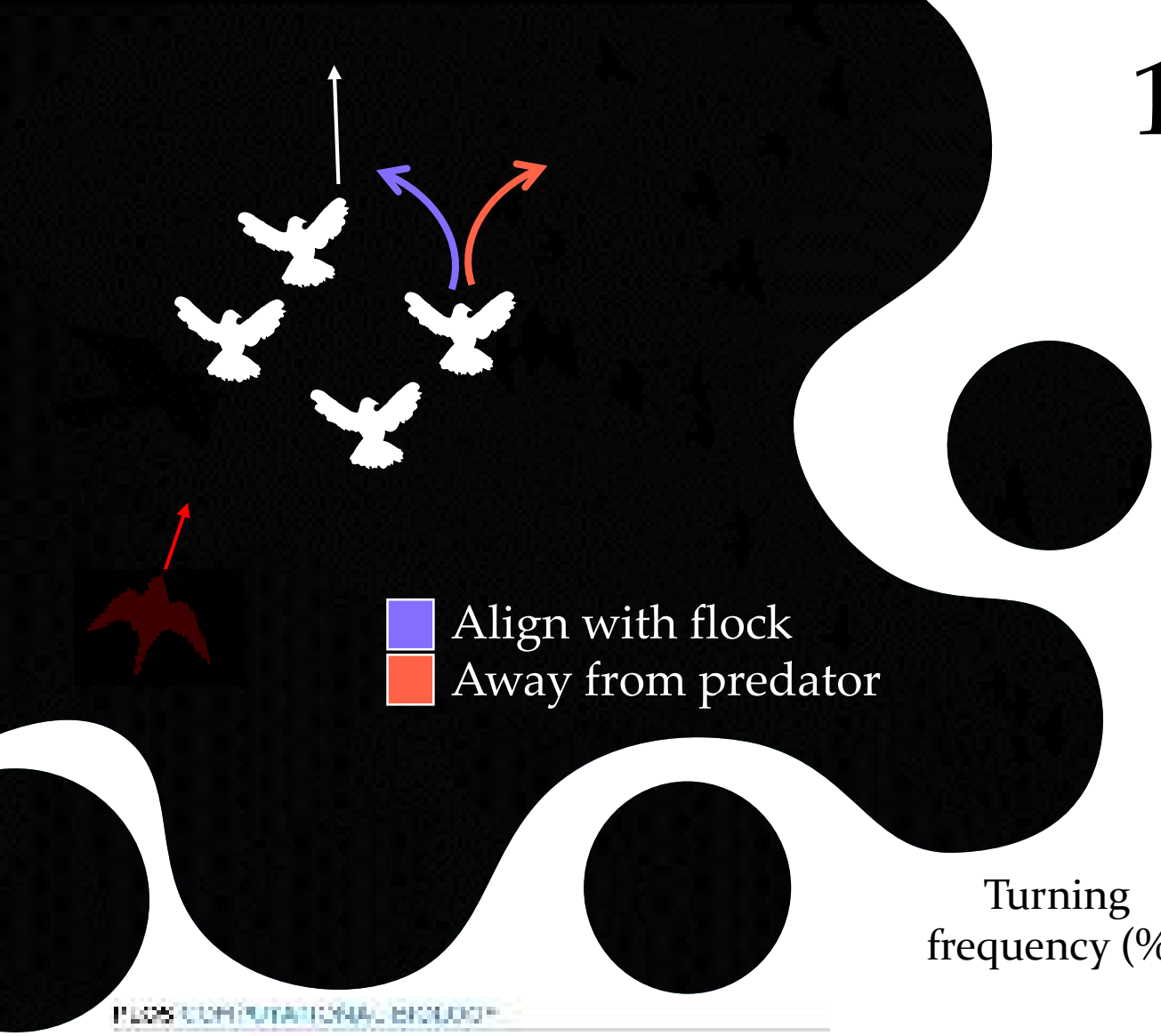


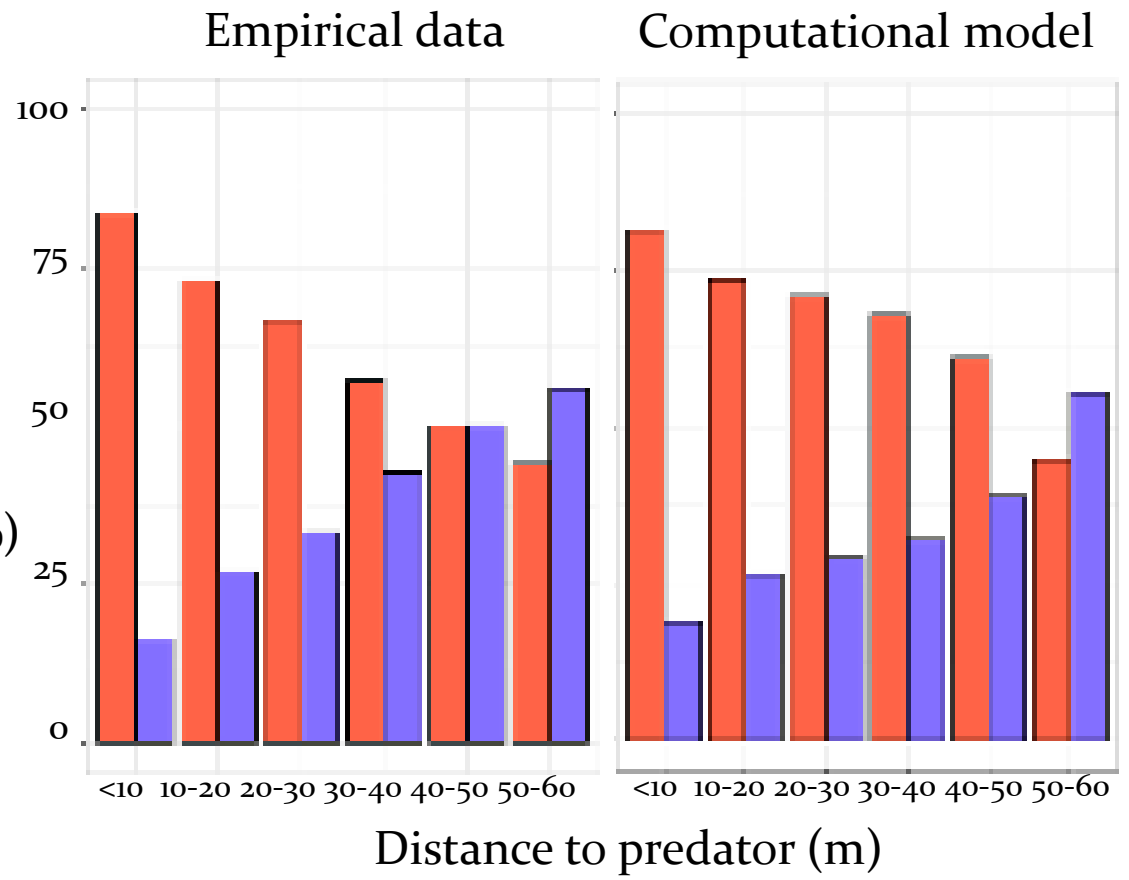
- Creating a null model..



