COLLECTIVE MOTION

T. Vicsek

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

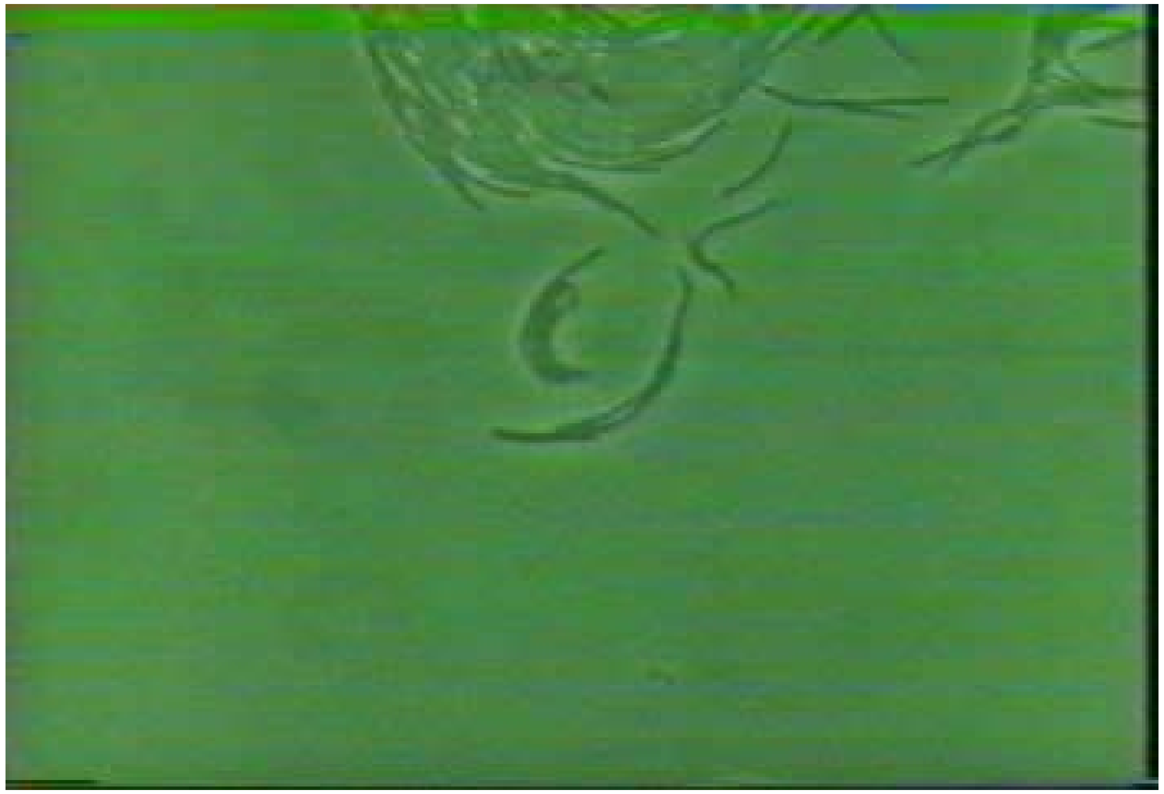
Collective behaviour-> Collective decision-making-> Collective motion

from bacteria to animals, people and drones

PART I

Introduction to collective motion

Collective motion of



From BBC (I. Couzin)

