Collective Motion

http://hal.elte.hu/~vicsek

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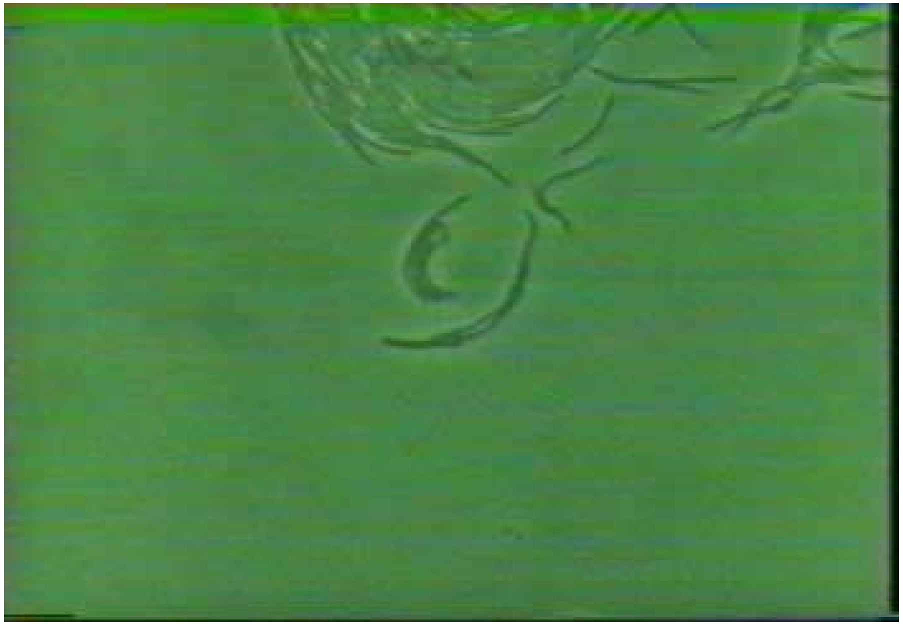
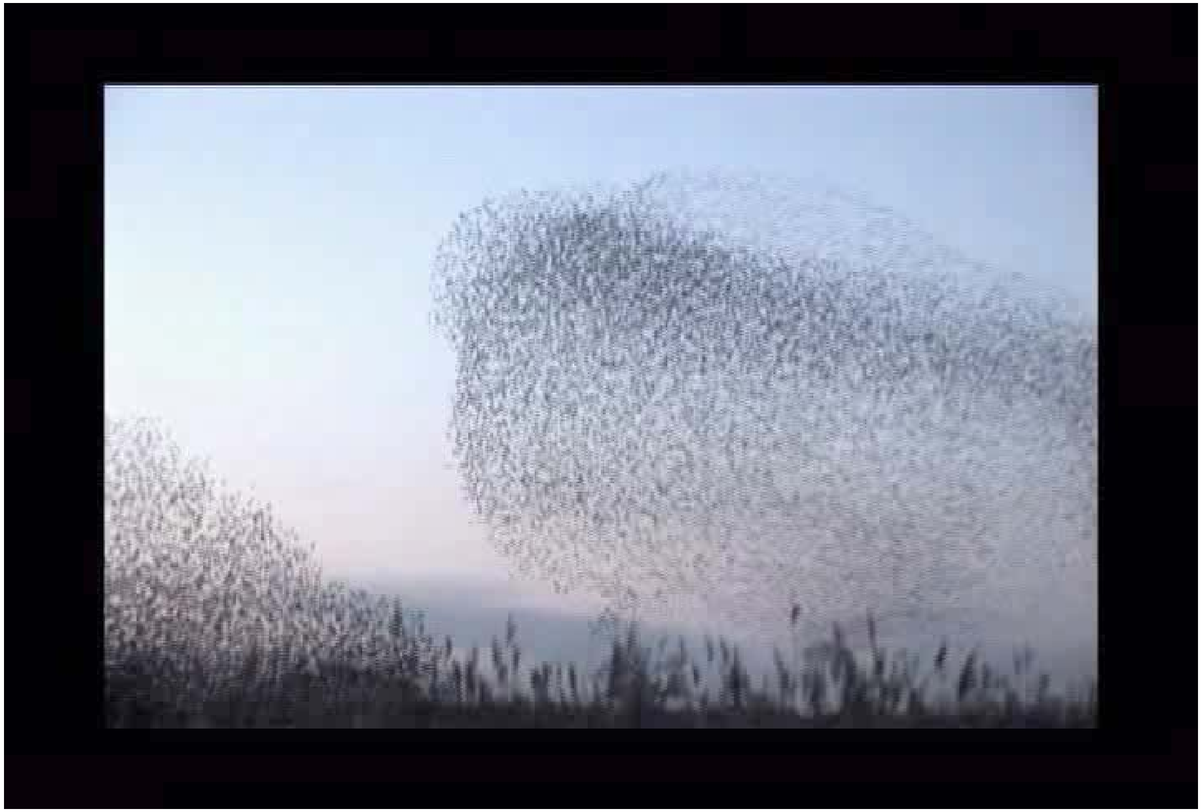
First part:

A brief introduction to the statistical mechanics of collective motion



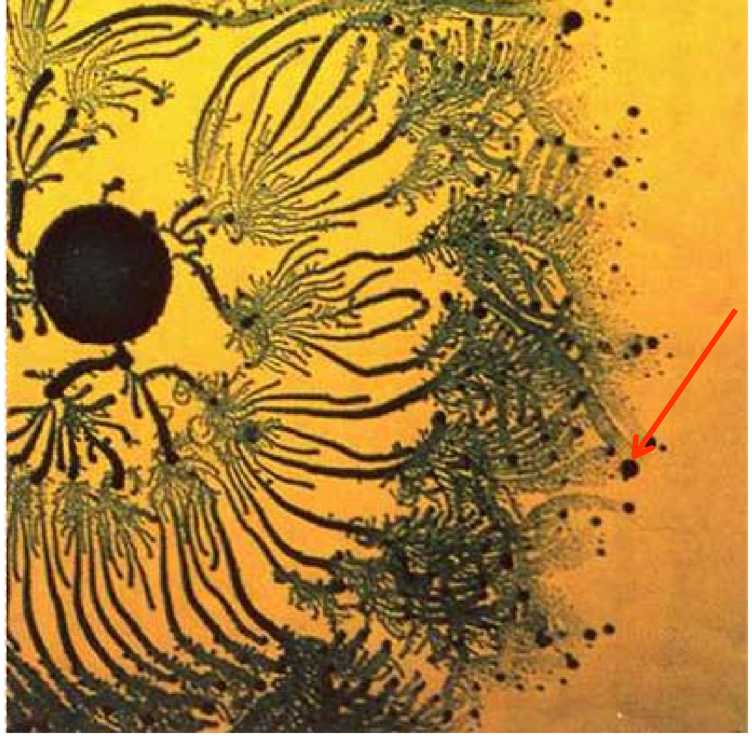
From BBC (I. Couzin)

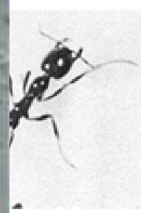


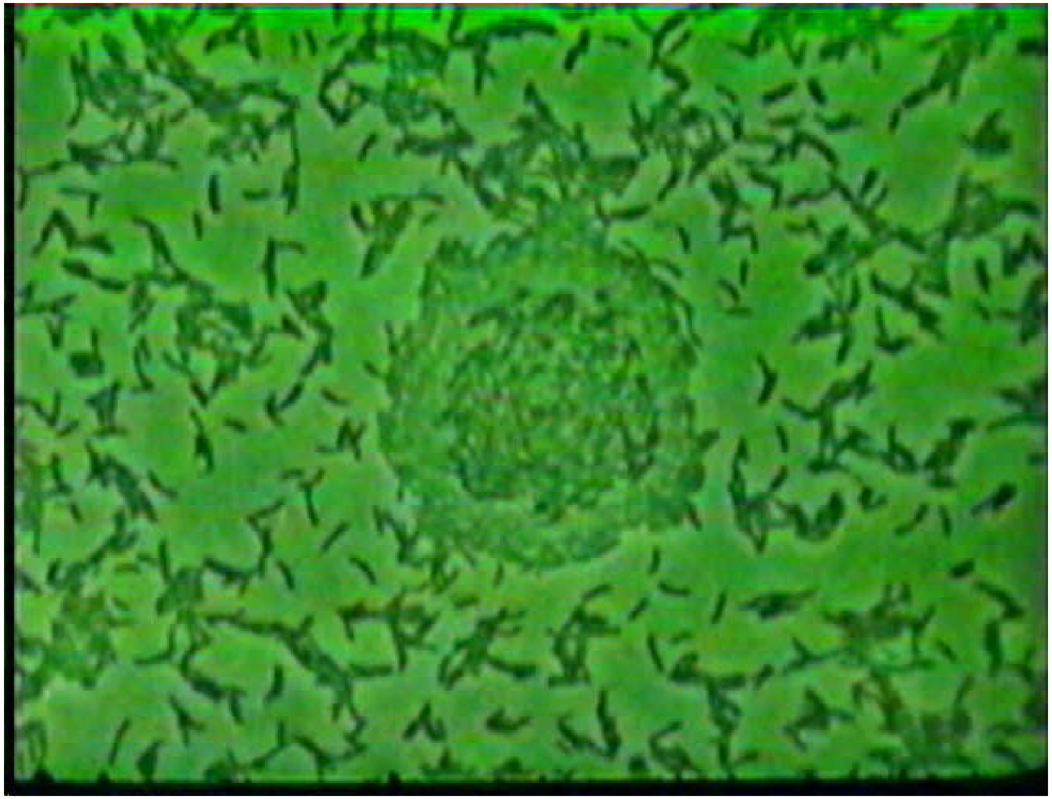
http://www.dailymail.co.uk/sciencetech/article-1365538/Japan-earthquake-Swarms-fish-co

Fish

A universal pattern of motion







swirling motion II

video4 - supplement to Fig. 3D

filament density: $\rho = 20\ \mu m^{-2}$
labeling ratio: $R = 1{:}320$

E27


Self-Organized Flocking
of Kobots in a Closed Arena
Ali E. Turgut, Hande Çelikkanat,
Fatih Gökçe and Erol Şahin
KOVAN Research Lab.
Dept. of Computer Eng.
Middle East Technical University
Ankara, Turkey

Observation: complex units exhibit simple collective behaviours (collective motion patterns)

and

simple units produce complex patterns

Our goals are: - classification of patterns

- finding the basic laws (microscopic versus global)

of collective motion

„Universality” (versus specificity)

Universal classes of flocking patterns ("phases")

i) *disordered* (particles moving in random directions)

ii) *fully ordered* (particles moving in the same direction)

iii) *rotational* (within a rectangular or circular area, lattice of vertices)

vi) *critical* (flocks of all sizes moving coherently in different directions. The whole system is very sensitive to perturbations)

v) *Other, such as* quasy long range velocity correlations, ripples, lattice of vertices …?

vi) *Jamming*

Types of transitions

- Continuous (second order)
- Discontinuous (first order)
- No singularity in the level of directedness
- Jamming

Collective motion

Phys. Reports
80 pages, 60 Figs.,280 Refs.