1. Predator avoidance

***Emergent property**, not individual rule.*





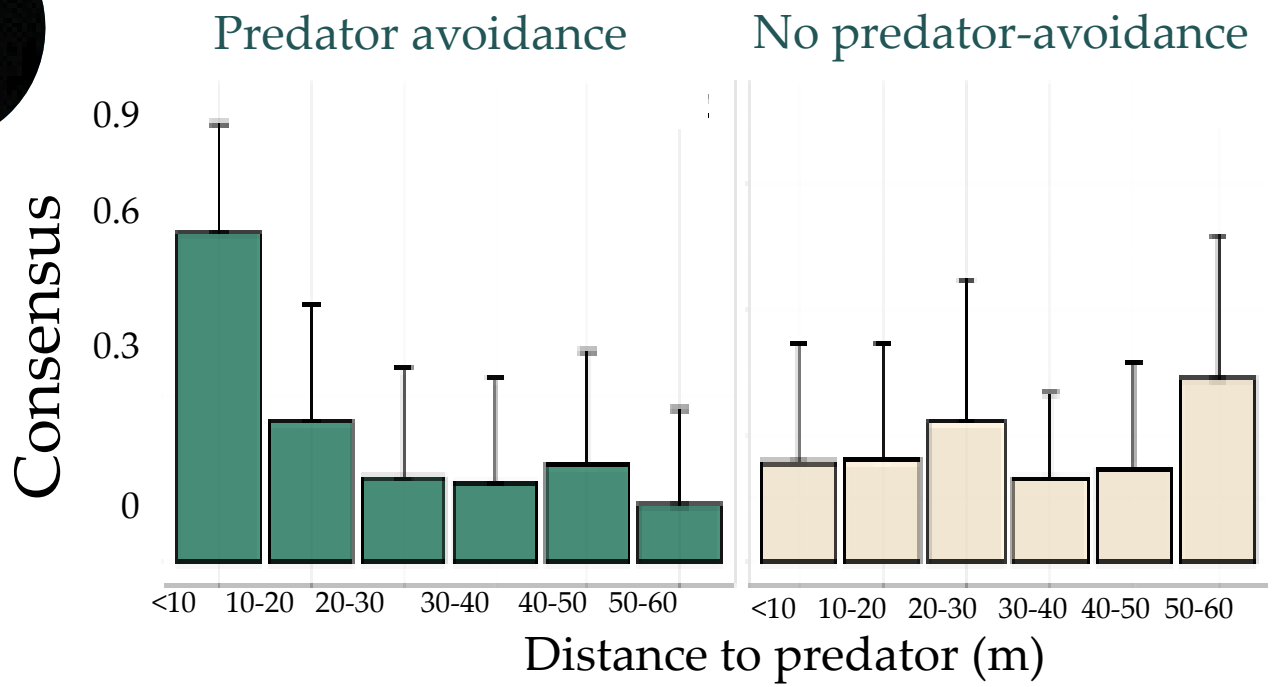
1. Predator avoidance

Consensus measurement

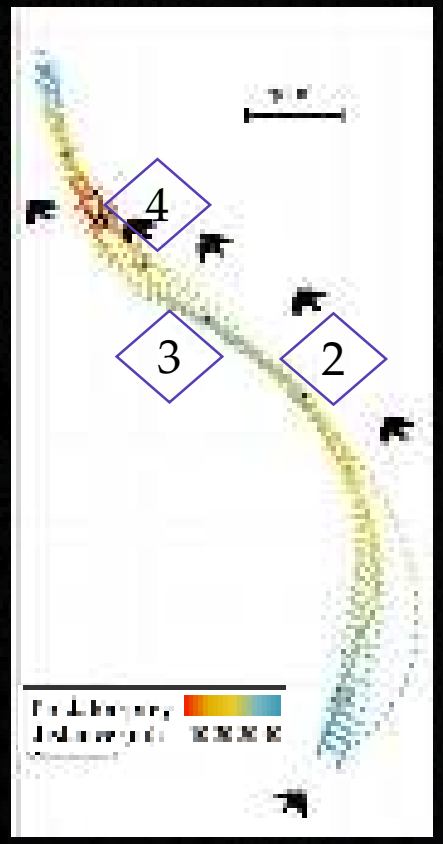
escape direction

Consensus = 0

A. Reaching consensus



1. Predator avoidance

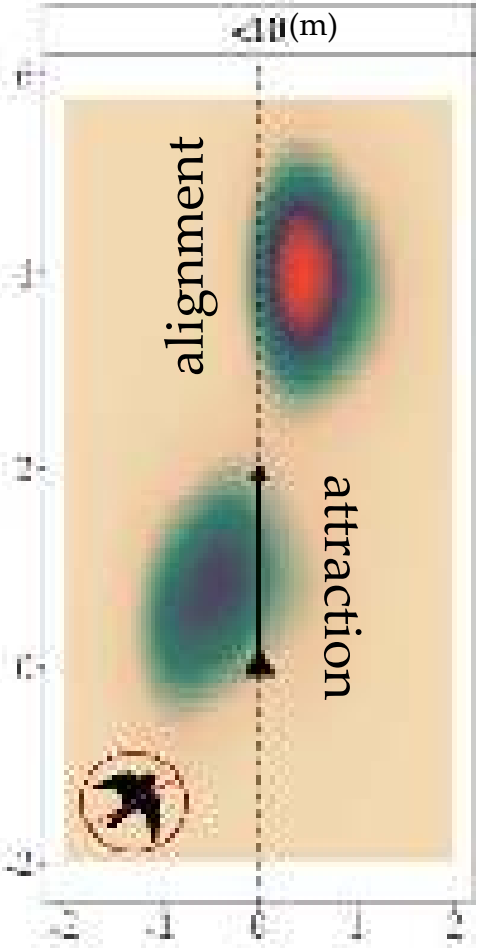


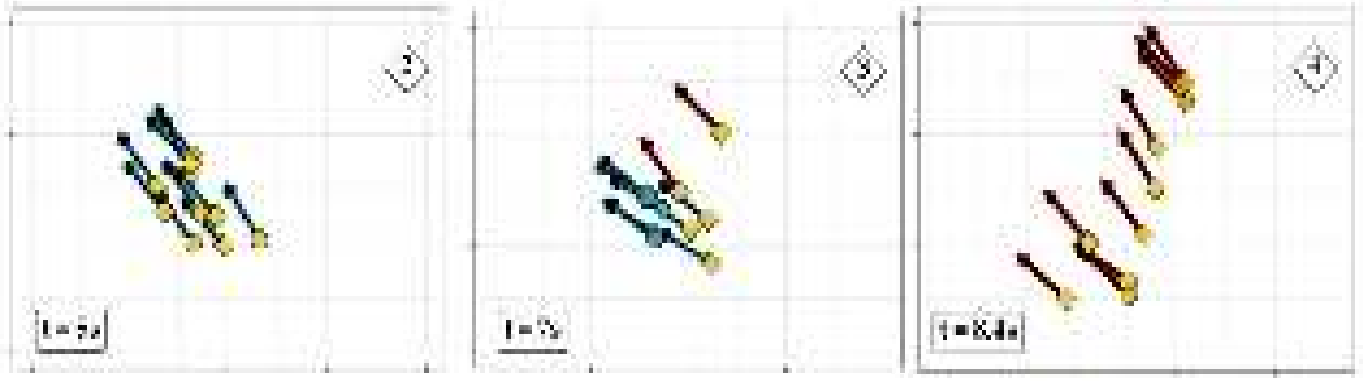
A. Reaching consensus

B. Group shape & coordination

→ Oblong shape: centroid aligned with flock's heading

→ Wide shape: centroid towards escape direction





Escape direction

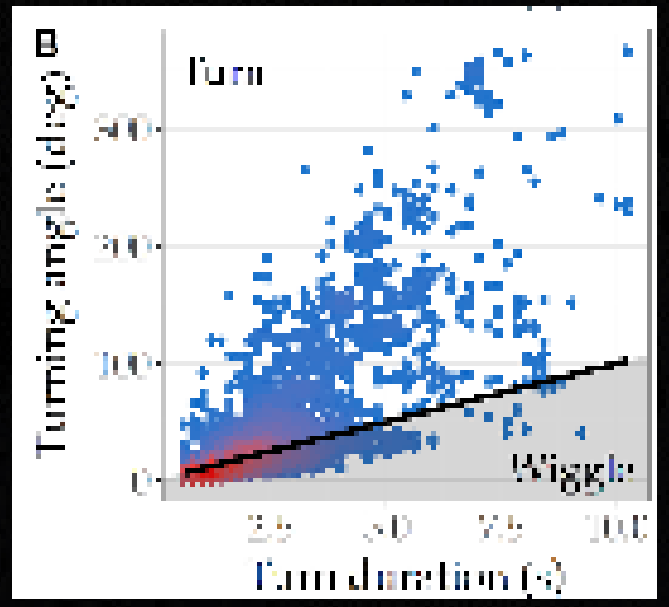
Not a distance-dependent behavior!

A self-reinforcing effect of collective turning

1. Predator avoidance

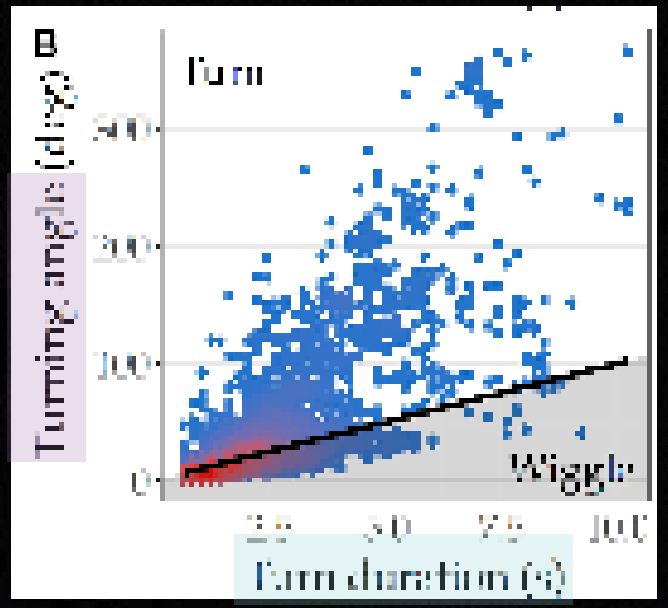
* *Grouping individuals save cognitive costs of minding the predator's position*