swirling motion II

video4 - supplement to Fig. 3D

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

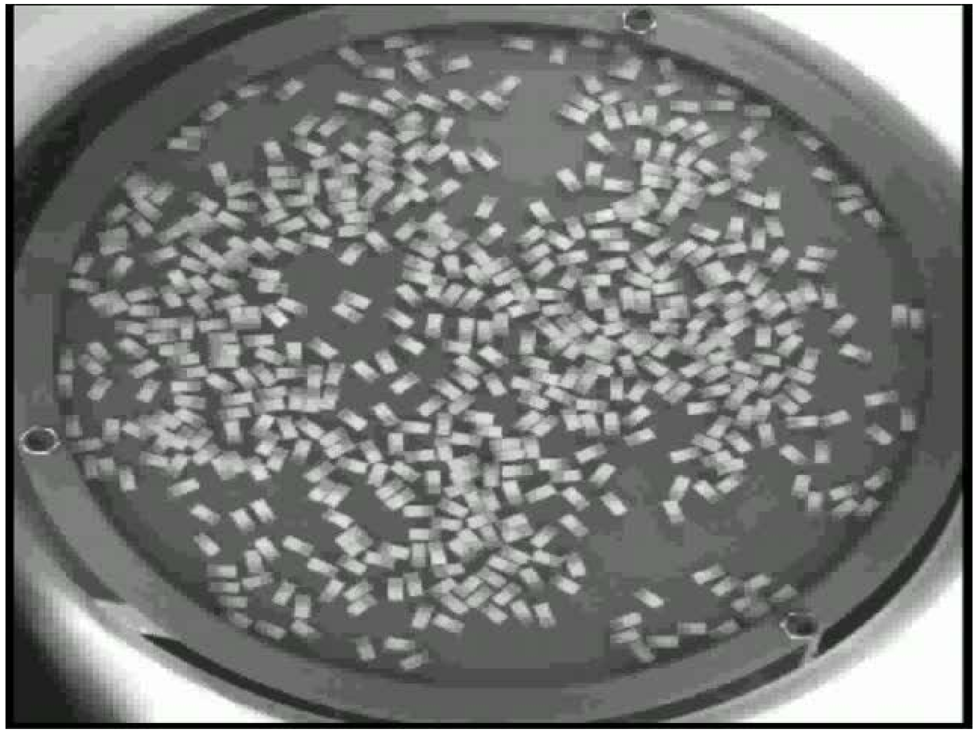
E27

Bausch group, Munich

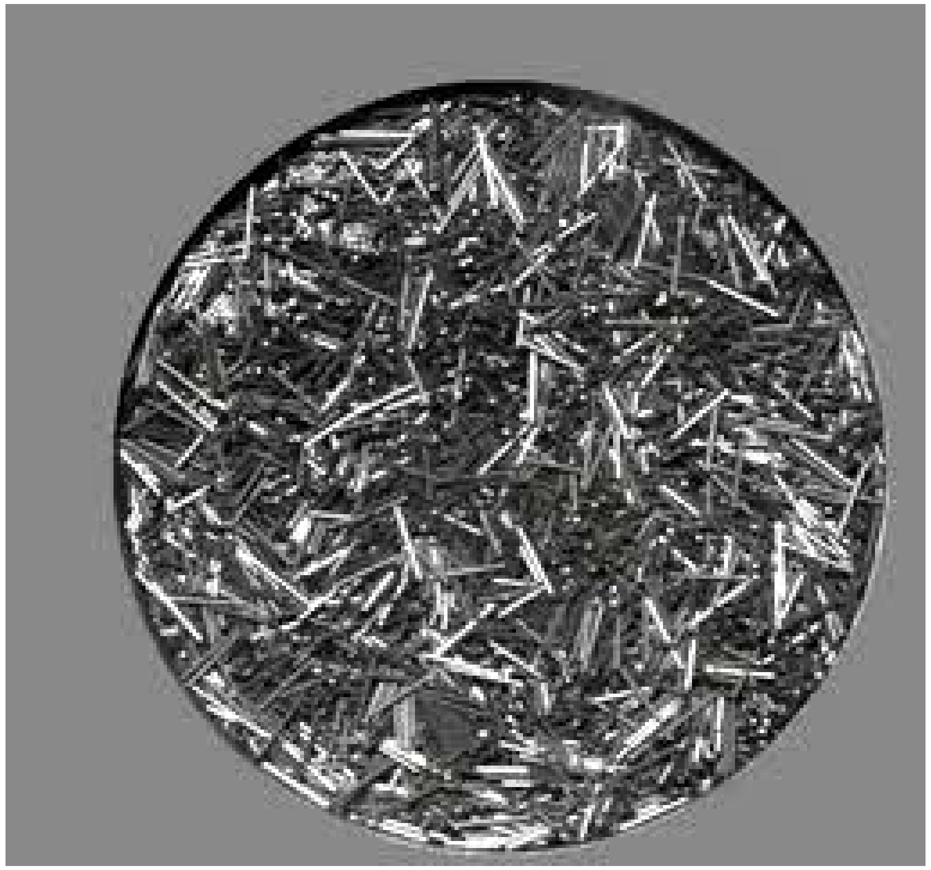