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We review the observations and the basic laws describing the essential aspects of collective motion – being one of the most common and spectacular manifestation of coordinated behavior. Our aim is to provide a balanced discussion of the various facets of this highly multidisciplinary field, including experiments, mathematical methods and models for simulations, so that readers with a variety of background could get both the basics and a broader, more detailed picture of the field. The observations we report on include systems consisting of units ranging from macromolecules through metallic rods and robots to groups of animals and people. Some emphasis is put on models that are simple and realistic enough to reproduce the numerous related observations and are useful for developing concepts for a better understanding of the complexity of systems consisting of many simultaneously moving entities. As such, these models allow the establishing of a few fundamental principles of flocking. In particular, it is demonstrated, that in spite of considerable differences, a number of deep analogies exist between equilibrium statistical physics systems and those made of self-propelled (in most cases living) units. In both cases only a few well defined macroscopic/collective states occur and the transitions between these states follow a similar scenario, involving discontinuity and algebraic divergences.

CONTENTS

Understanding through modeling

-**Aoki**, I.**1982**. A **simulation** study on the schooling mechanism in **fish**.
Bull. Jpn. Soc. Sci. **Fish**. 48:1081 –1088. Realistic details

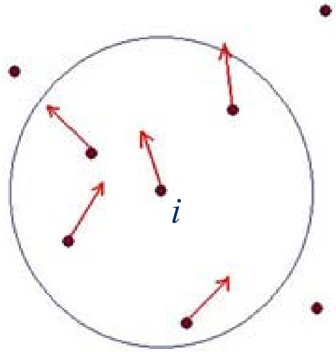
- **Graphical flocking model by C. Reynolds, 1987,**
  - few dozen “boids”, computer graphics appl.
  - attraction, repulsion, common direction (continuous, deterministic)

- **Statistical physics model for flocking**, T.V. et al, 1995
  - many thousands of particles (SPP)
  - average direction + noise (discrete in time) phase transition (continuous)

Recent models (stat. phys.):
  - vectorial noise, first order phase trans. (2004 Gregoire, Chaté)
  - models with “leaders” (Couzin, others, 2005)
  - „soft” interaction potential (Cucker and Smale, 2007)
  - model with escape and pursuit (Romanczuk, Couzin, & Schimansky-Geier, 2009)
  - model with physical collisions only (Grossman et al 2008)
  - self-propelled rods (Chaté and co-workers, 2010)

Swarms, flocks and herds

- **Model* (SPP) :** The particles



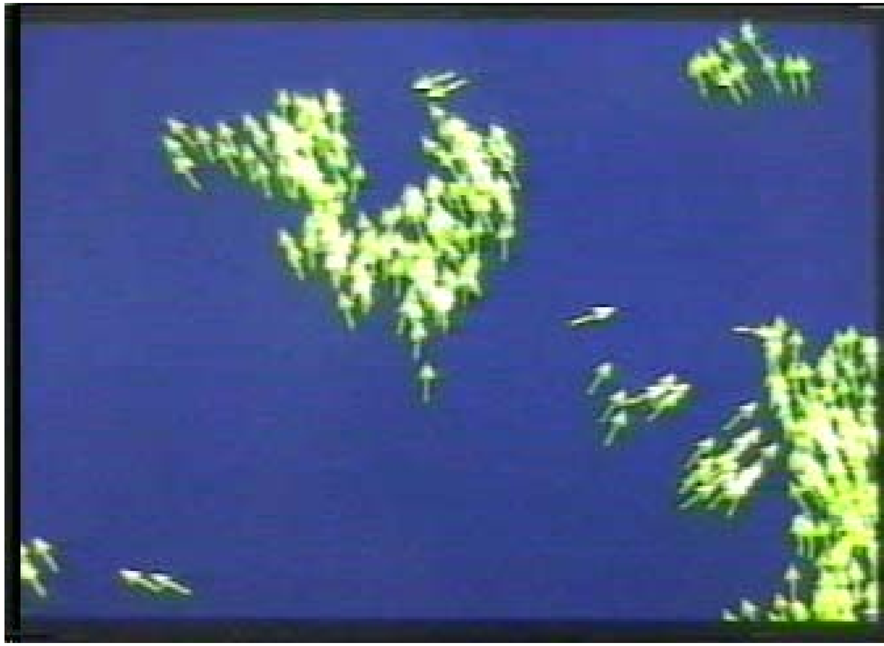
- maintain a given absolute value of the velocity v_0
- follow their neighbours
- motion is perturbed by fluctuations η

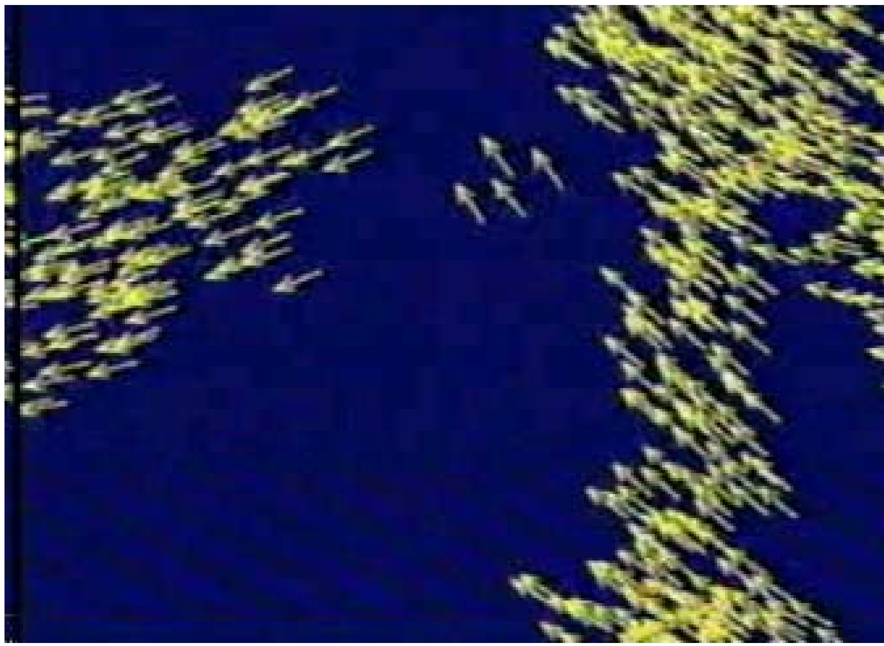
$$\vec{e}_i\,(t+1) = E\Big[E[\langle \vec{e}_j\,(t)\rangle_j] + \vec{\eta}(t)\Big]$$

(E normalizes the magnitude into unity)

- Follow the neighbours rule is an abstract way to take into account interactions of very different possible origins

- Result: *ordering is due to motion*





* T.V, A. Czirok, E. Ben-Jacob and I. Cohen, PRL, 1995

A few nice recent *theoretical* results related to SPP mode

- Network models related to SPP models show both first and second order phase transitions depending on the nature of nois (Aldana et al 2007)

- Equilibrium stat. mech. type finite-size scaling is valid for the original ('95) SPP model, with a hyperscaling relationship (Baglietto, Albano, 2008)

$$\varphi(\eta,L) = L^{-\beta/\nu}\tilde{\varphi}((\eta-\eta_c)L^{1/\nu})$$

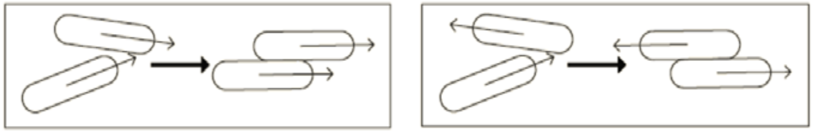
$$\chi(\eta,L) = L^{\gamma/\nu}\tilde{\chi}((\eta-\eta_c)L^{1/\nu})$$

$$d\nu - 2\beta = \gamma$$

$$\chi = \mathrm{Var}(\varphi)L^2$$

- Deriving continuum (hydrodynamic equations for self-propelled particle and rods. (Bertin et al 2006-2010, Mishra,Baskaran, Marchetti, 2009,2010)

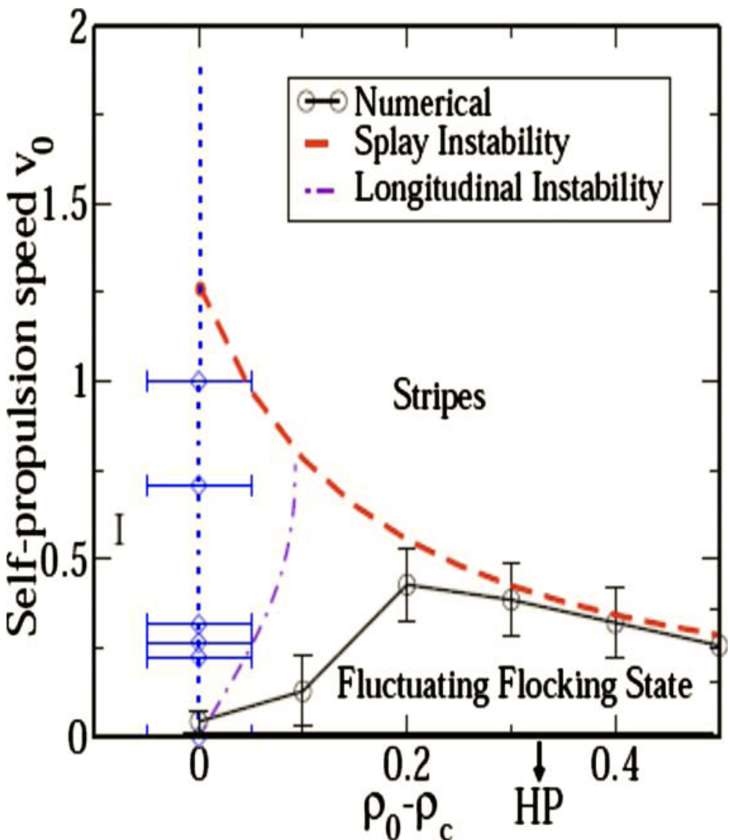
- Cucker and Smale model (2007) exact results for flocking