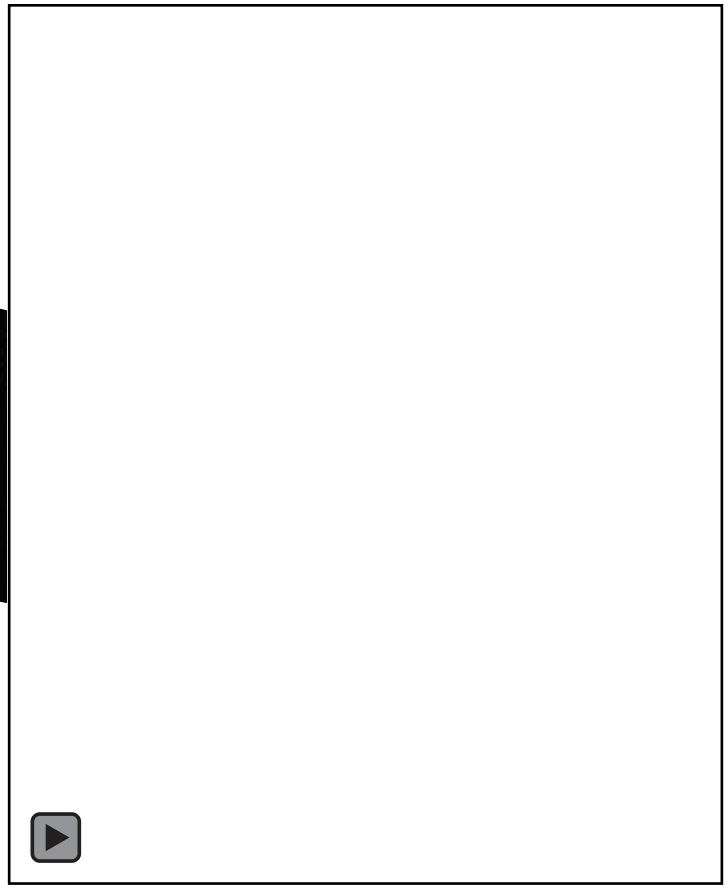
2. Collective patterns



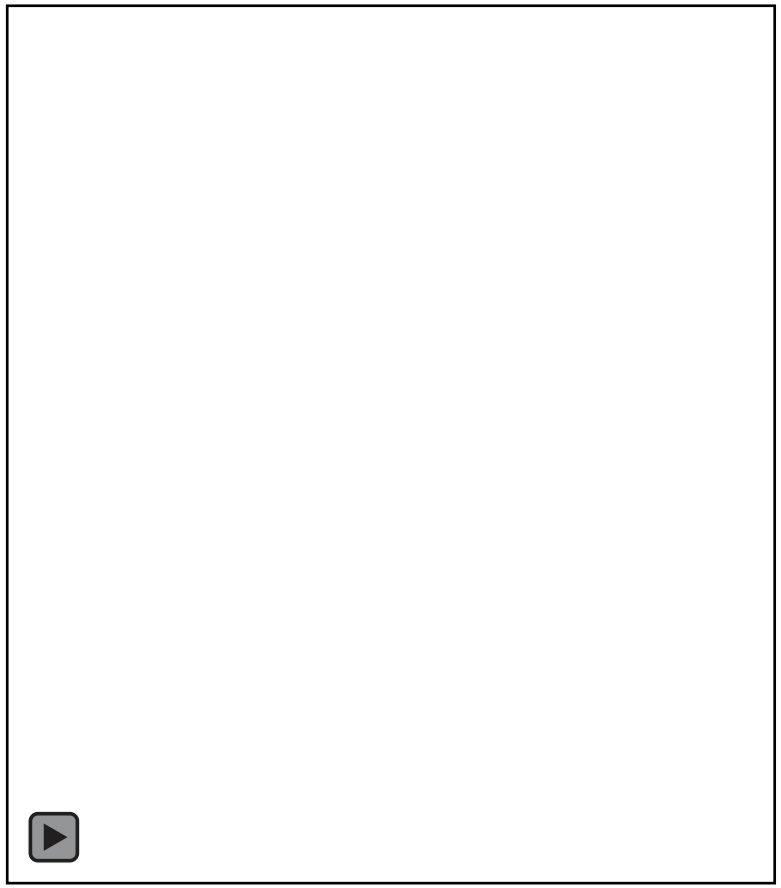
2. Collective patterns

- Escape Manoeuvre & Initiators





Collective turns



Splits

2. Collective patterns

- Escape Manoeuvre & Initiators

Initiator characteristics

edge & fast individuals split more

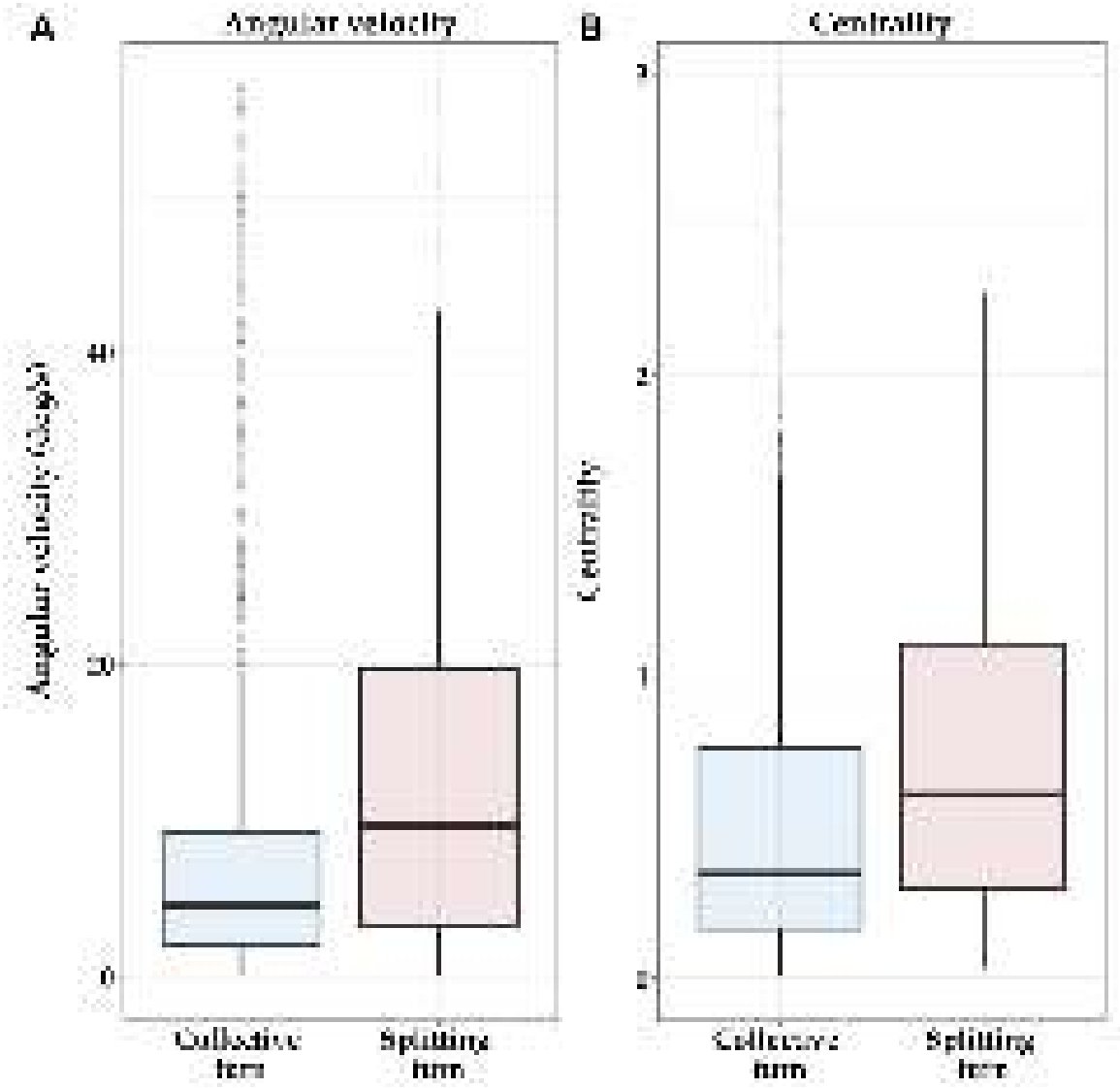
Collective turns

Splits

2. Collective patterns

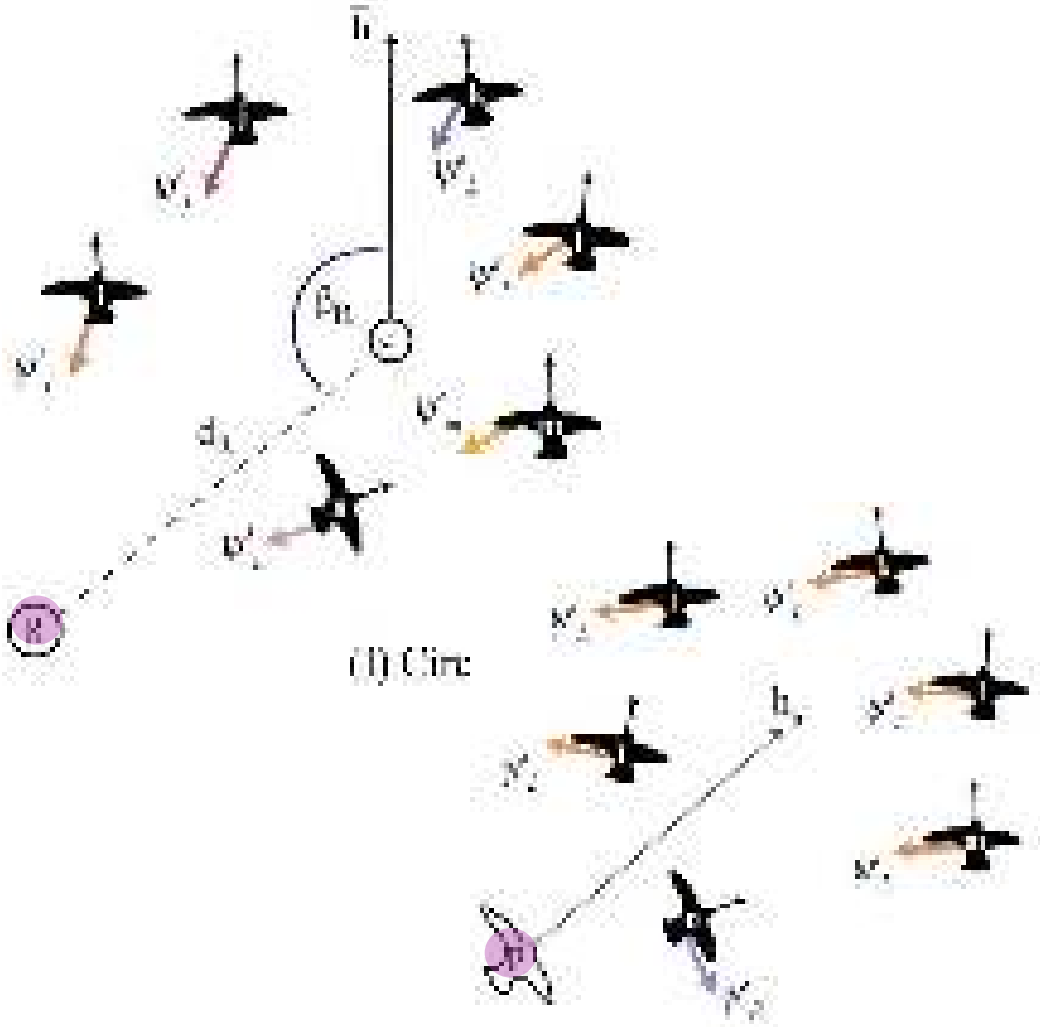
Initiator characteristics

edge & fast individuals split more



3. Collective turning

Turning tendency specifics:



(I) Circ

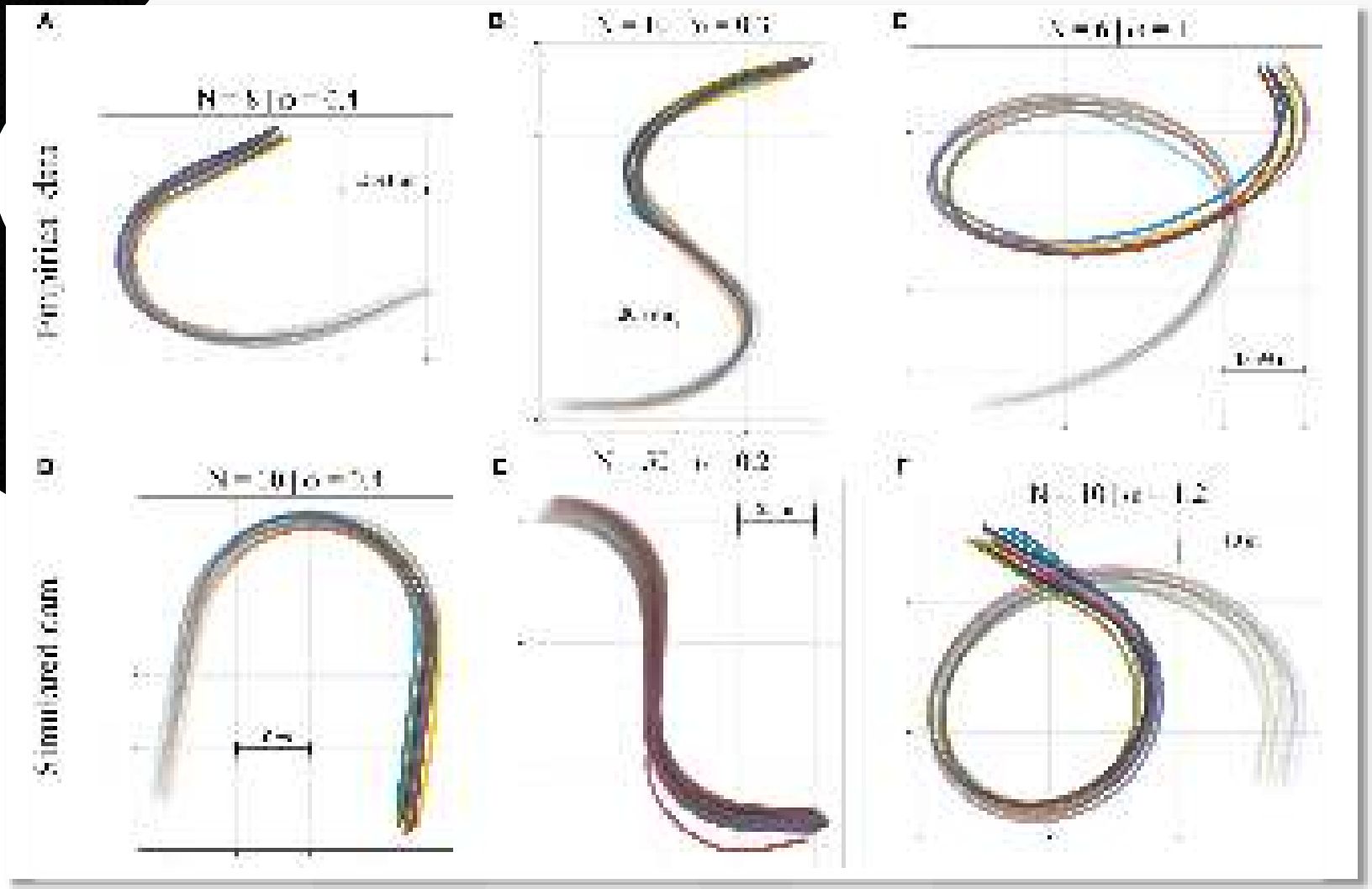
(II) Unidirectional evasion

ColT Model

Diffusion during collective turns in bird flocks under predation

ColT Model

3. Collective turning

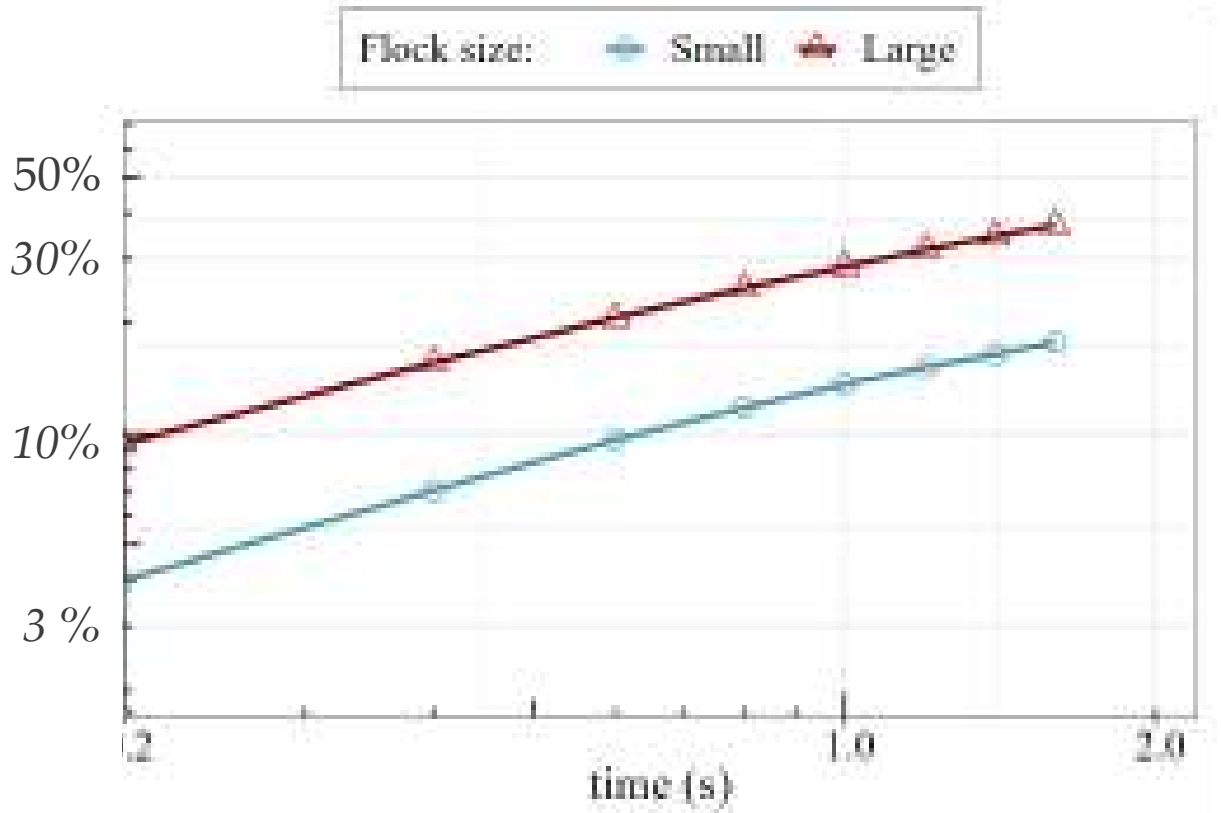


Diffusion during collective turns in bird flocks under predation

3. Collective turning

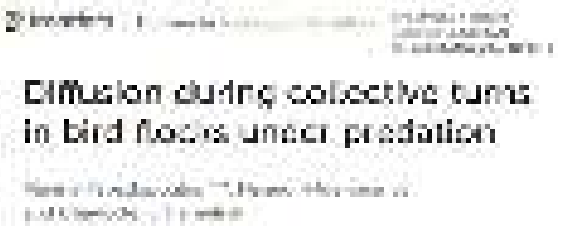
How quickly pigeons change their neighbours?

Diffusion ~ Predator confusion



Slower than starlings

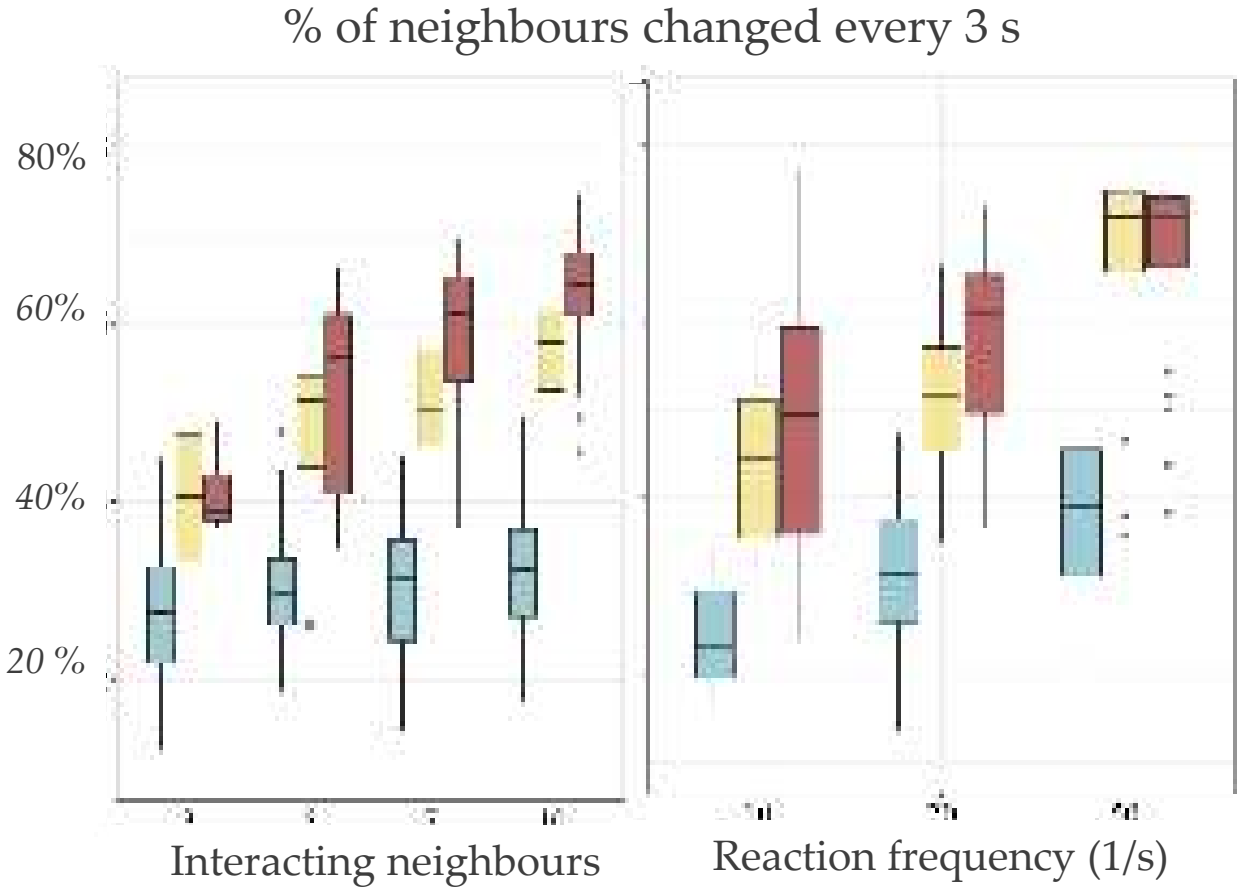
(20% vs 40% per sec, *Cavagna et al. 2015)*


Diffusion during collective turns in bird flocks under predation

3. Collective turning

Which interaction properties affect diffusion?