Collective motion of rods (physics) shaken from below

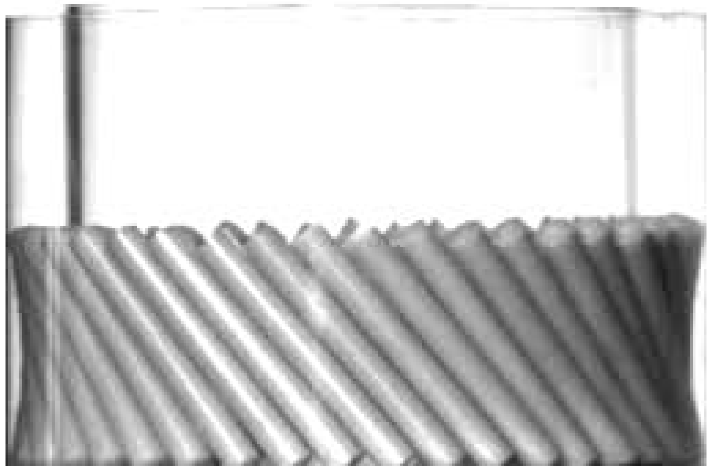
Asymmetric units



Just simple rods

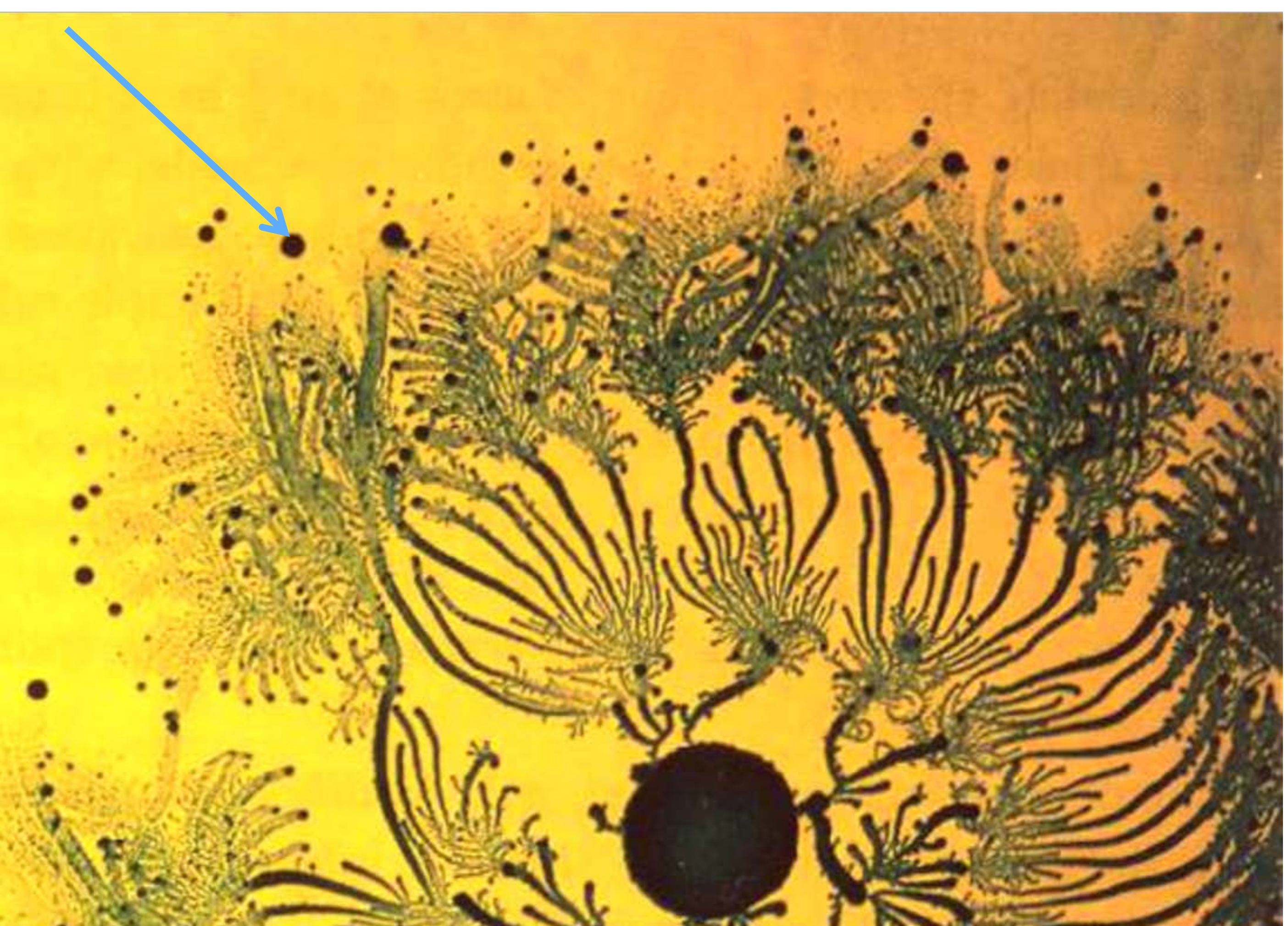


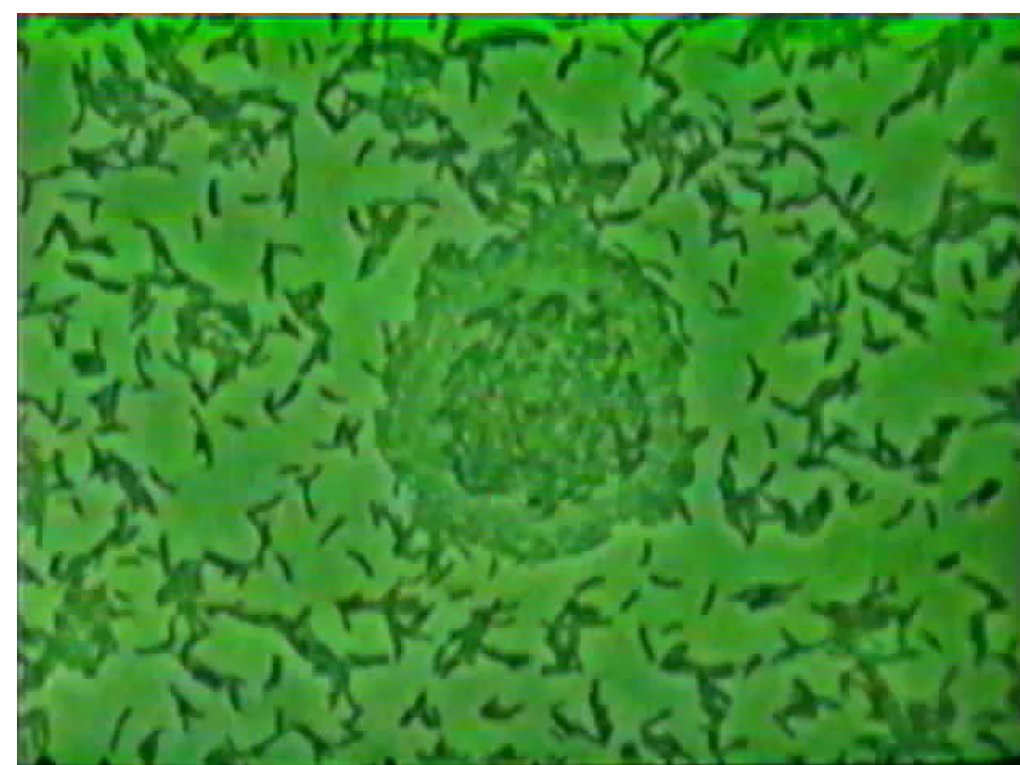
Kudrolli et al PRL, (2003), (2008)