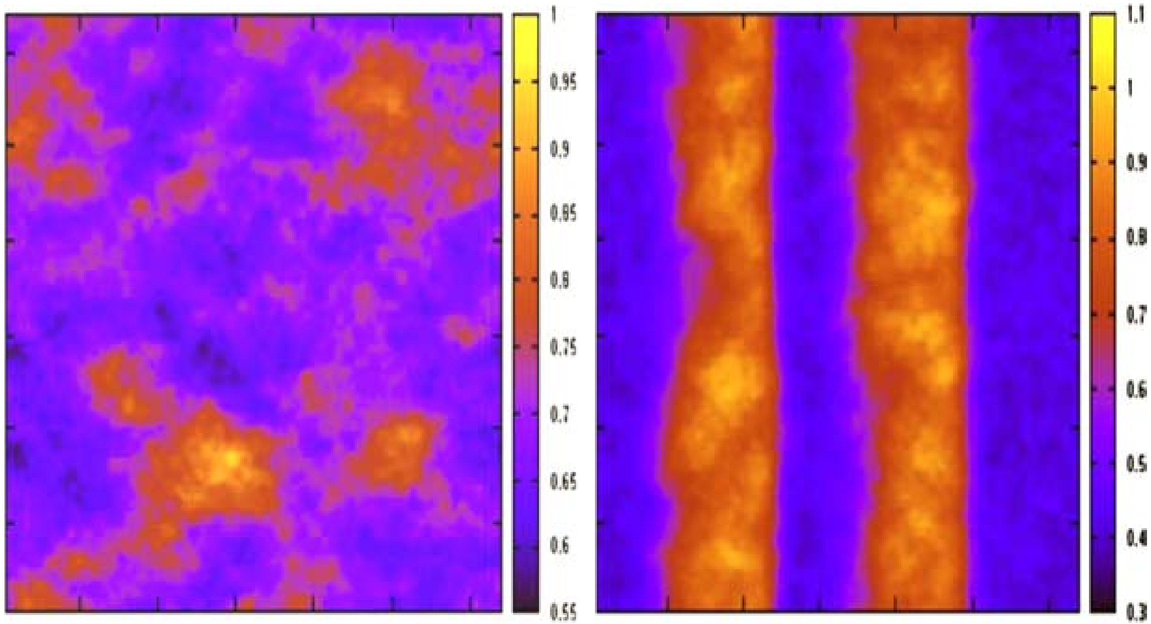


Model!

$$\partial_t \vec{v} + \lambda_1 (\vec{v}\nabla)\vec{v} + \lambda_2 (\nabla \vec{v})\vec{v} + \lambda_3 \nabla(|\vec{v}|^2) =$$
$$\alpha \vec{v} - \beta |\vec{v}|^2 \vec{v} - \nabla P + D_L \nabla(\nabla \vec{v}) + D_1 \nabla^2 \vec{v} + D_2 (\vec{v}\nabla)^2 \vec{v} + \vec{\xi}$$

$$\partial_t \rho + \nabla(\rho \vec{v}) = 0. \qquad P = P(\rho) = \sum_{n=1}^{\infty} \sigma_n (\rho - \rho_0)^n$$





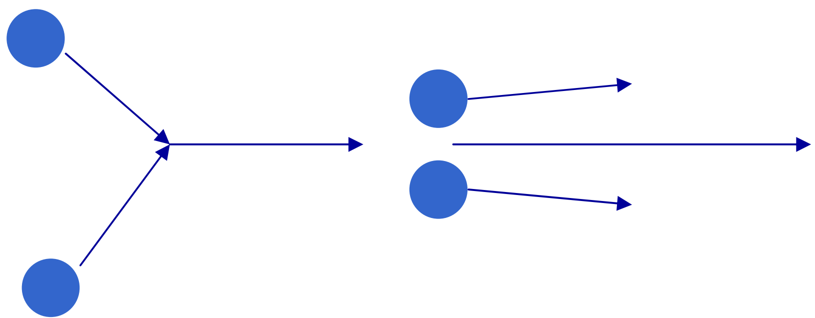
Lessons:

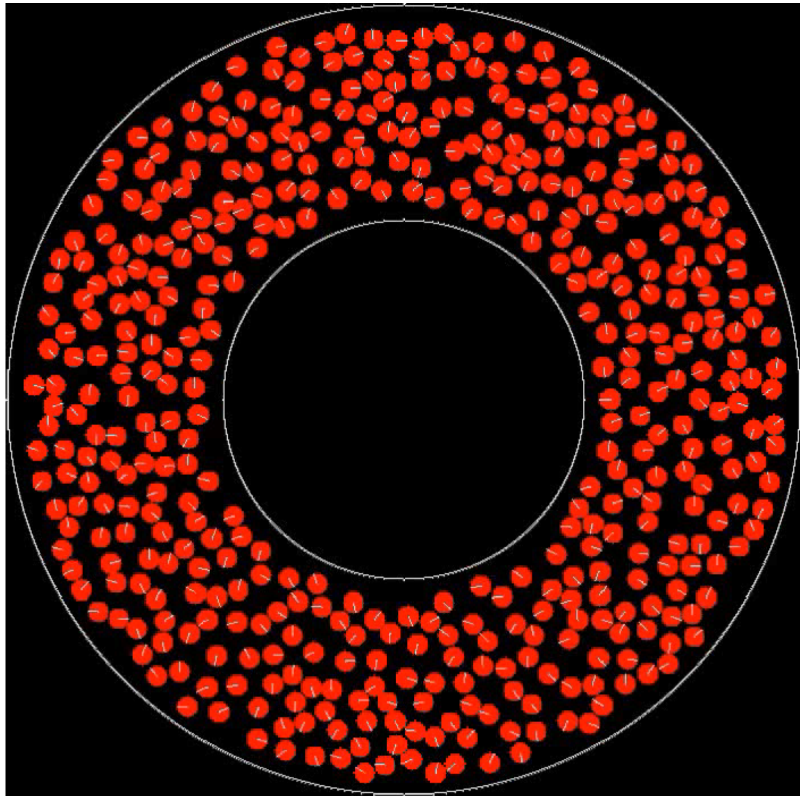
1. Most patterns of collective motion are *universal*

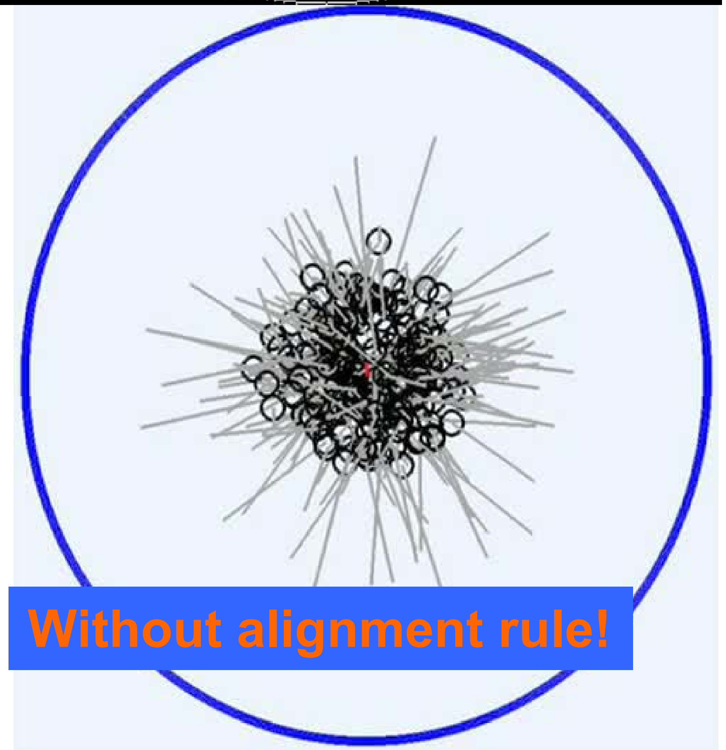
2. Simple models can reproduce this behavior

3. A simple noise term can account for numerous complex deterministic factors

4. In many cases ordering is due to motion! In other words: in SPP systems momentum is not conserved!







Collective motion beyond similar units

Segregation of two types of collectively moving cells

Hierarchical organization of pigeons within a flock

Dominance hierarchy in a loft

Collective motion-mediated cell segregation in vitro

Motivation: patterning mechanism based on collective cell motility, e.g., during *embryonic development*

Inpired by

Slow (logarithmic) segregation with random motion vs. fast (power law) segregation with collective (self-propelled) motion

Belmonte JM, Thomas GL, Brunnet LG, de Almeida RM, Chaté H. 2008 Phys Rev Lett.

Can collective cell migration enhance cell segregation?

In vitro system:

- Mixed co-culture

- No prepattern

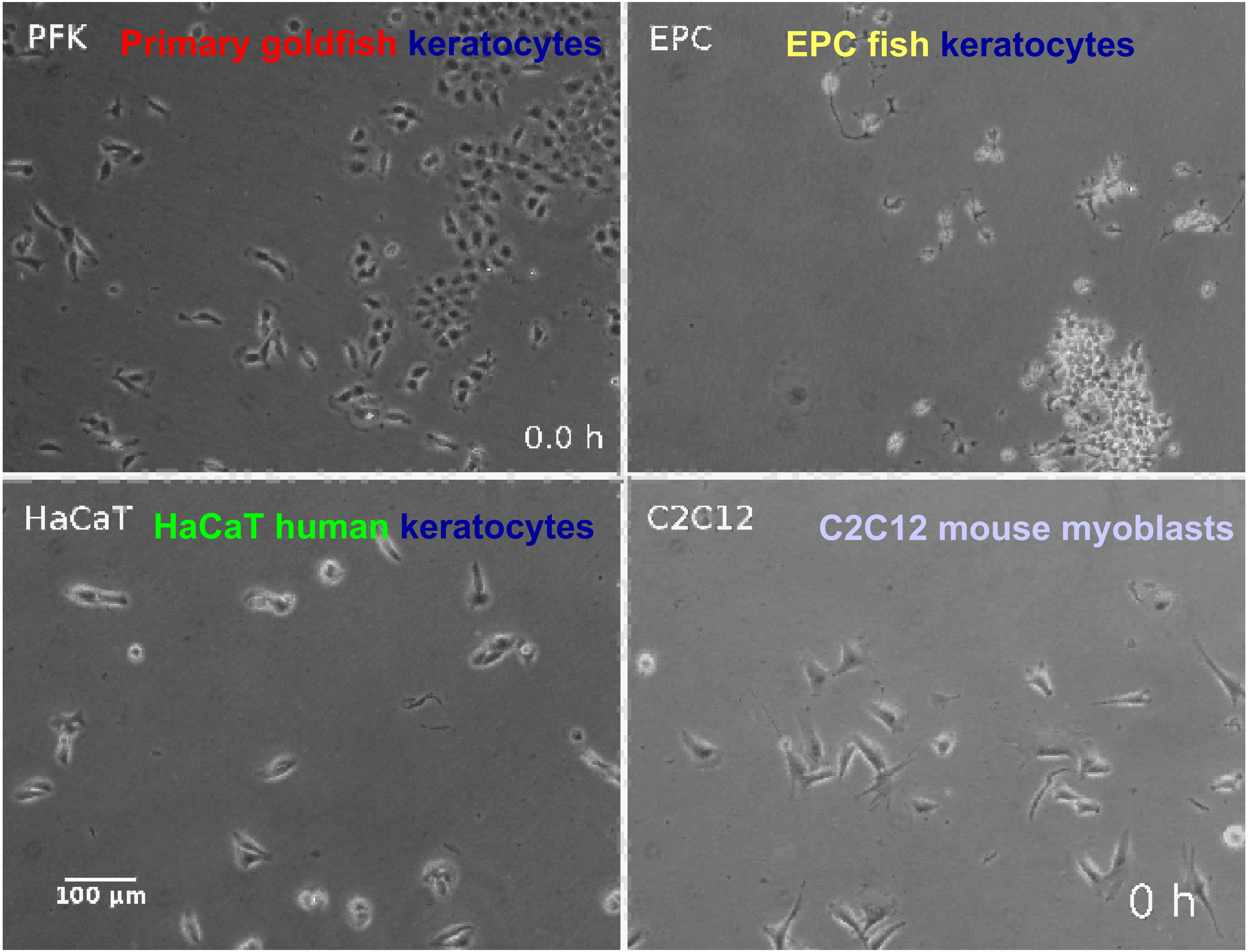
  - Differential adhesion

$A \rightarrow A$

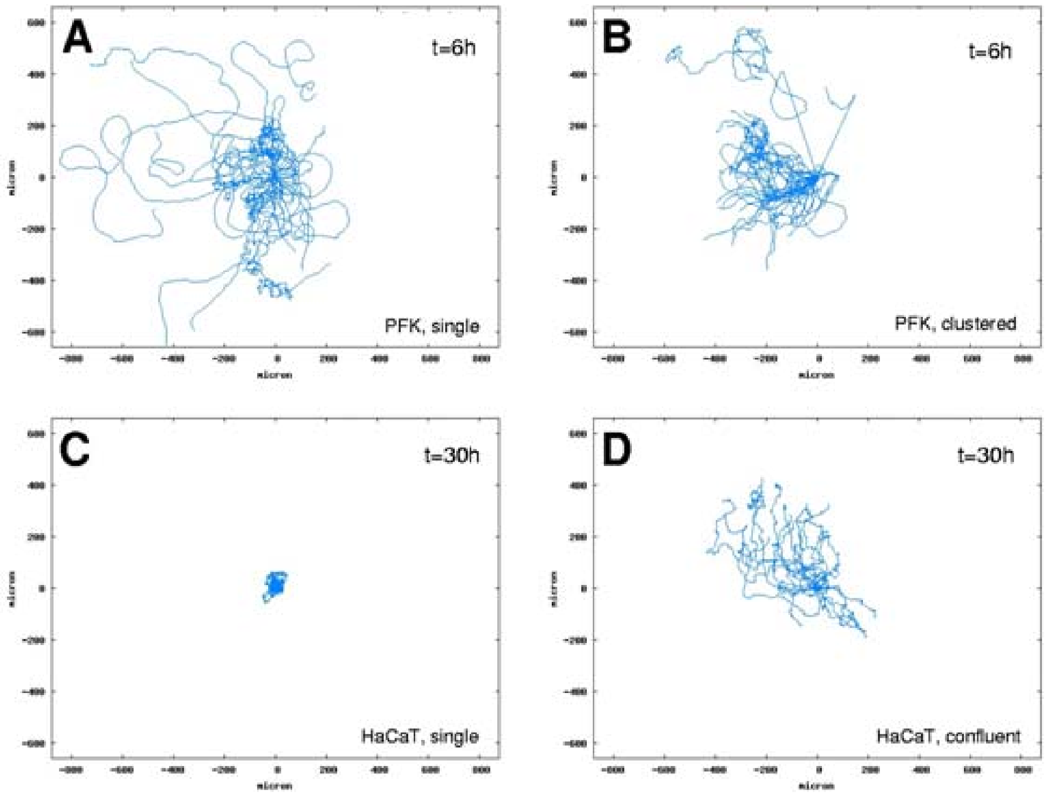
$B \rightarrow B$

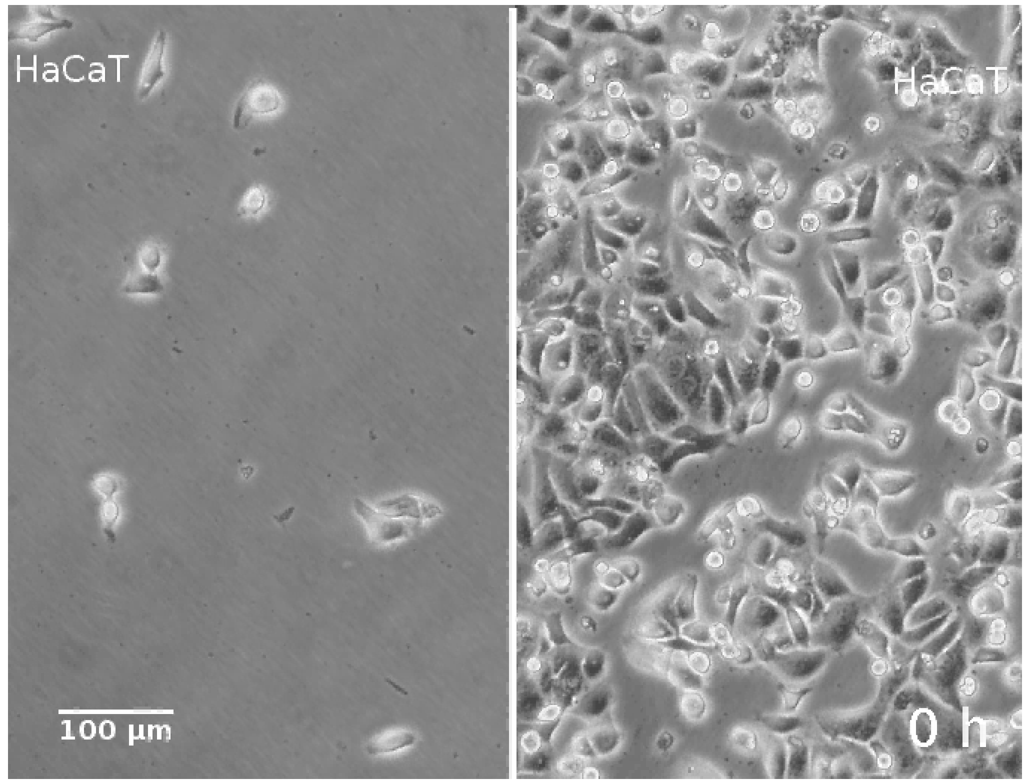
$A \cancel{-\!\!-} B$

Comparing the motility of different cell types



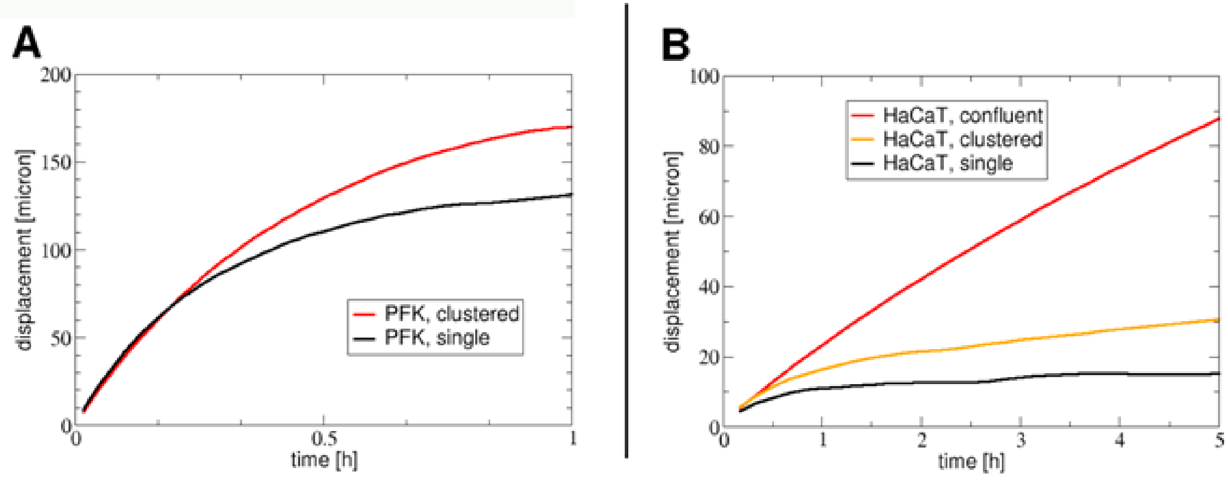
Clustering increases directional persistence