Diffusion ~ Predator confusion



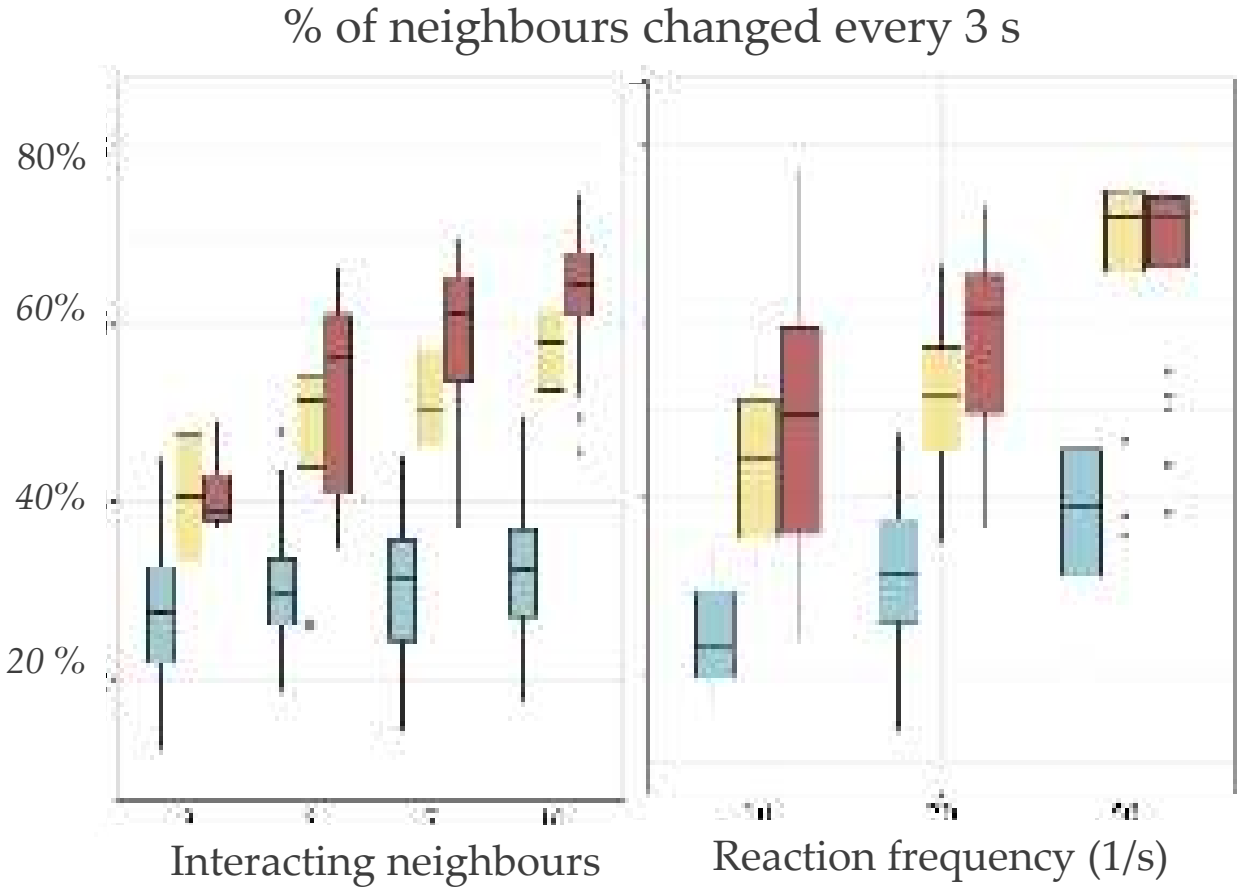

Diffusion during collective turns in bird flocks under predation

More and frequent interactions lead to higher predator confusion

3. Collective turning

Which interaction properties affect diffusion?

Diffusion ~ Predator confusion




Diffusion during collective turns in bird flocks under predation

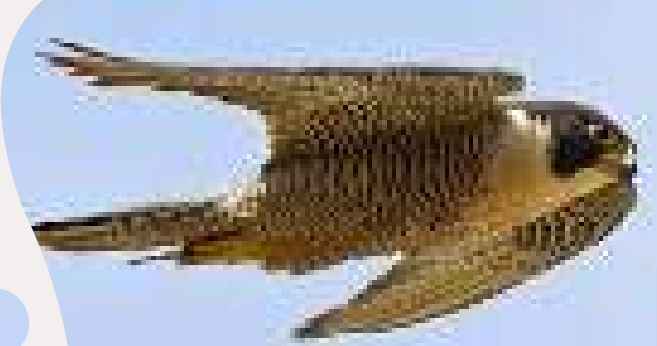
*** Advantages of predation-induced behavioural changes**

Case studies -

Escaping the RobotFalcon

- A. Pigeons

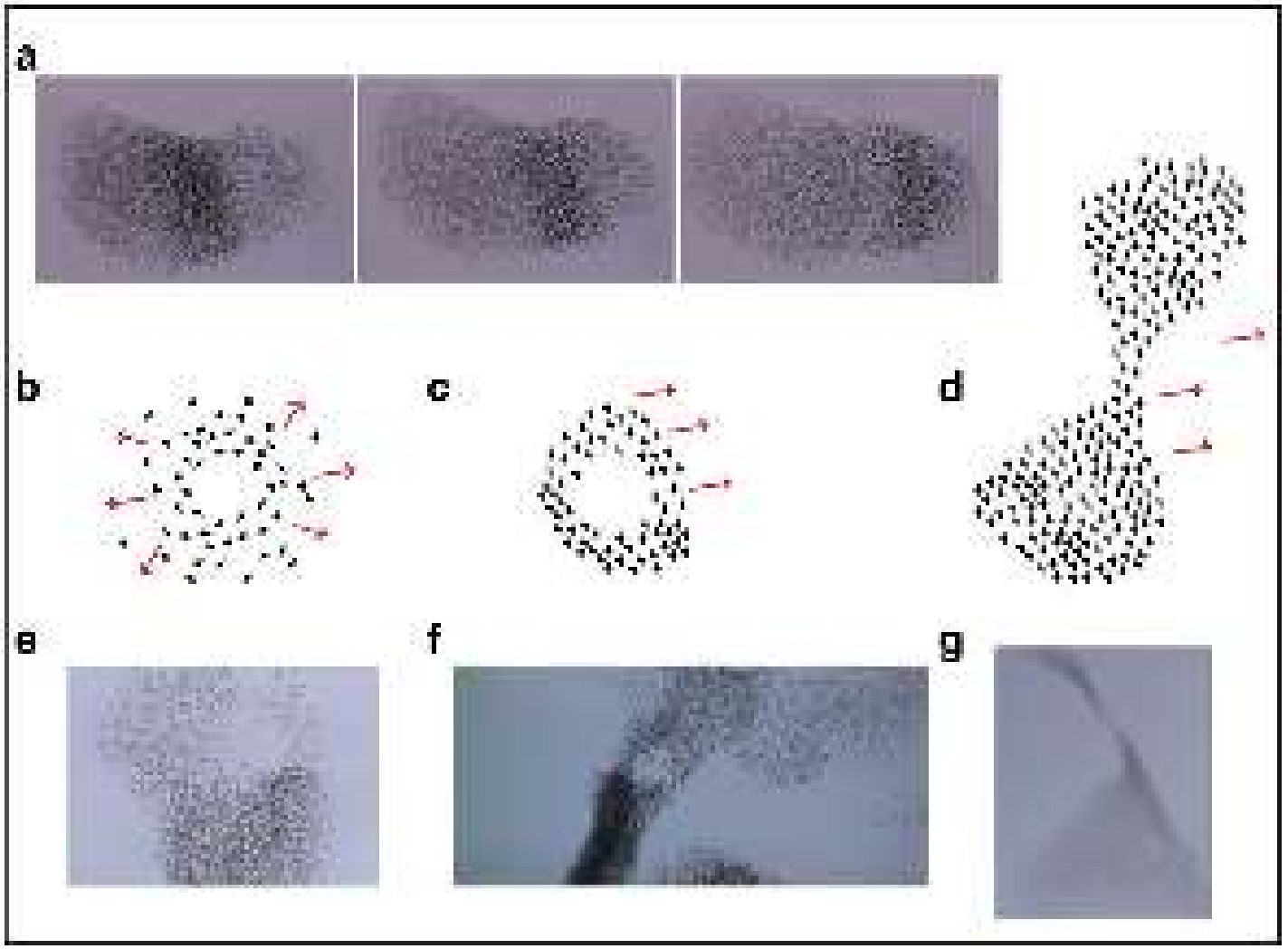
- **B. Starlings**



Robert Musters (Roflight – avibird.com)

Rolf Storms

Starlings escape



Storms et al. (2019) Beahav.Eco.Sociobiol.

Robert Musters (Roflight – avibird.com)

Rolf Storms

Empirical data

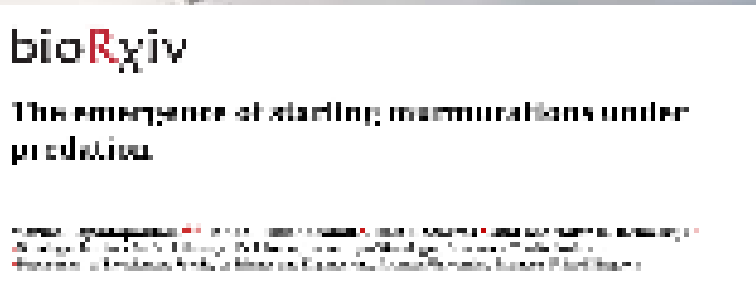
Robert & the Starlings

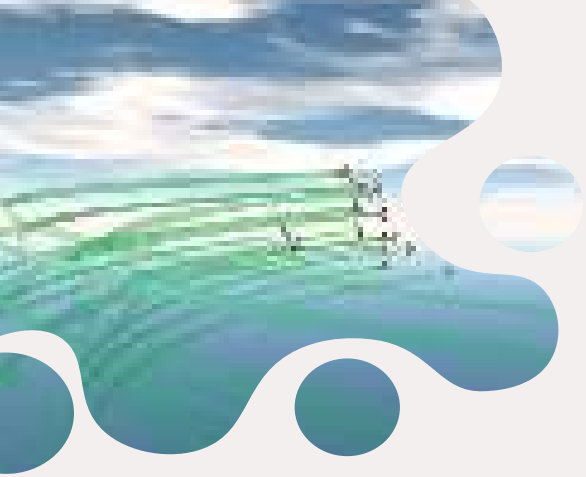
Papadopoulou et al. (2024) In prep.