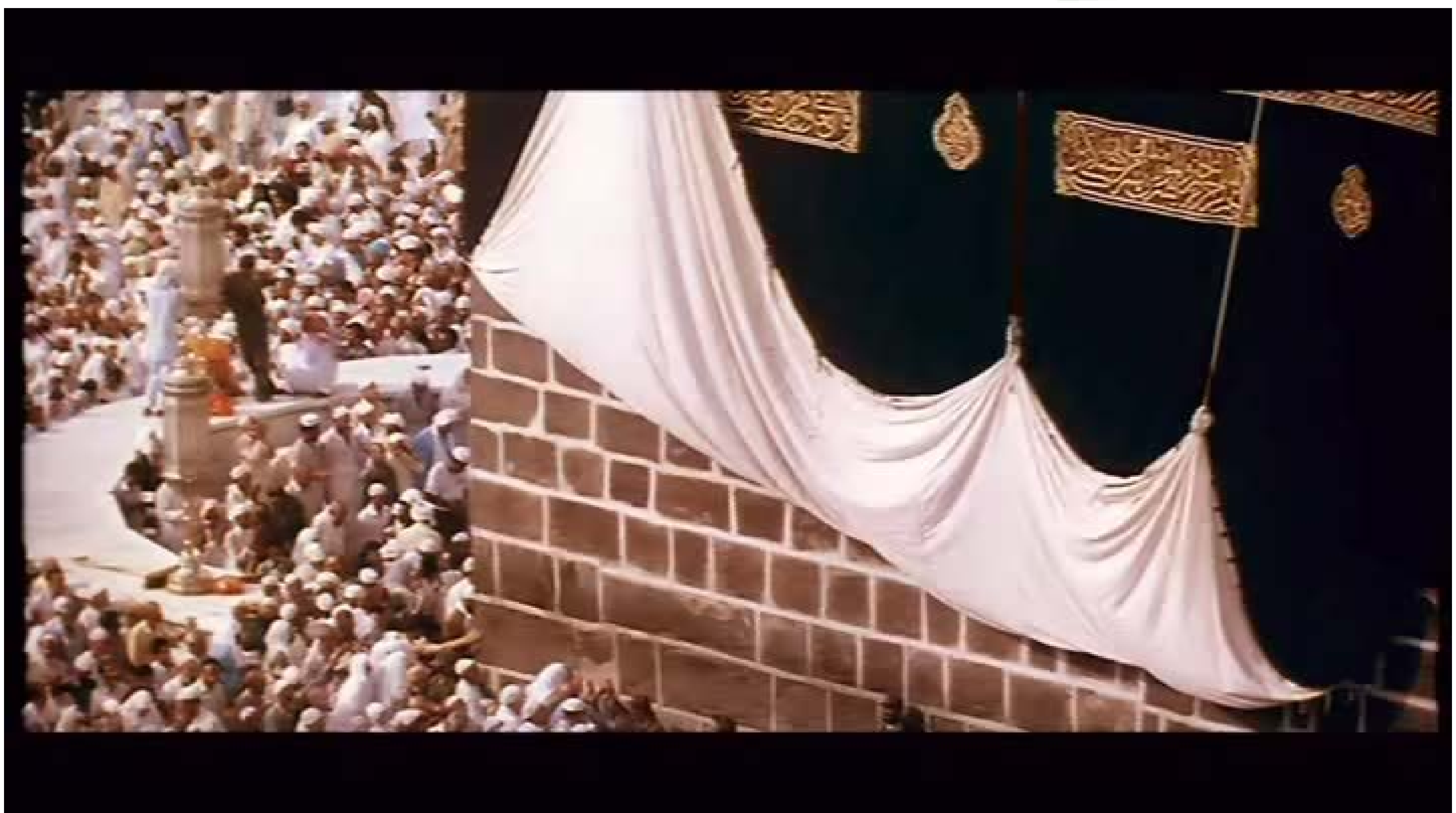
A universal pattern of motion

Locusts (Buhl, Sumpter, Couzin et al, *Science*, 2006)



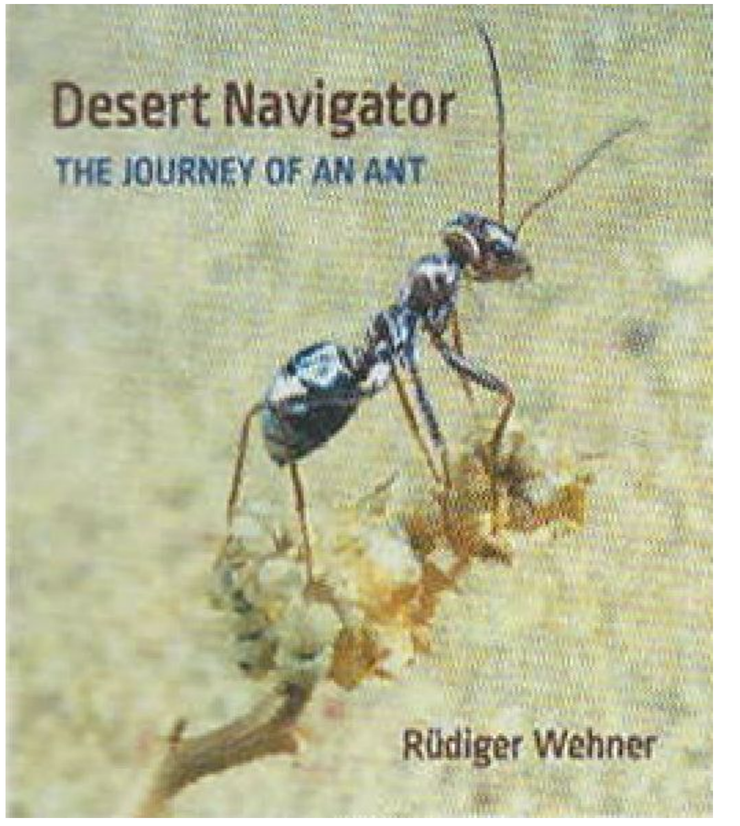



Self-Organized Flocking
of Kobots in a Closed Arena
Ali E. Turgut, Hande Çelikkanat,
Fatih Gökçe and Erol Şahin
KOVAN Research Lab.
Dept. of Computer Eng.
Middle East Technical University
Ankara, Turkey



Ants are amazing both individually and when

collaborating



A school of striped eel catfish babies

by Dr. Brigitta Zics, artist, 2018, https://www.ravensbourne.ac.uk/

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

and

simple units produce **complex** patterns

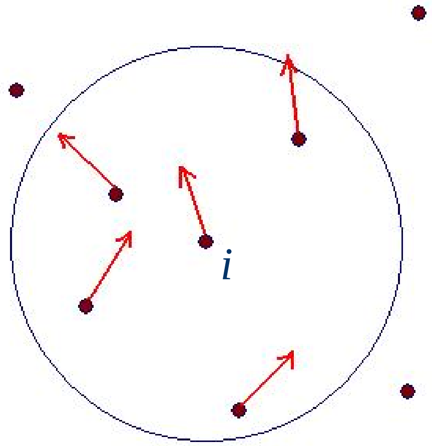
Our goals are: - **classification** of patterns } of collective motion

- finding the **basic laws** (microscopic versus global)

„Universality” (versus specificity)