$$d^2(t) = 4D\left[t - T_p\left(1 - e^{-t/T_p}\right)\right],$$

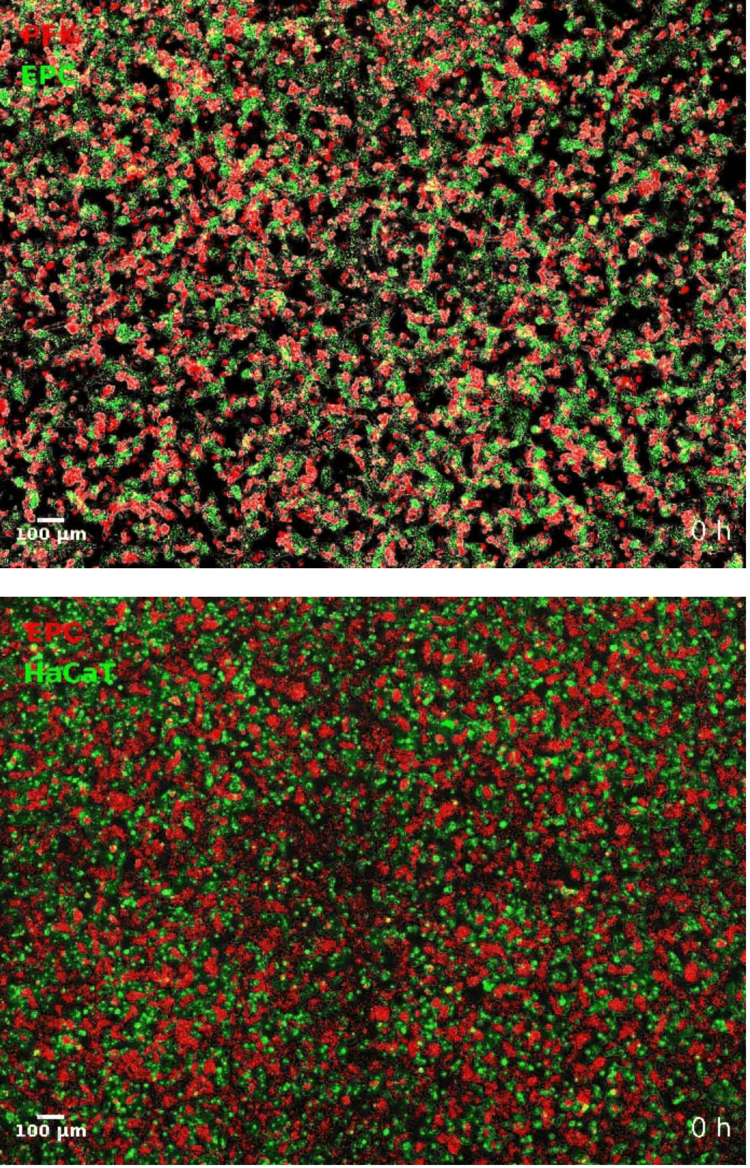
→ Persistence length

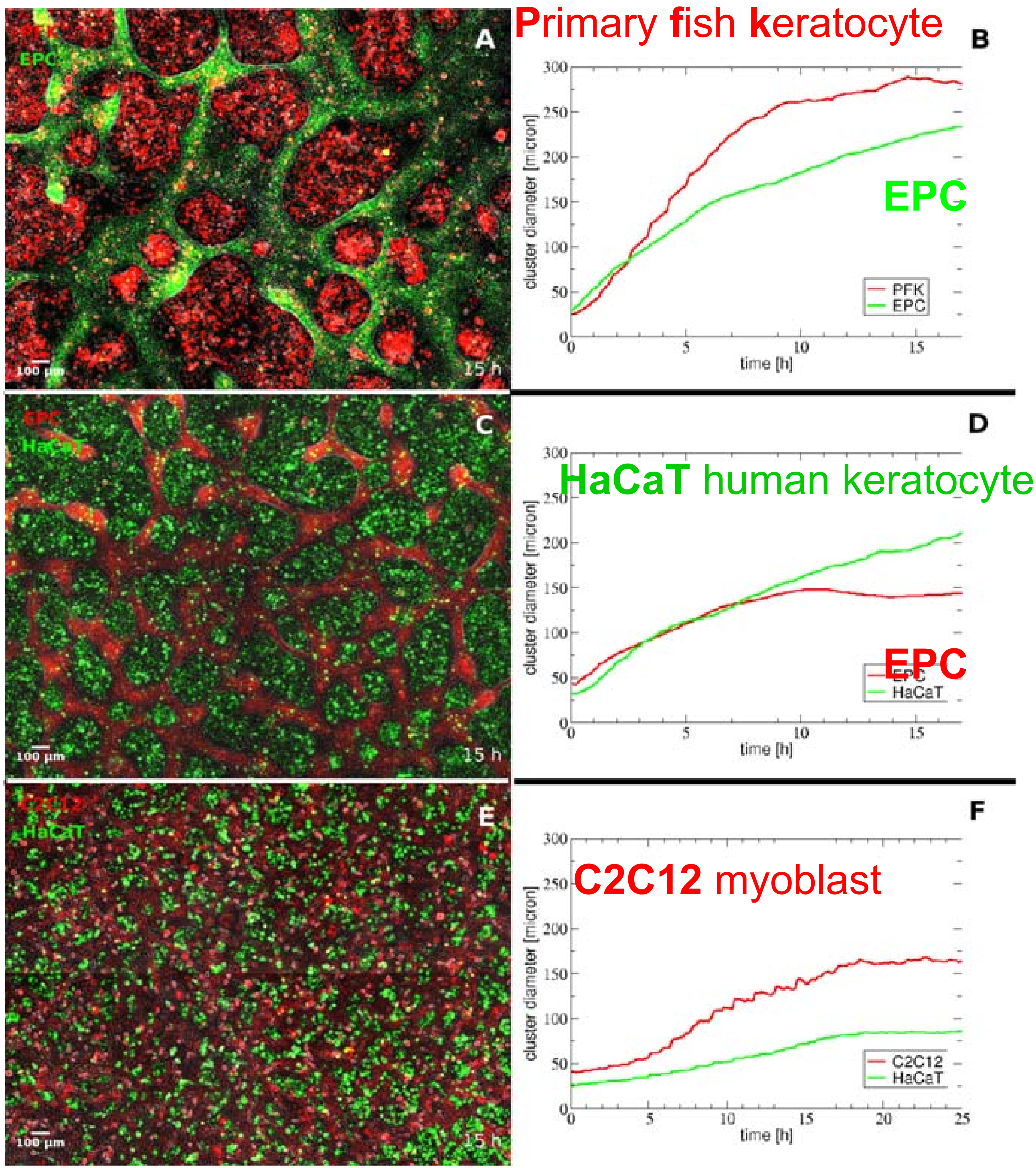


high directional persistence

↓

collective migration



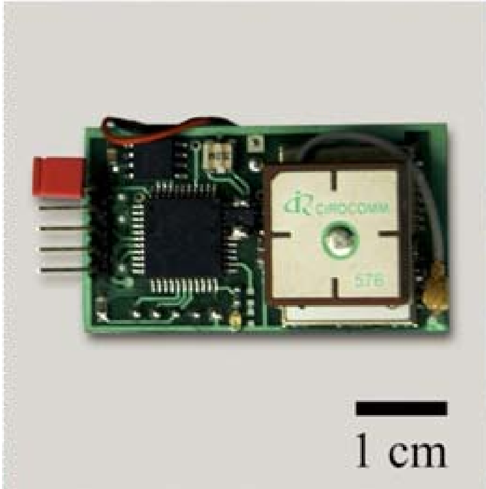


High directional persistence

facilitates

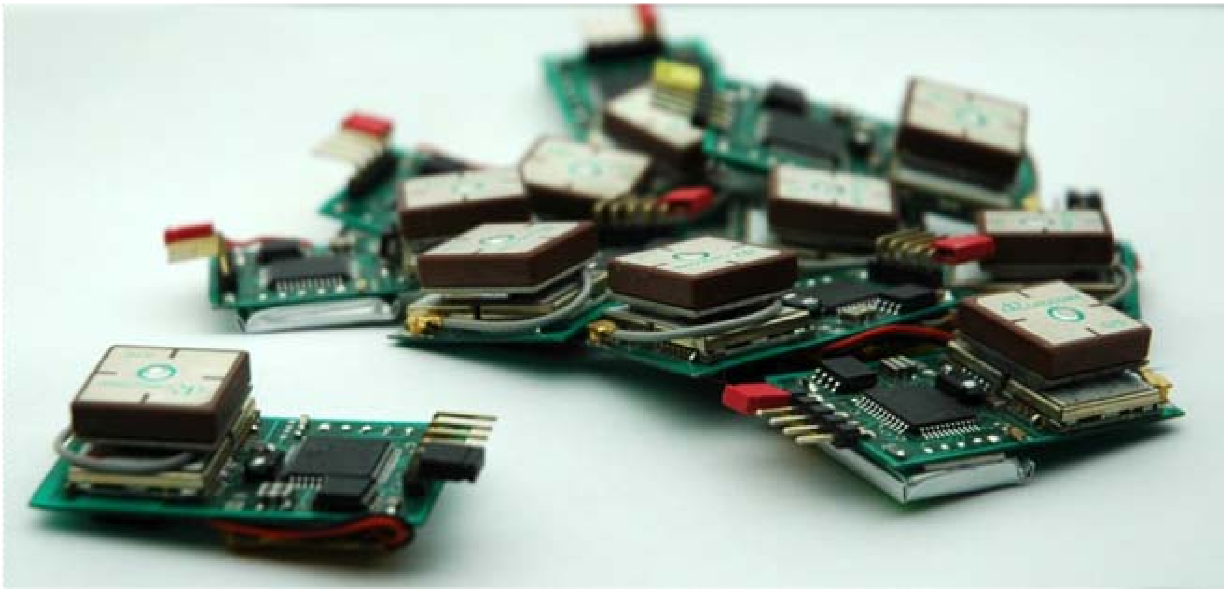
cell segregation

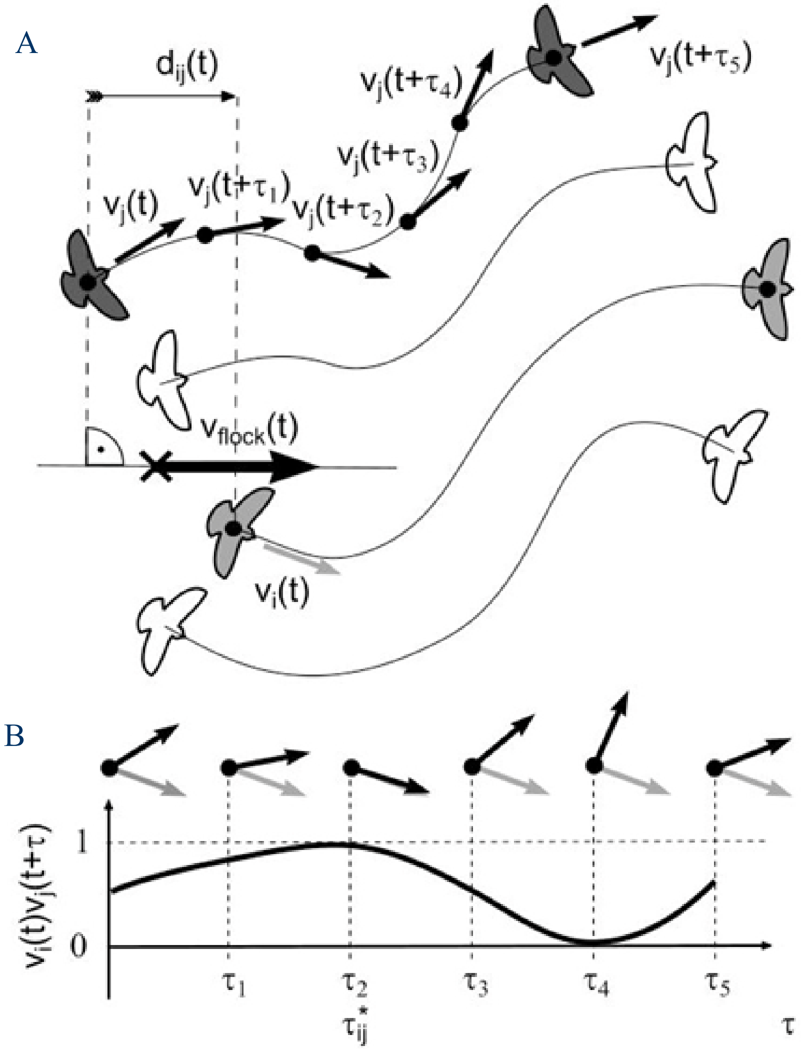
Hierarchical dynamics in pigeon flocks

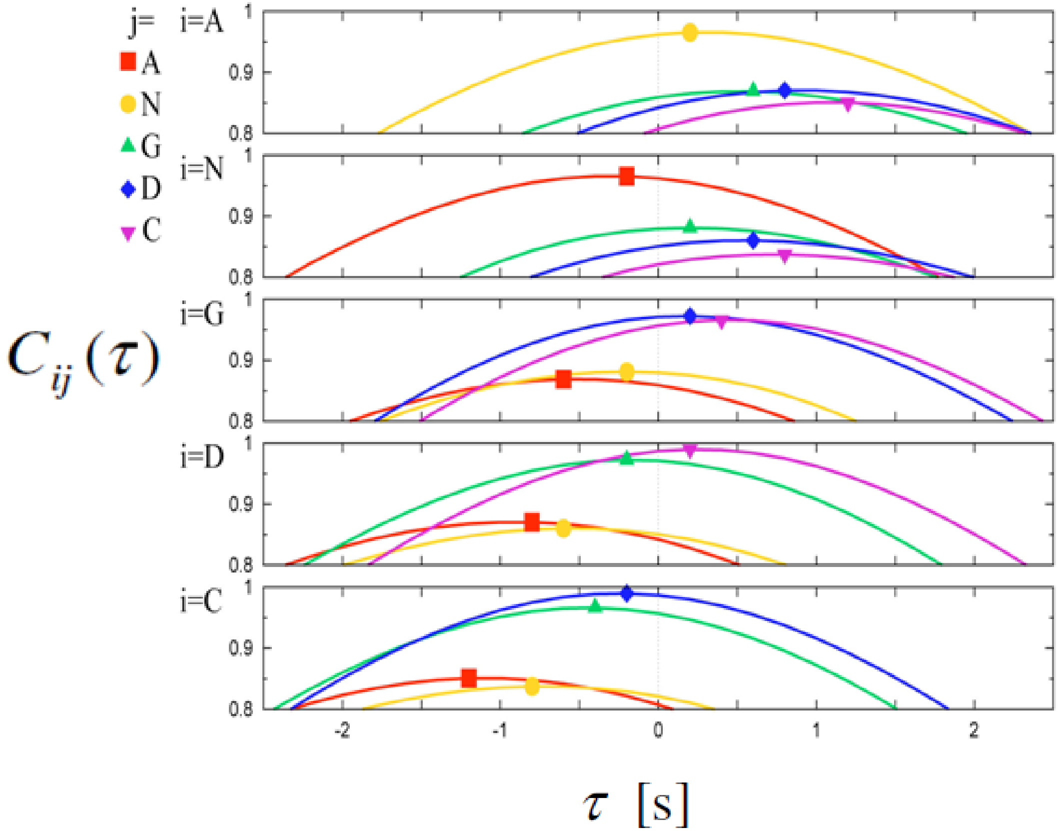


GPS : Switzerland, U-blox, (17 X 22 mm, 2,1g), 5Hz (2,5 Hz)