1 | 3D 2 | Behavioural units 3 | Co-occurrence of patterns

Starlings -

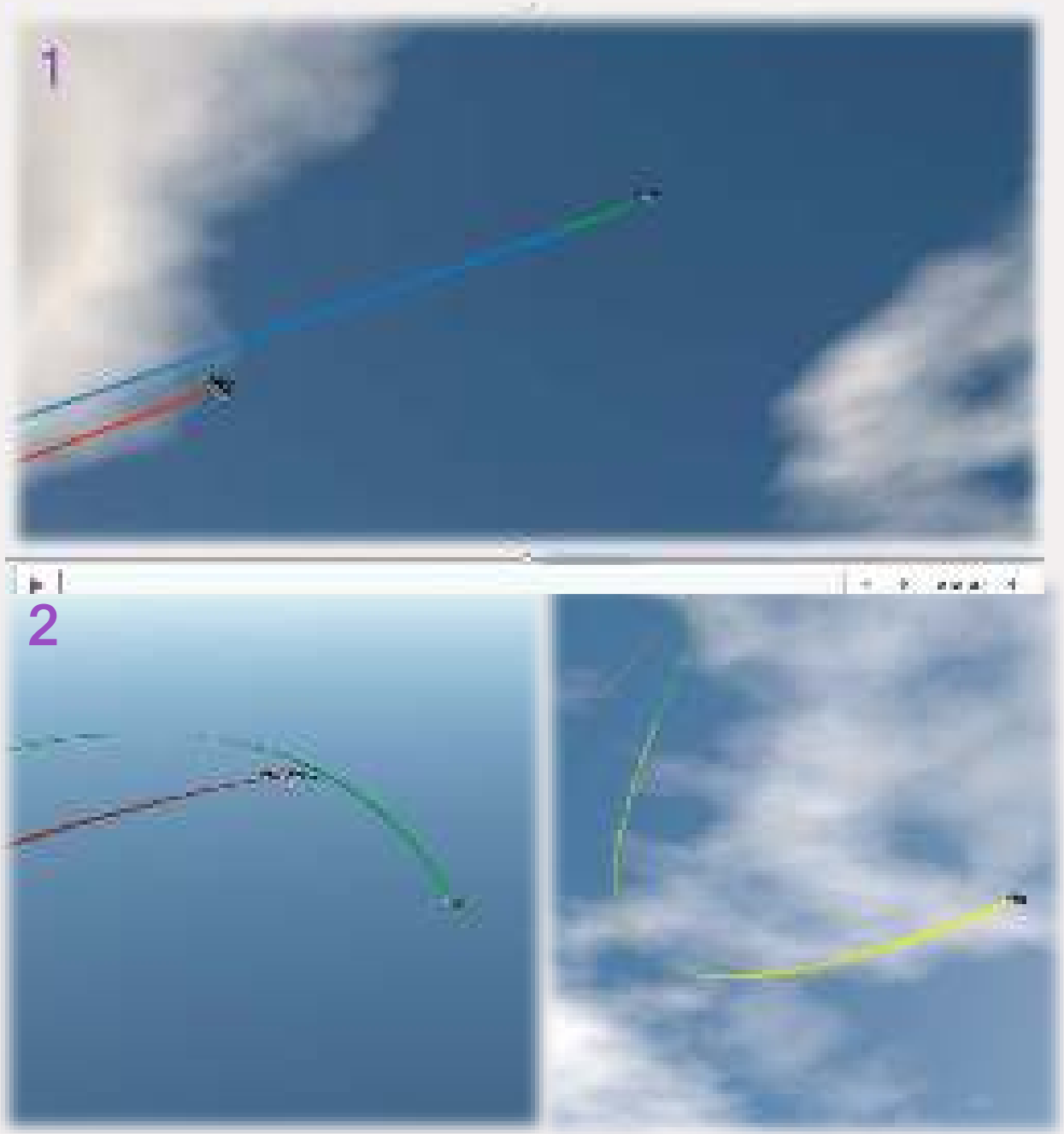
the StarEscape model



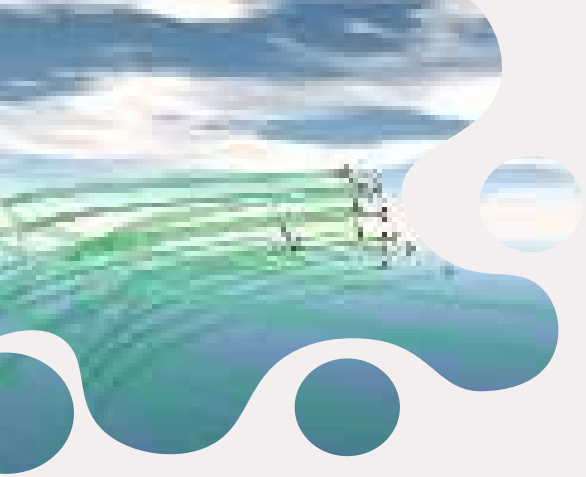


Species-specific adjustments

- Escape manoeuvres
  1. Level turn
  2. Dive

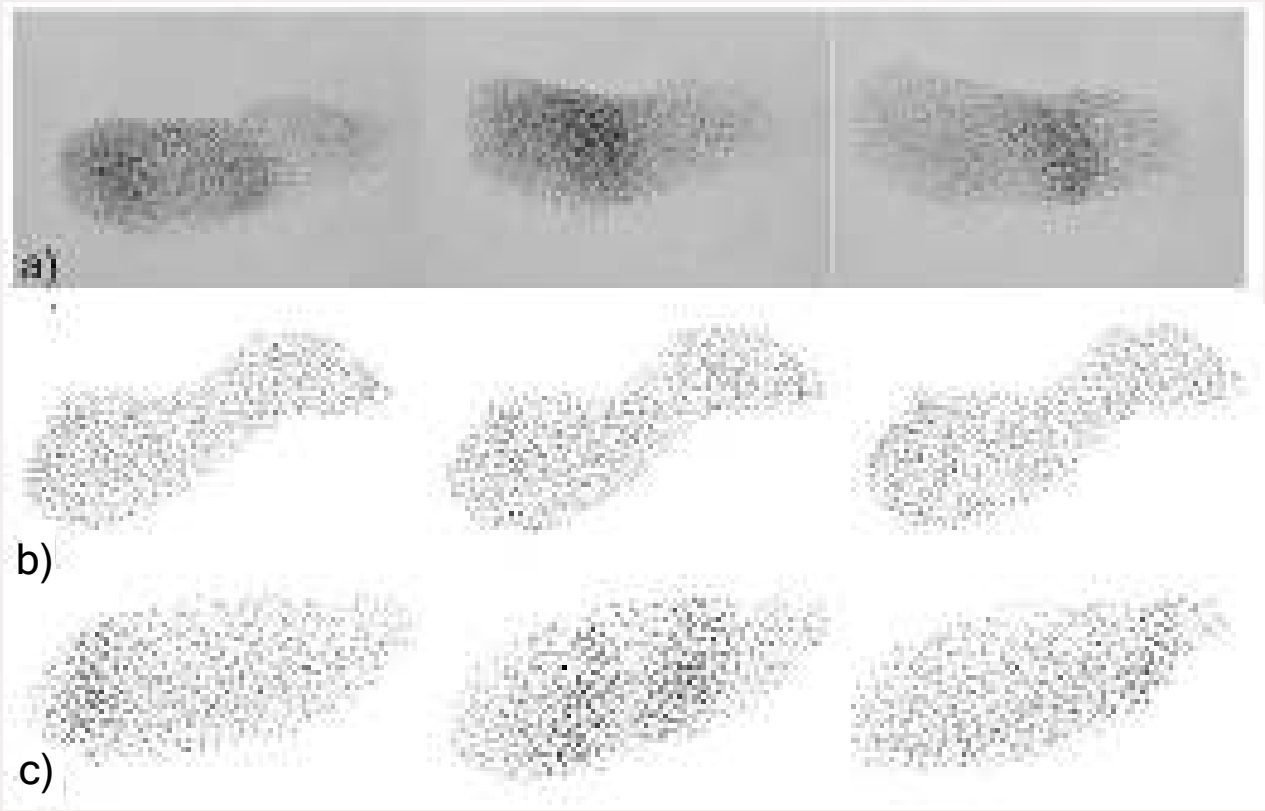


Papadopoulou et al. (2024) In prep.



Species-specific adjustments

- Visualization



Density (b) vs orientation (c) wave

Hemelrijk et al. (2015) Behav Ecol Sociobiol

Collective motion in StarEscape

Papadopoulou et al. (2024) In prep.

Collective escape patterns

Papadopoulou et al. (2024) In prep.