Swarms, flocks and herds

- **<u>Model* (SPP) :</u>** The particles



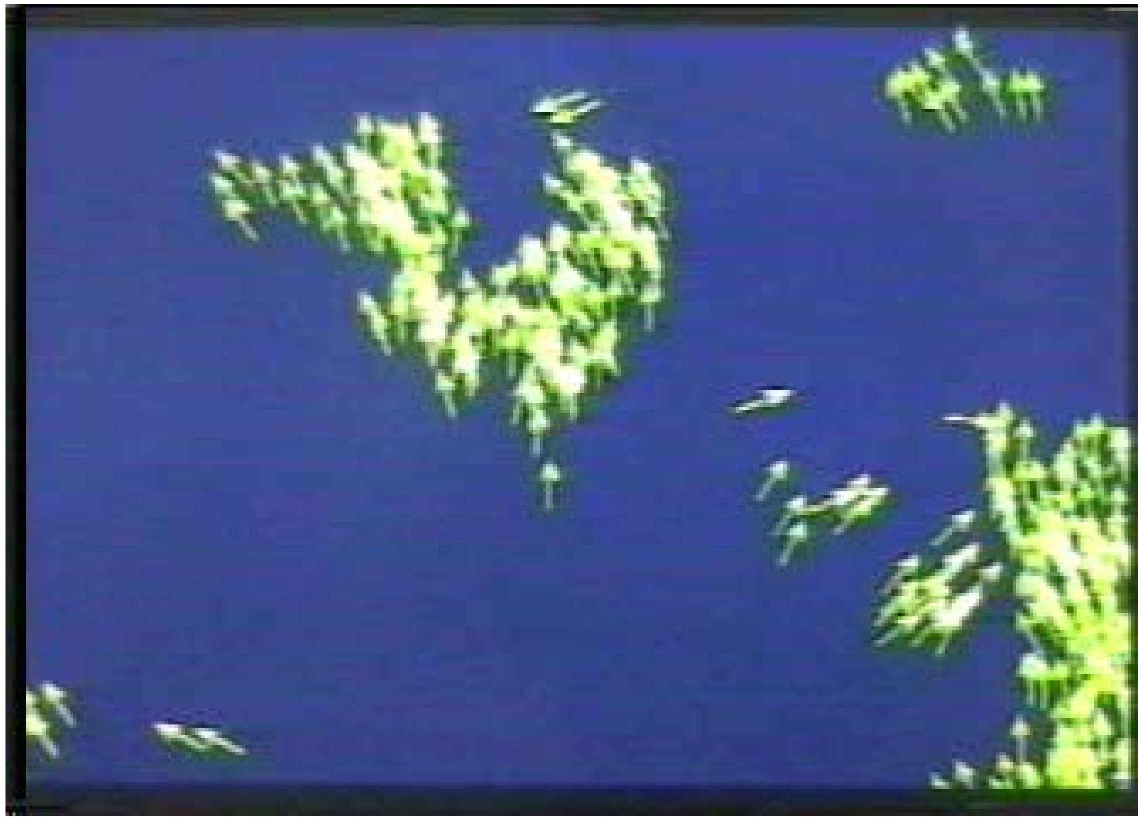
 - maintain a given absolute value of the velocity v_0
 - follow their neighbours called „**ALIGNMENT RULE**"
 - motion is perturbed by fluctuations □

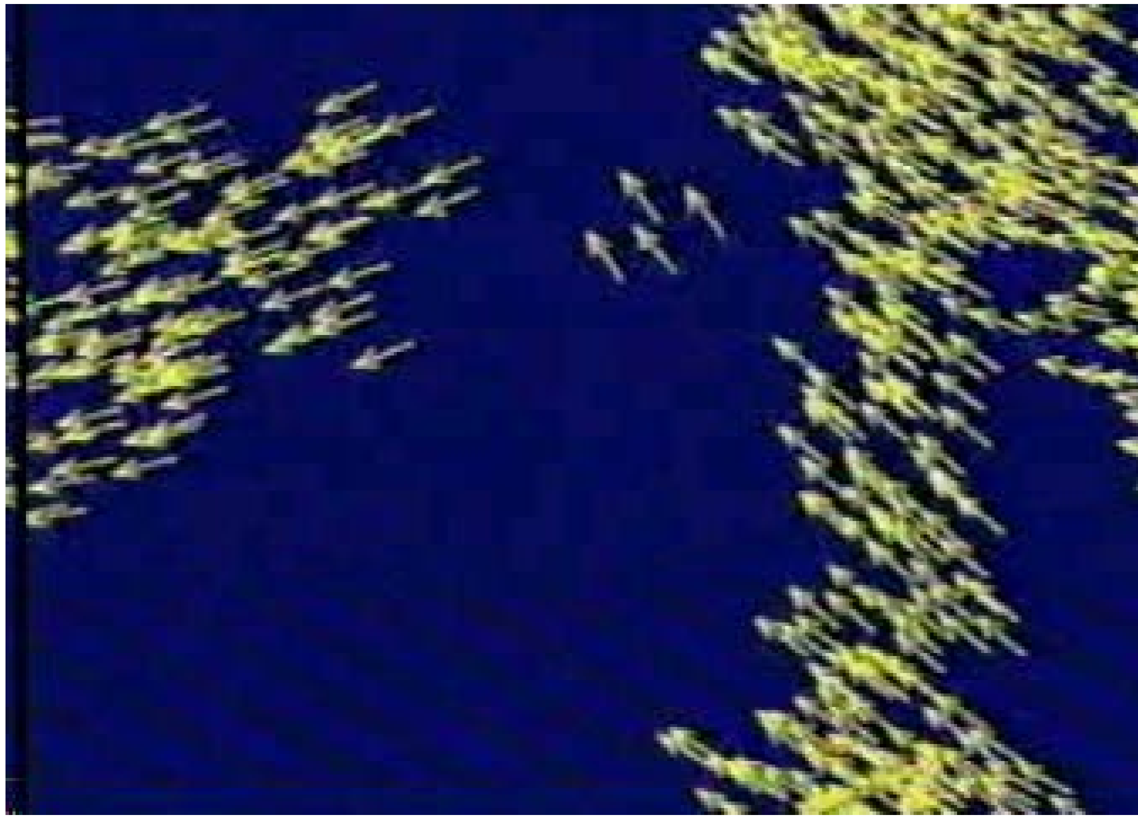
$$\vec{e}_i\,(t+1) = E\left[E[\langle \vec{e}_j\,(t)\rangle_j\,] + \vec{\eta}(t)\right]$$