Total weight : 16g

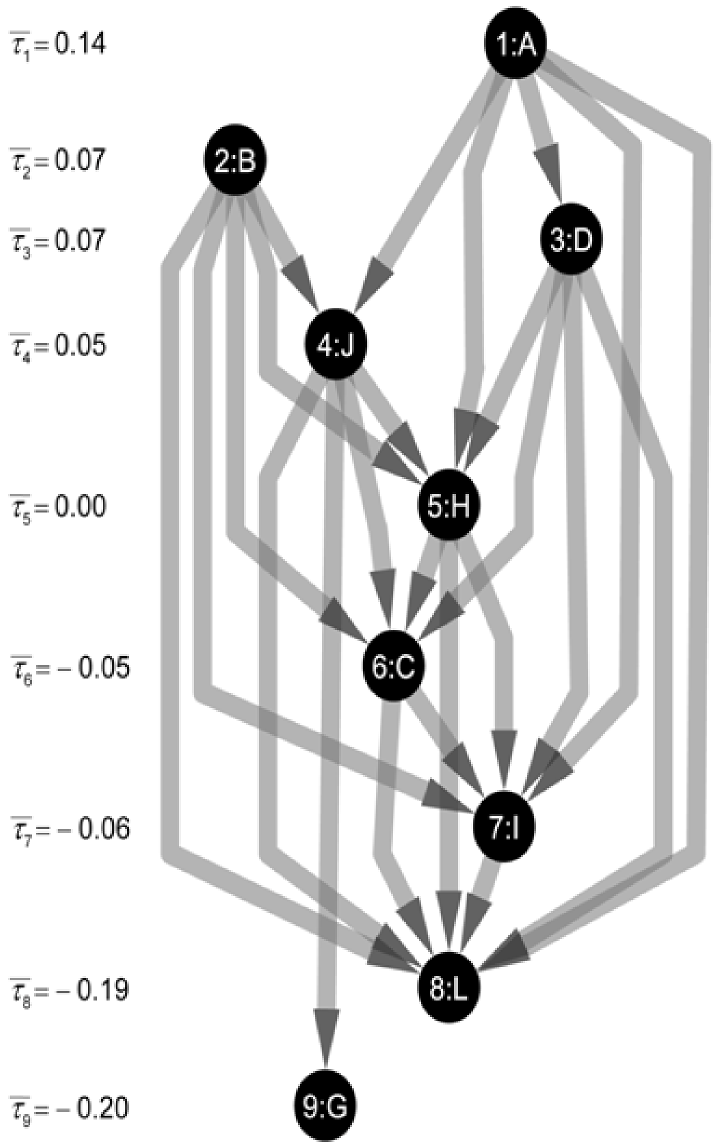




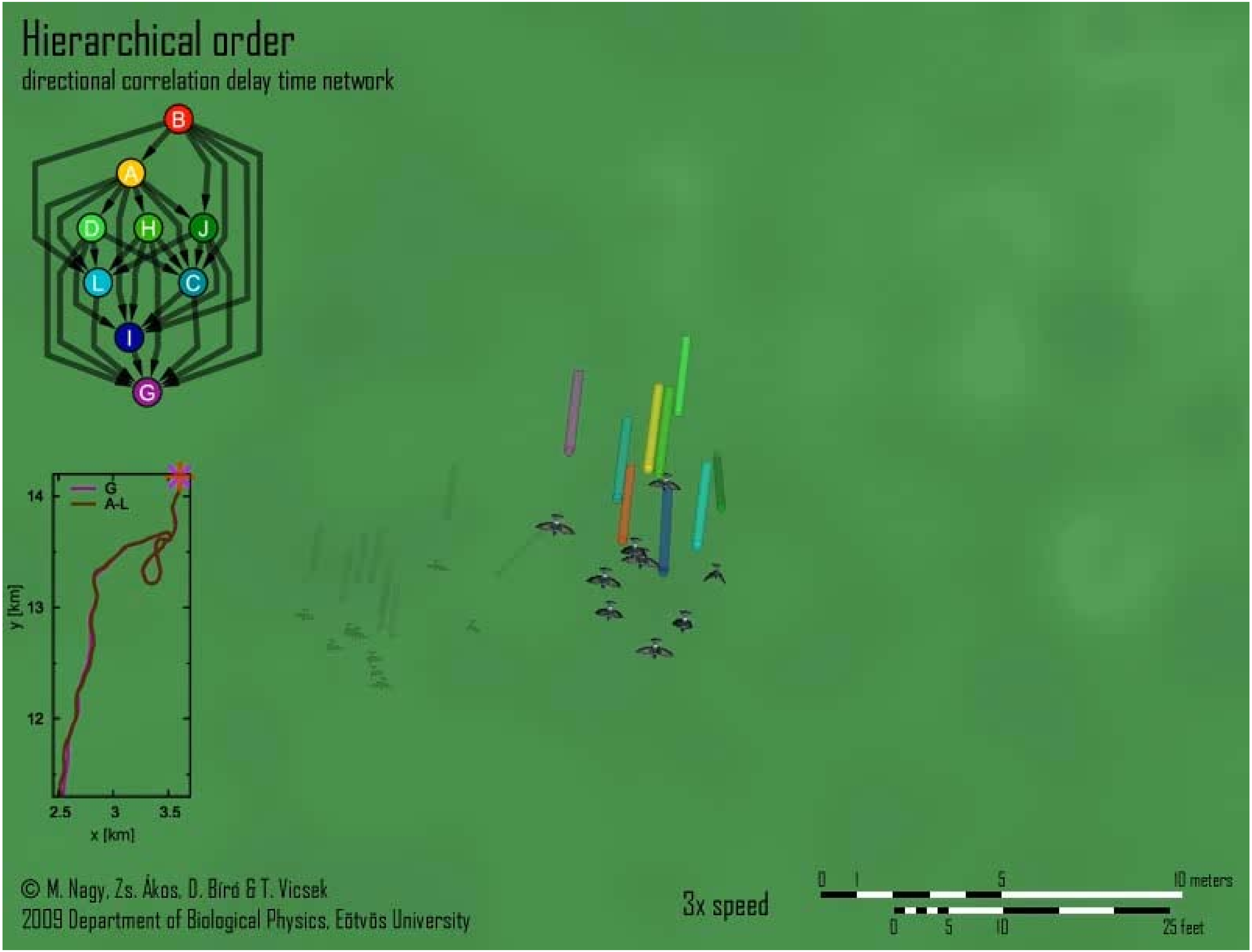


Velocity autocorrelation function

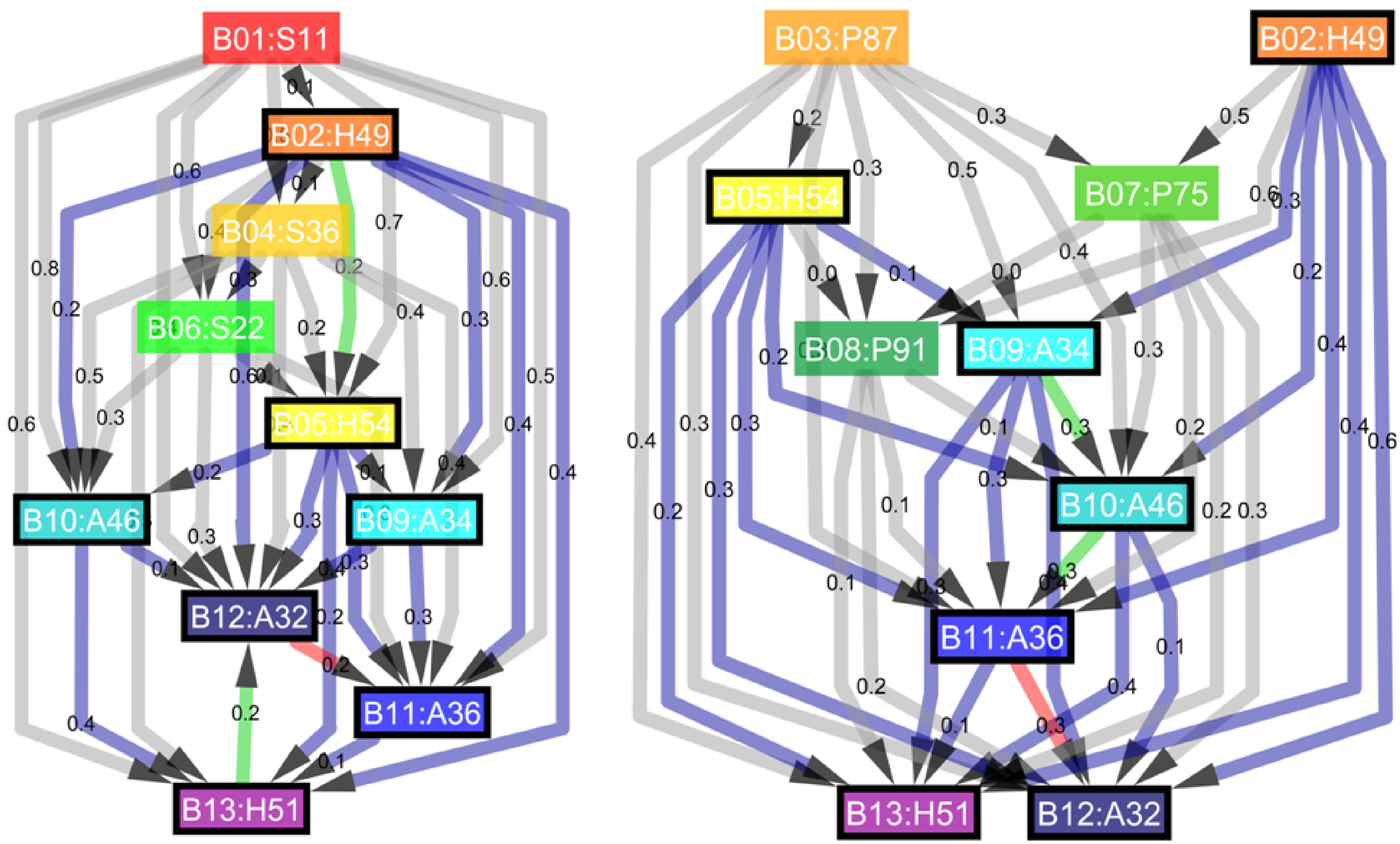
$$C_{ij}(\tau) = \left\langle \overrightarrow{v_i}(t) \cdot \overrightarrow{v_j}(t+\tau) \right\rangle$$

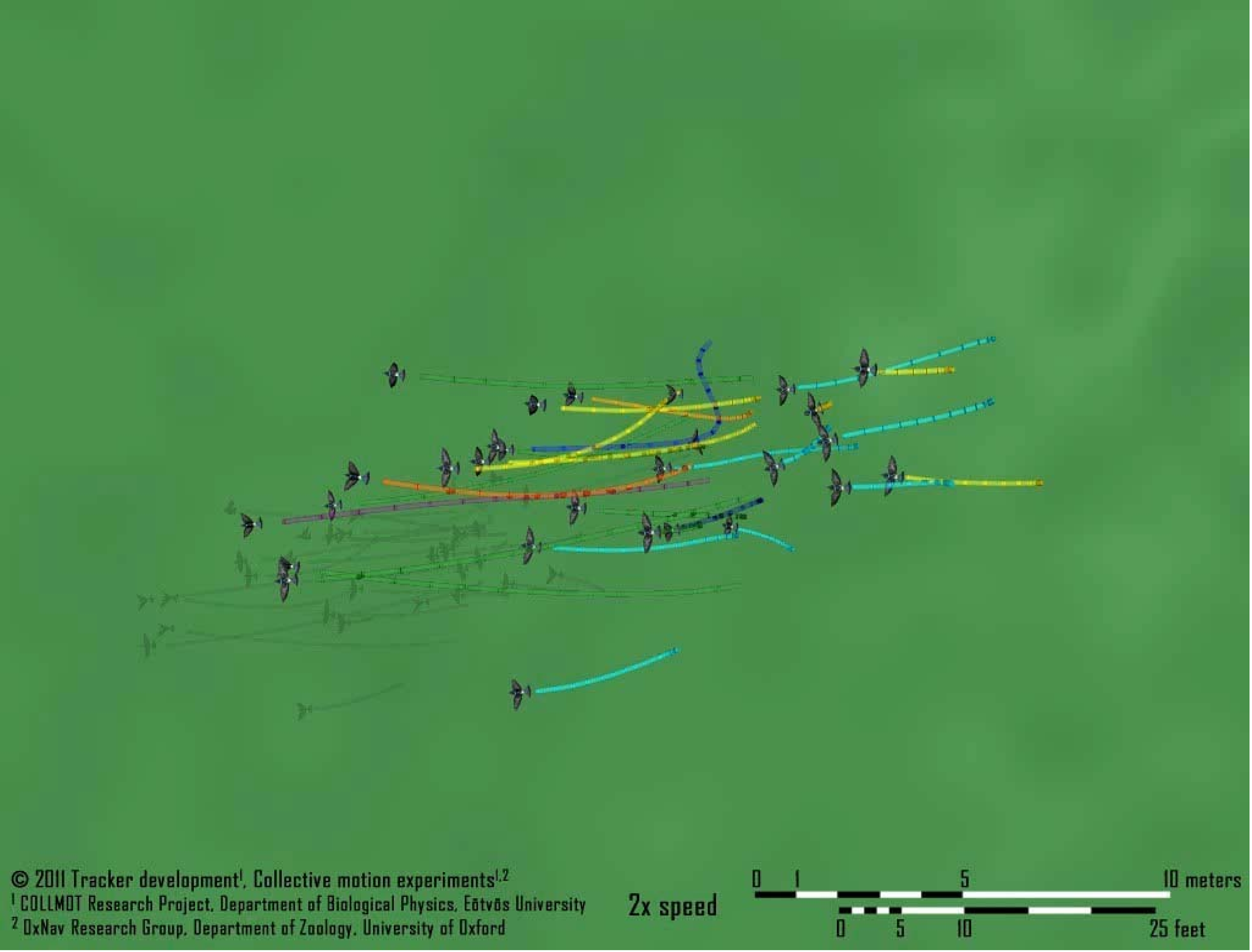


$\overline{\tau}_1 = 0.14$
$\overline{\tau}_2 = 0.07$
$\overline{\tau}_3 = 0.07$
$\overline{\tau}_4 = 0.05$
$\overline{\tau}_5 = 0.00$
$\overline{\tau}_6 = -0.05$
$\overline{\tau}_7 = -0.06$
$\overline{\tau}_8 = -0.19$
$\overline{\tau}_9 = -0.20$
1:A
2:B
3:D
4:J
5:H
6:C
7:I
8:L