Hysteresis

Papadopoulou et al. (2024) In prep.

bioRxiv

The emergence of starling murmurations under predation

Challenges & Future

- *Quantitative collective empirical data*
- *Individual escape empirical data*
- ***Automatic identification of patterns***

[1]
The Swarm-Verse

Understanding collective behaviour across species and ecological contexts

[2]
Individual heterogeneity

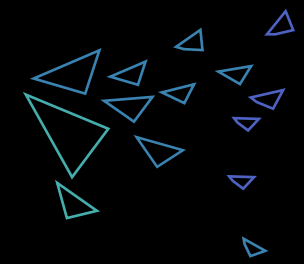
Morphology, Personality & Social networks

[3]
Collective escape in bird flocks

Insights from data-inspired agent-based models

[4]
Coda

In progress, future aims & applications



I | Individual heterogeneity & collective escape

SCIENTIFIC REPORTS

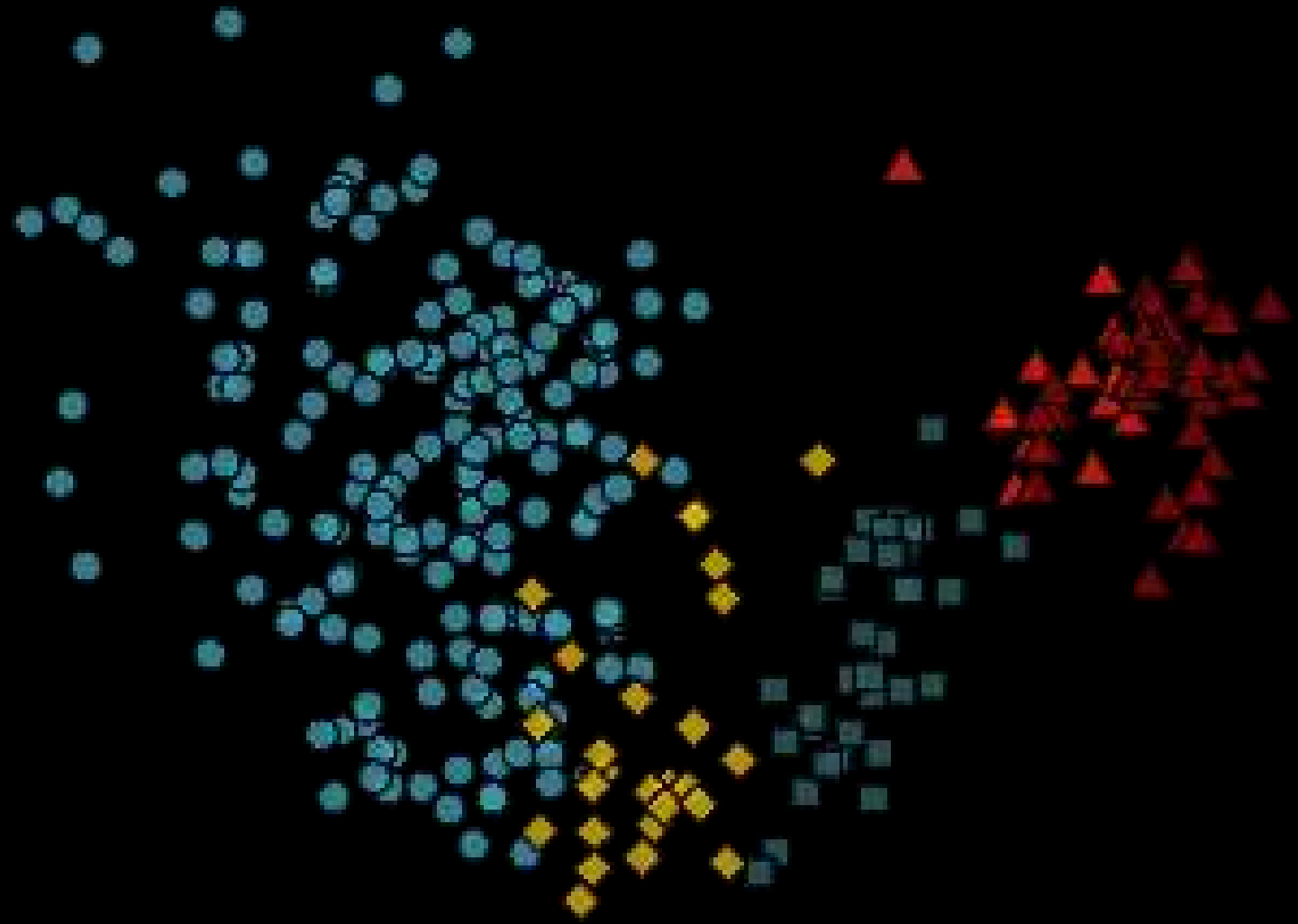
OPEN Personality and morphological traits affect pigeon survival from raptor attacks

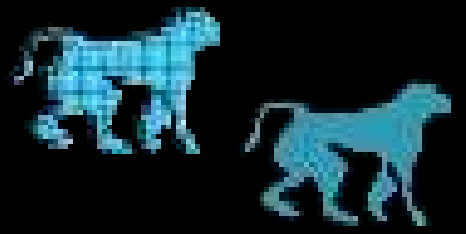
Influence of group personality composition on dynamics of collective escape by the RobotFalcon

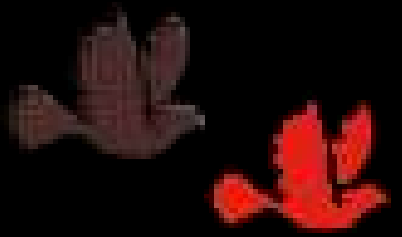
Claudio Carere

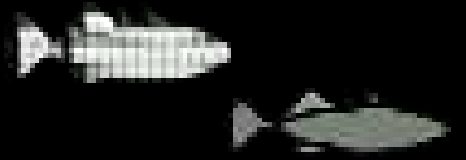
II | Biohybrid Swarm Space

In progress..









Hanno Hildenbrandt

university of groningen

DaNCES

a modelling framework for Data-iNspired Collective Escape Simulations

Papadopoulou et al. (2024) Under review

“ ..

- Simple is better than complex

- Complex is better than complicated

.. “

~ the Zen of Python

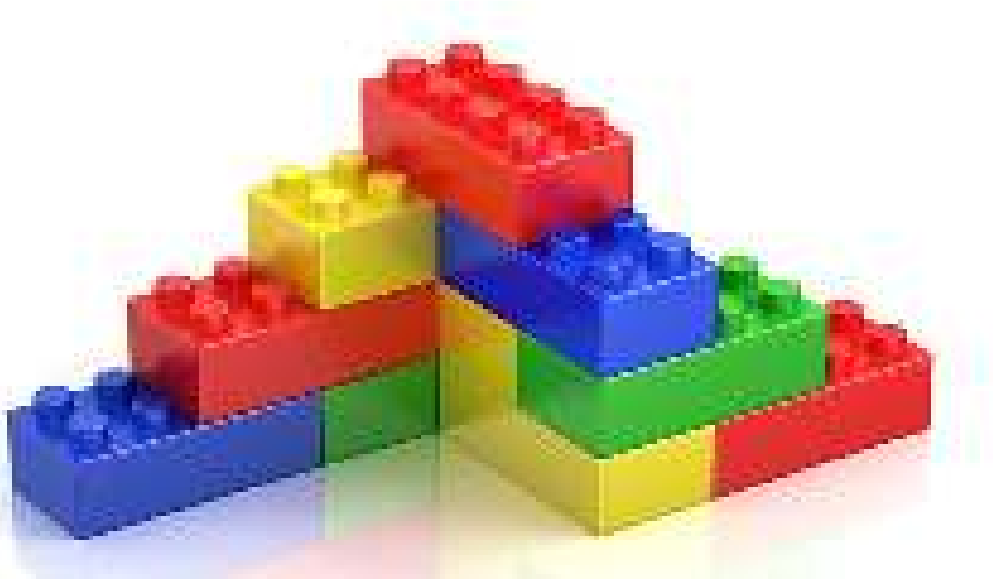
Hanno Hildenbrandt

university of groningen

DaNCES

a modelling framework for Data-iNspired Collective Escape Simulations

Behavioral building blocks

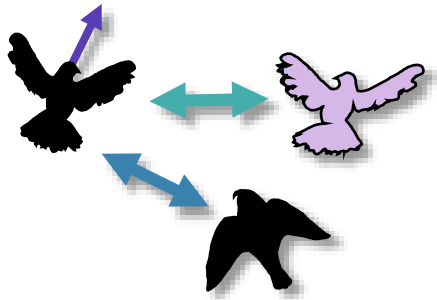


Internal-state control units

A rule of motion

An interaction

An escape or attack



Papadopoulou et al. (2024) Under review

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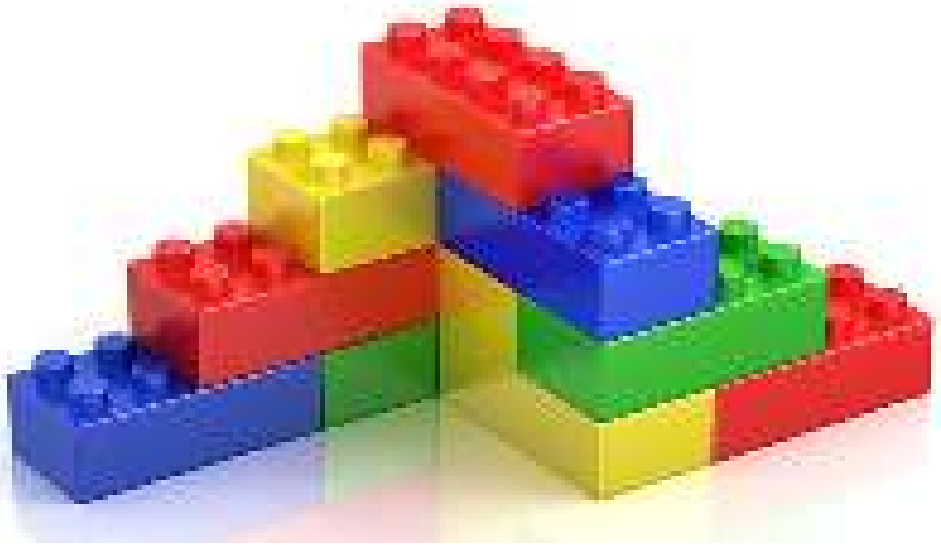
university of groningen

DaNCES

a modelling framework for Data-iNspired Collective Escape Simulations

Behavioral building blocks



Internal-state control units

A rule of motion

An interaction

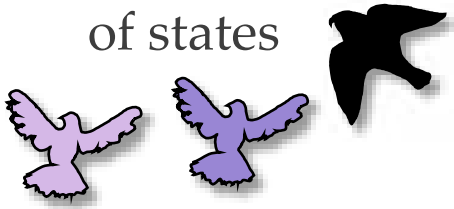
An escape or attack

States

(coordination, escape)