(*E* normalizes the magnitude into unity)

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

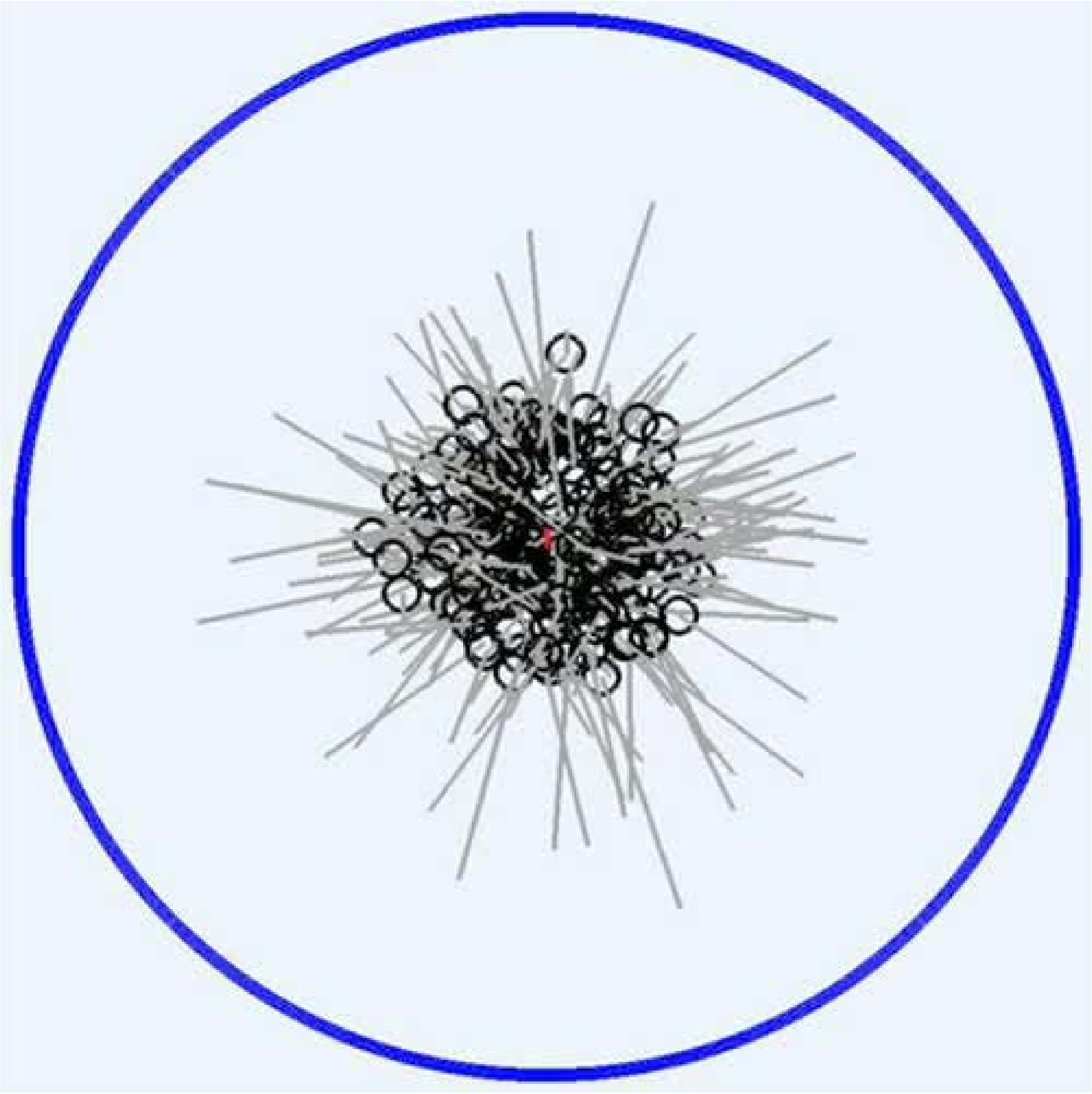
- **<u>Result: *ordering is due to* *motion*</u>**