9:G


Hierarchical order
directional correlation delay time network
B
A
D
H
J
L
C
I
G
G
A-L
14
13
12
y [km]
2.5
3
3.5
x [km]
© M. Nagy, Zs. Ákos, D. Bíró & T. Vicsek
2009 Department of Biological Physics, Eötvös University
3x speed
0
1
5
10 meters
0
5
10
25 feet

Newcomers hardly perturb the original hierarchy



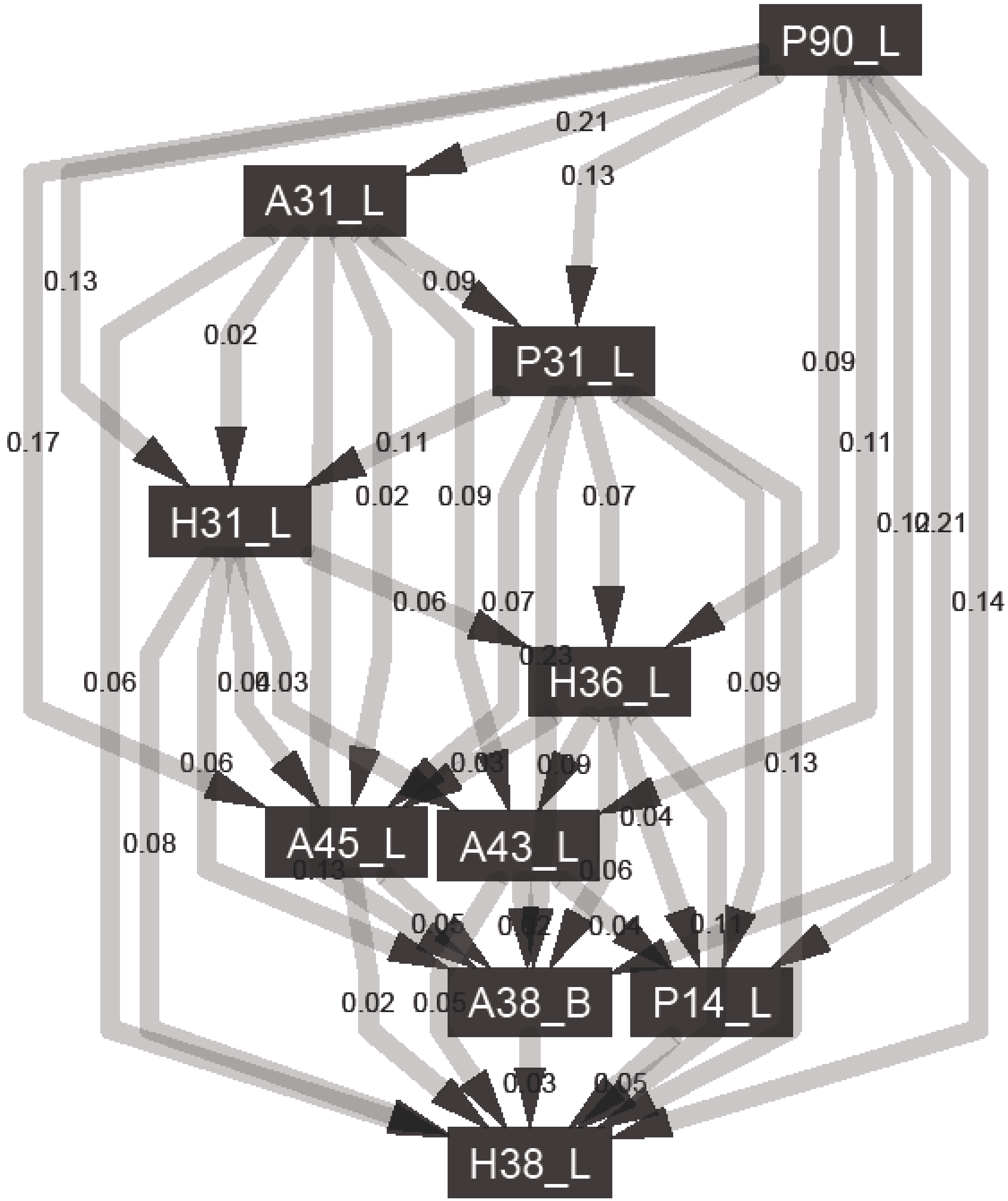

© 2011 Tracker development[1], Collective motion experiments[1,2]
[1] COLLMOT Research Project, Department of Biological Physics, Eötvös University
[2] OxNav Research Group, Department of Zoology, University of Oxford
2x speed
0 1 5 10 meters
0 5 10 25 feet