Agent

a combination of states



Papadopoulou et al. (2024) Under review

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university of groningen

DaNCES

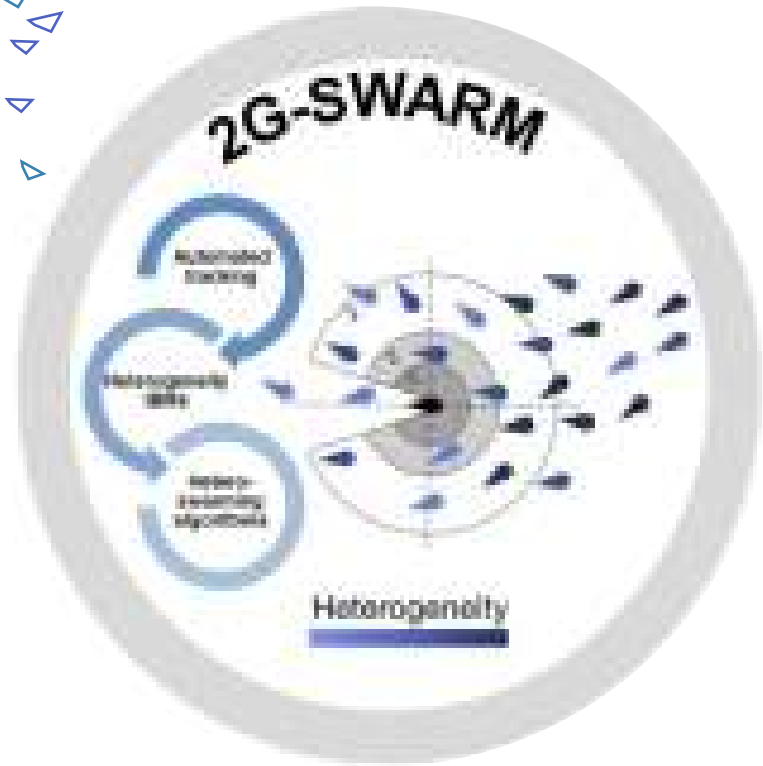
a modelling framework for Data-iNspired Collective Escape Simulations

(kind of) **Packaged:**

- Multi-level parameterization
- Stand alone locomotion type
- Real time visualization & data analysis

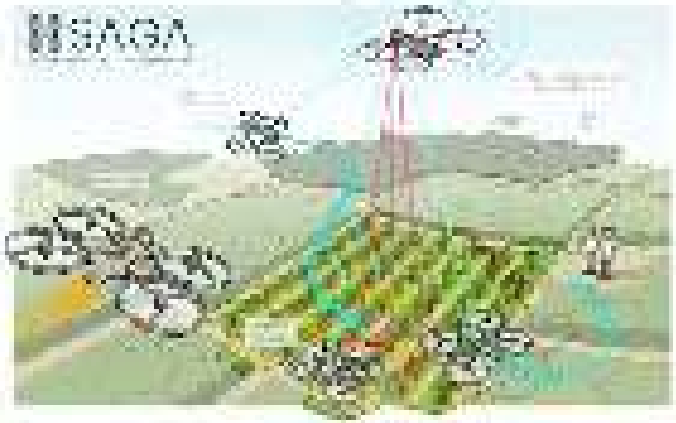
(C++ & Dear ImGui & OpenGL)

Papadopoulou et al. (2024) Under review



Animals are not particles: a framework for second generation hetero-swarm robotics

Rescue missions
(Carrillo-Zapata et al. 2020)



Crops monitoring
(SAGA - CNR & WUR)

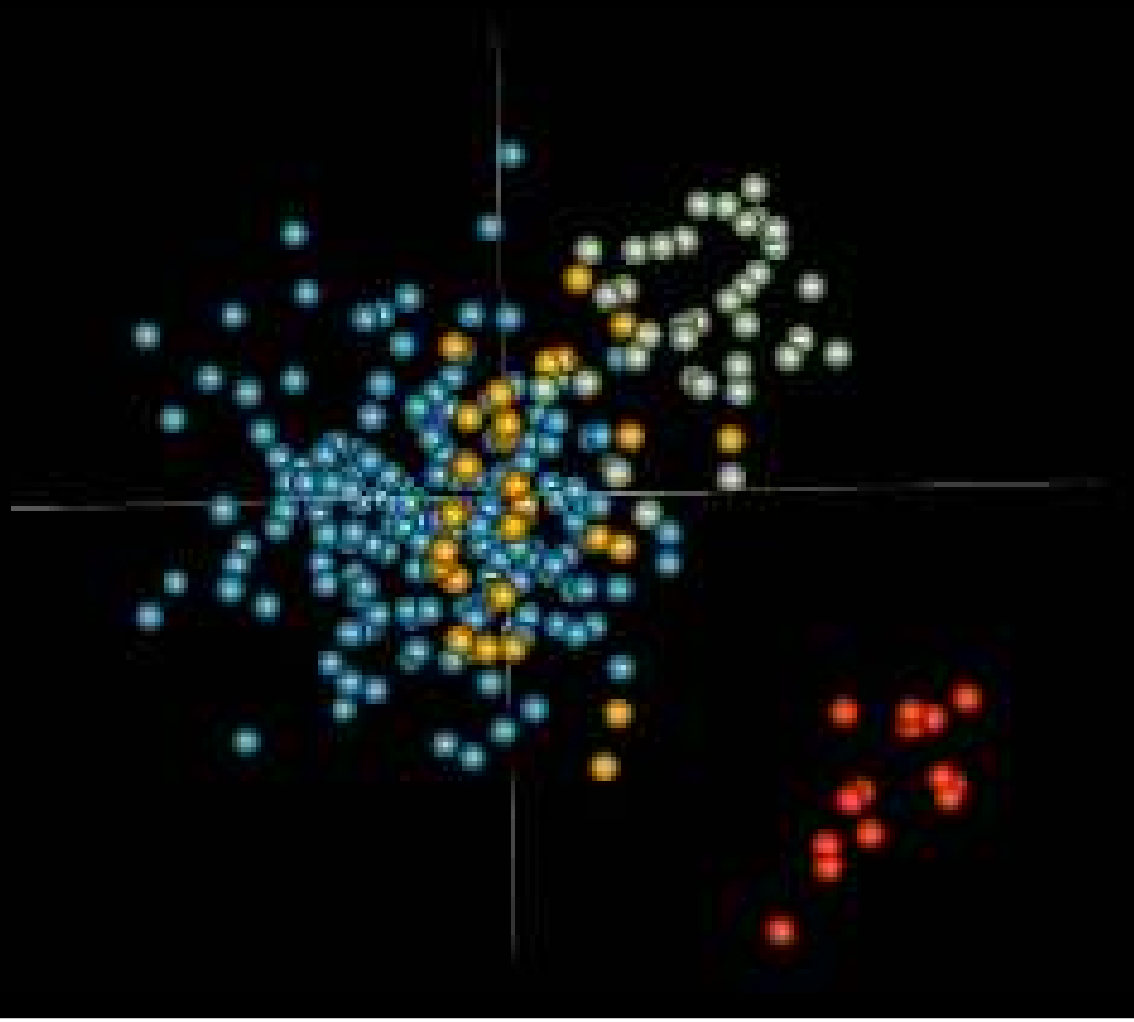
Species-specific models most fitting to a given task

Application I: **Swarm Robotics**

Bio-inspiration according to the species most adapted to a function

Papadopoulou et al. (2023) Proceeding of the 13th International Conference on Swarm Intelligence

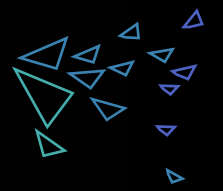
Expanding the Swarm Space



Andrew King

Will Allen

Rob Heathcote



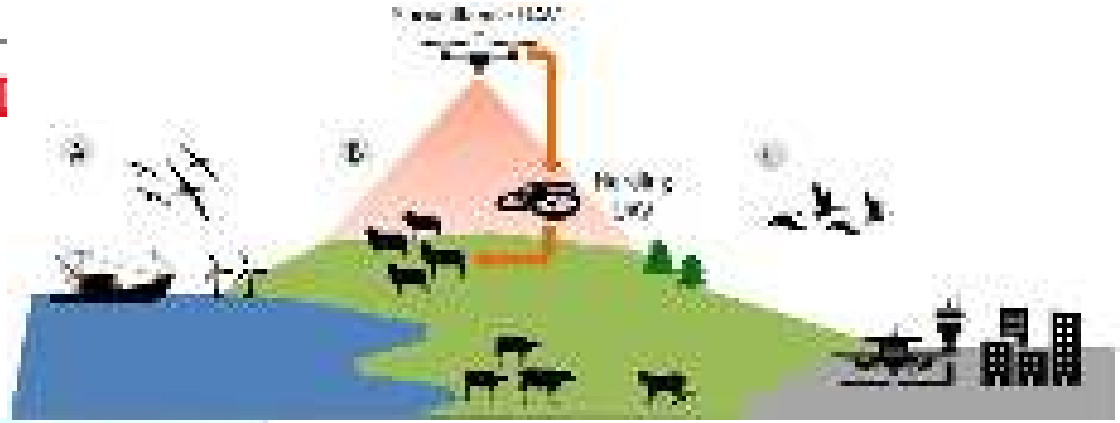
III | EVOLCOL

Evolutionary Ecology of Collective Movement in Vertebrates

PERSPECTIVE

Biologically inspired herding of animal groups by robots

Andrew J. King | Steven J. Portugal | Dora Strömbom | Richard P. Mann | José A. Carrillo | Dora Gaile | Guido de Croon | Heather Barnett | Paul Scerri | Roderich Groß | David R. Davies | Marina Papadopoulou



Application II: **Bio-herding**

Applying our knowledge on collective behavior to resolve human-wildlife conflicts

King et al. (2023) Methods in Ecology and Evolution

Application II: **Bio-herding**

Applying our knowledge on collective behavior to resolve human-wildlife conflicts

King et al. (2023) Methods in Ecology and Evolution

Outlook:

Quantifying collective motion

New metrics for package expansion

v.0.1.1

Which collective properties matter per function?

Can we identify key metrics for model validation?

What is an event of collective motion?

Thank you!

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- *Berlin team:* Jens Krause, David Bierbach
- *Collaborators:* Simon Garnier, Lisa O'Bryan, Anna Bracken, Charlotte Christensen, Dimitra Georgopoulou, Daniel Sankey, Steve Portugal