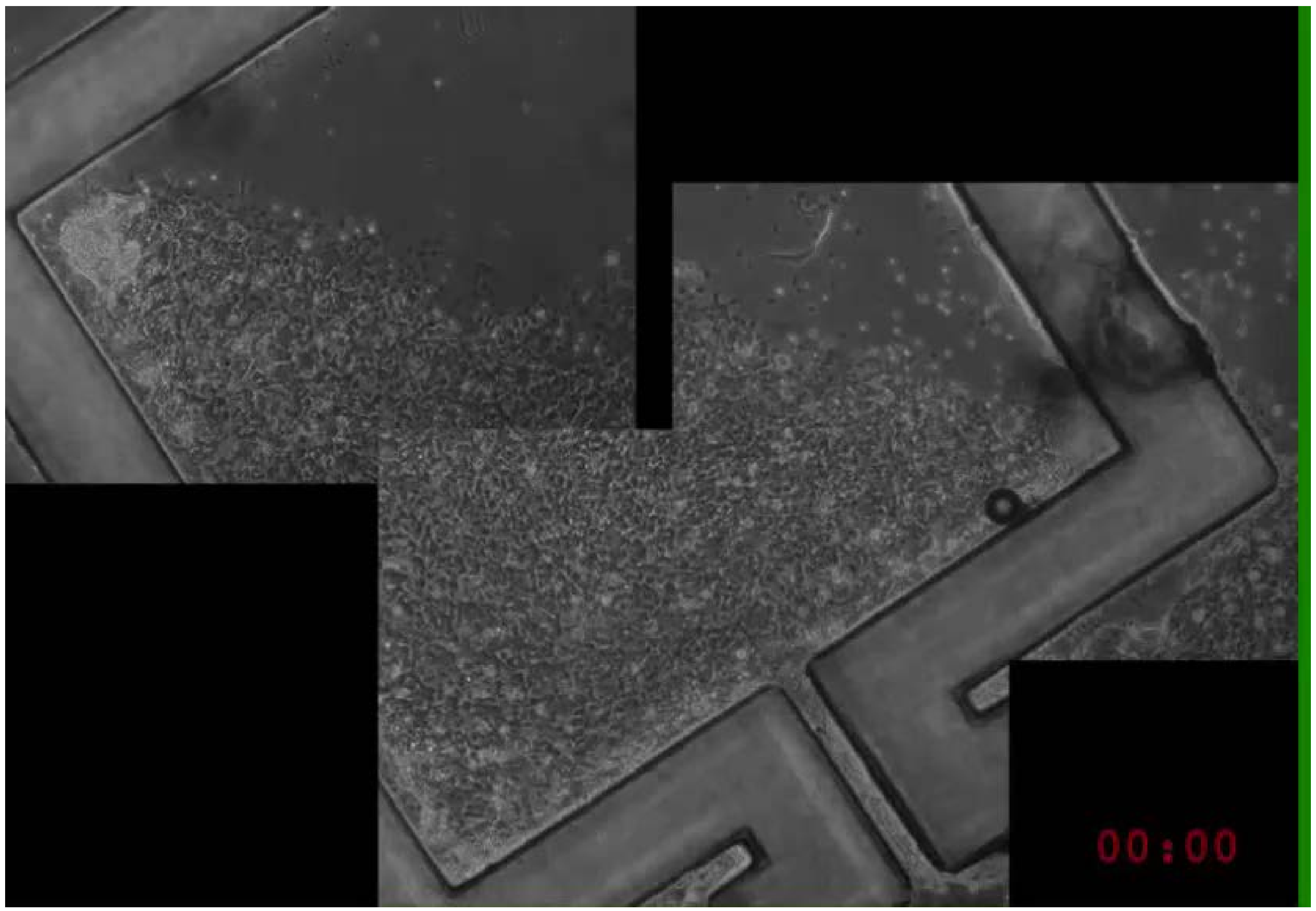


Just trying to keep going with repelling force (*no alignment rule*)

„sudden” ordering

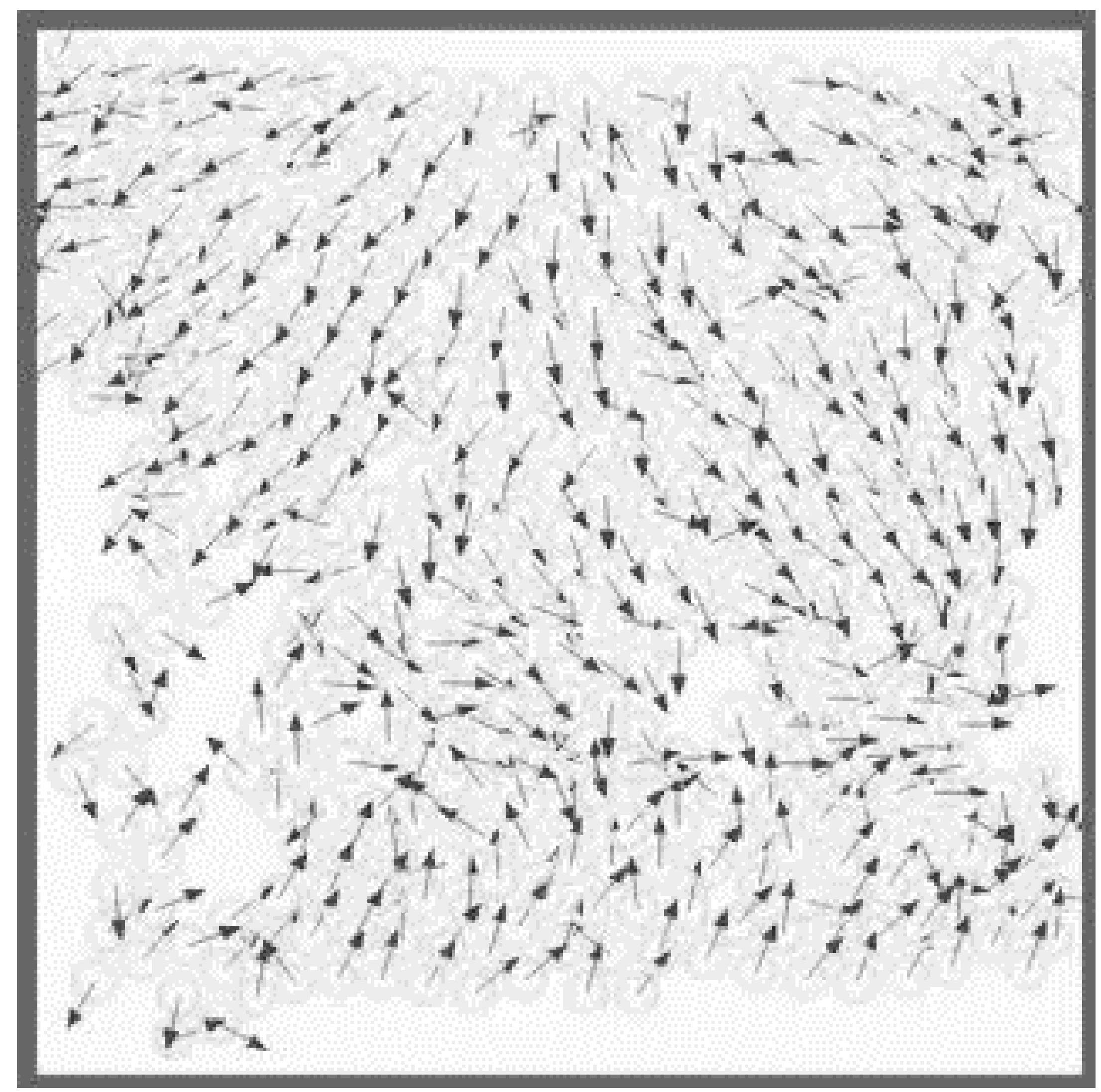


But, e.g., for cells (keratocites, taken from fish scales):