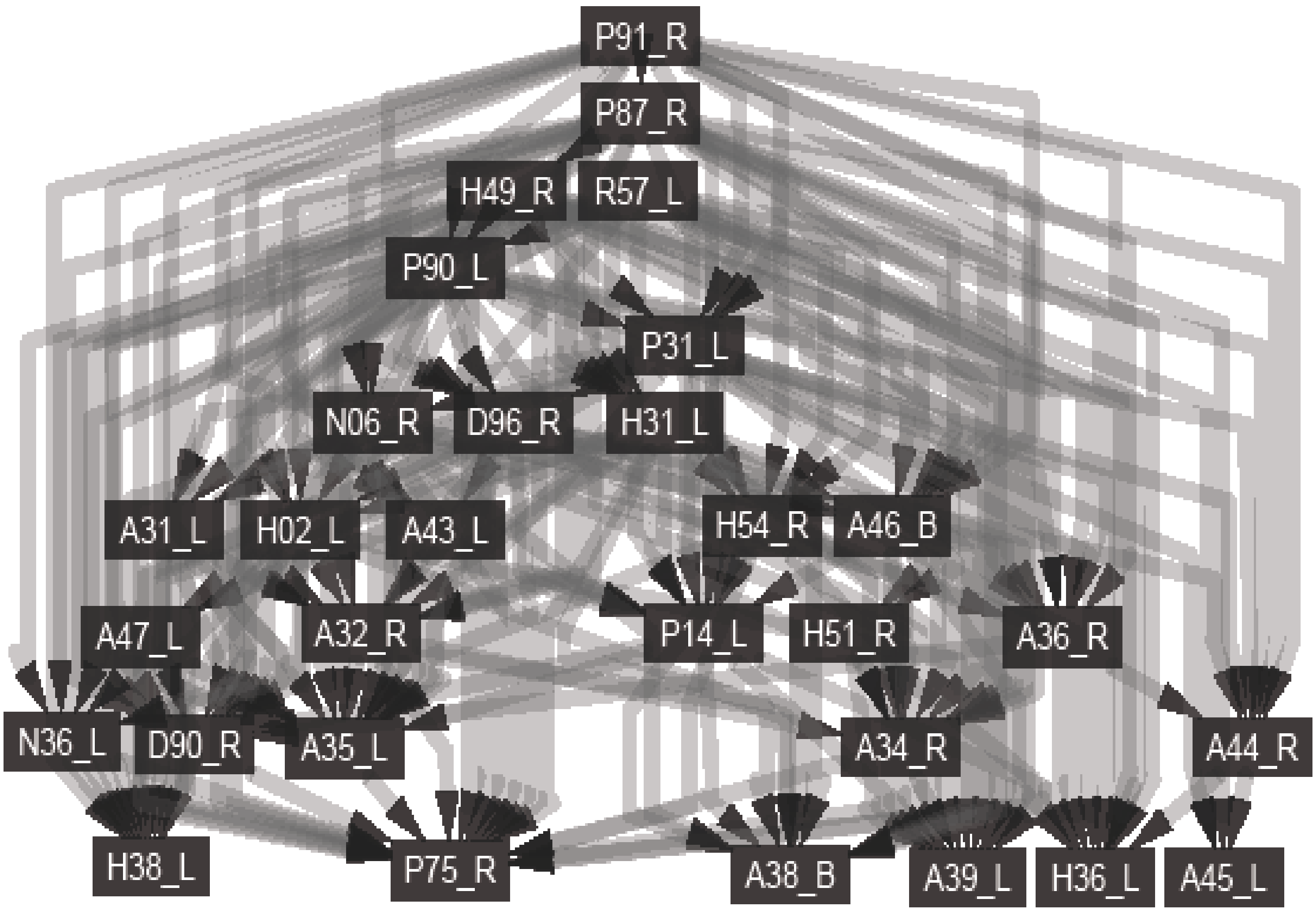
Pigeons at home:

Dominance hierarchy from digital video analysis

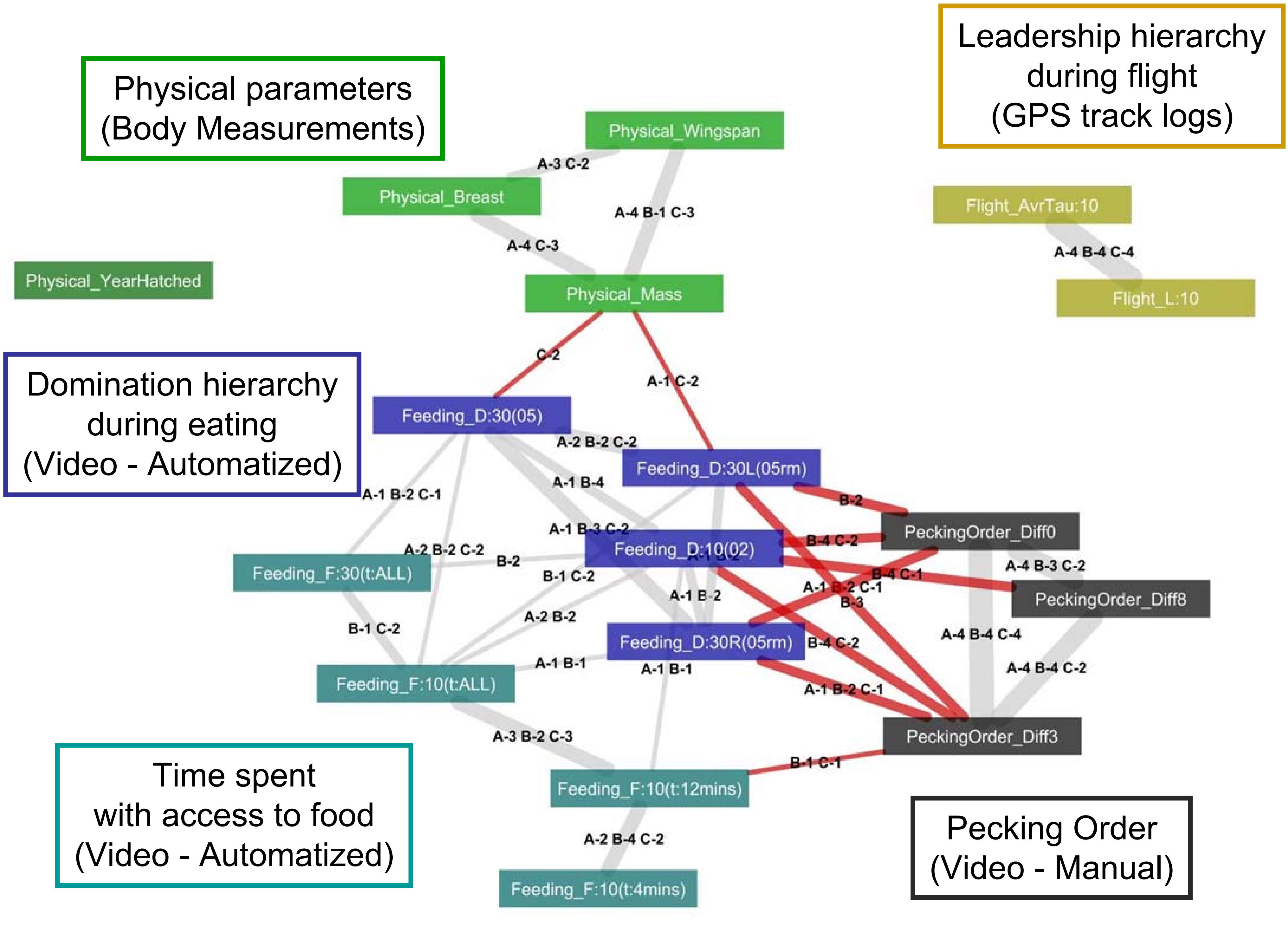
Digital video analysis of the moving pigeons around the feeding cup

Pairwise dominance graph as determined from „who is closer to the feeding cup”




P91_R
P87_R
H49_R
R57_L
P90_L
P31_L
N06_R
D96_R
H31_L
A31_L
H02_L
A43_L
H54_R
A46_B
A47_L
A32_R
P14_L
H51_R
A36_R
N36_L
D90_R
A35_L
A34_R
A44_R
H38_L
P75_R
A38_B
A39_L
H36_L
A45_L

PECKING order



Physical parameters
(Body Measurements)
Leadership hierarchy
during flight
(GPS track logs)
Physical_Wingspan
A-3 C-2
Physical_Breast
A-4 B-1 C-3
Flight_AvrTau:10
A-4 C-3
A-4 B-4 C-4
Physical_YearHatched
Physical_Mass
Flight_L:10
C-2
A-1 C-2
Domination hierarchy
during eating
(Video - Automatized)
Feeding_D:30(05)
A-2 B-2 C-2
Feeding_D:30L(05rm)
A-1 B-4
A-1 B-2 C-1
B-2
A-1 B-3 C-2
PeckingOrder_Diff0
B-4 C-2
A-2 B-2 C-2
Feeding_D:10(02)
B-2
A-4 B-3 C-2
Feeding_F:30(t:ALL)
B-1 C-2
B-4 C-1
A-1 B-2 C-1
PeckingOrder_Diff8
A-1 B-2
B-3
B-1 C-2
A-2 B-2
Feeding_D:30R(05rm)
B-4 C-2
A-4 B-4 C-4
A-1 B-1
A-1 B-1
A-4 B-4 C-2
Feeding_F:10(t:ALL)
A-1 B-2 C-1
PeckingOrder_Diff3
A-3 B-2 C-3
B-1 C-1
Feeding_F:10(t:12mins)
Time spent
with access to food
(Video - Automatized)
Pecking Order
(Video - Manual)
A-2 B-4 C-2
Feeding_F:10(t:4mins)

A few questions arising

Does collective cell migration play an important role during embryonic development?

Do pigeons make use of a sophisticated hierarchical negotiation procedure to make collective decisions?

Are the knowledge based and the „physical” dominance roles related?

Thank you for your attention!