0.5mm

Model with „delicate" turning rule + repulsion



Lessons:

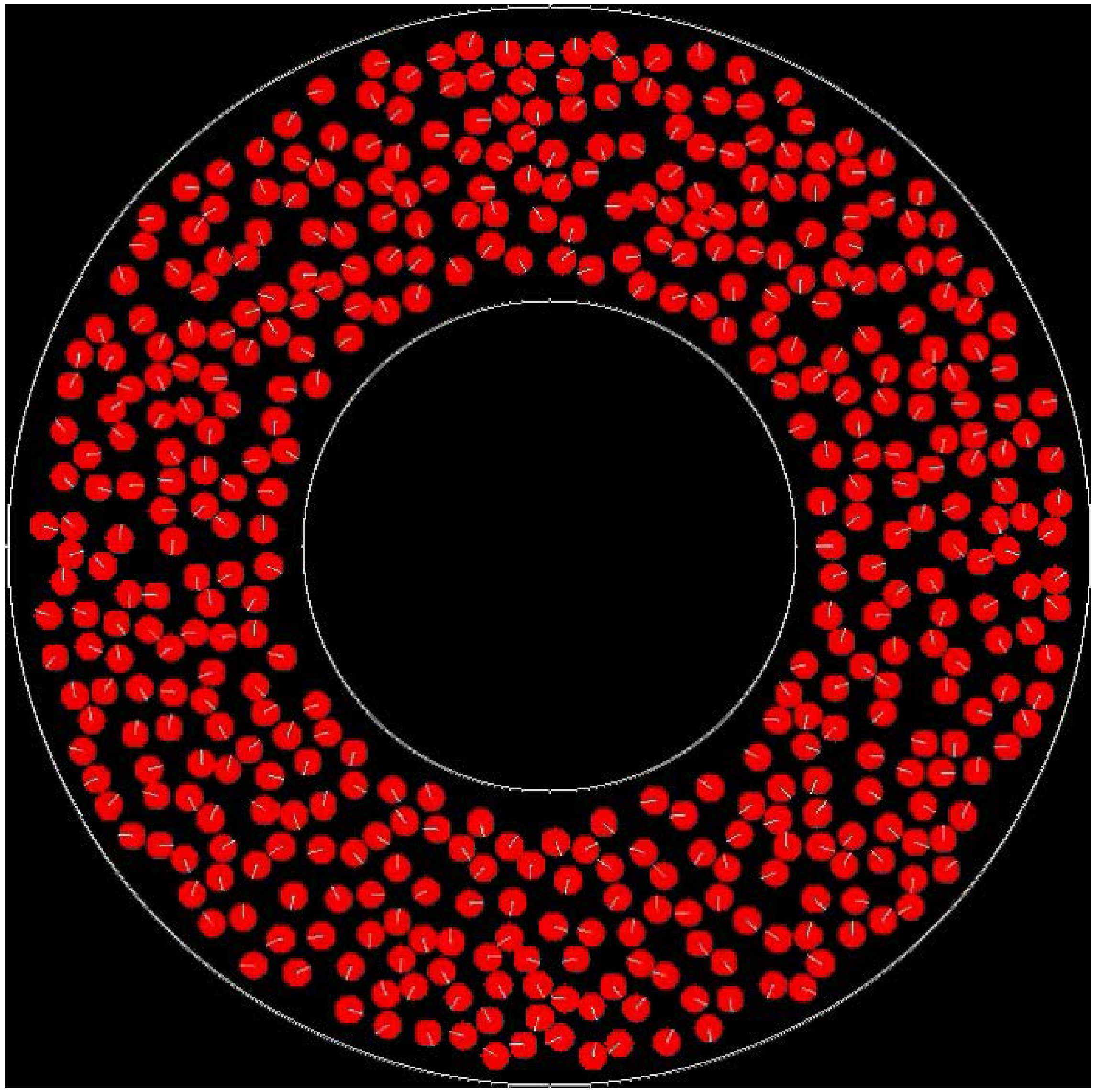
1. Most **patterns** of collective motion are ***universal***

2. **Simple models** can reproduce this behavior

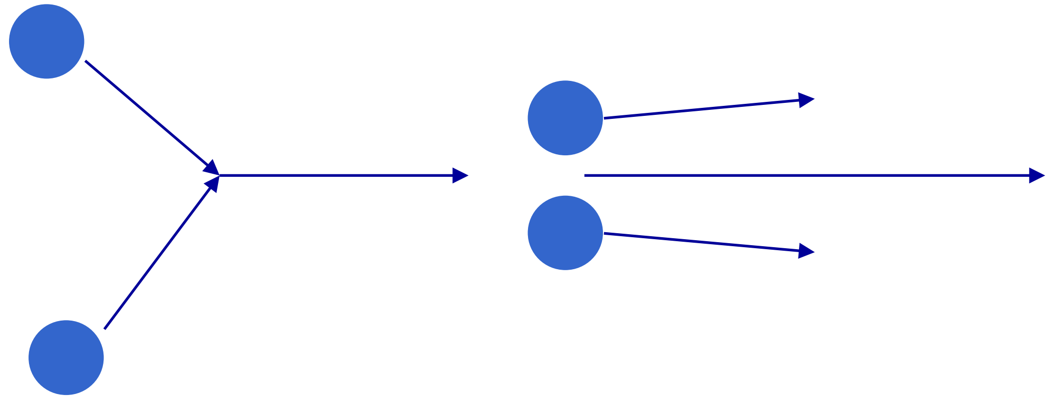
3. A **simple noise** term can account for numerous **complex deterministic** factors

4. **Role of border** is very different

5. Ordering is due to persistent motion! In other words: in SPP systems **momentum is not conserved!**



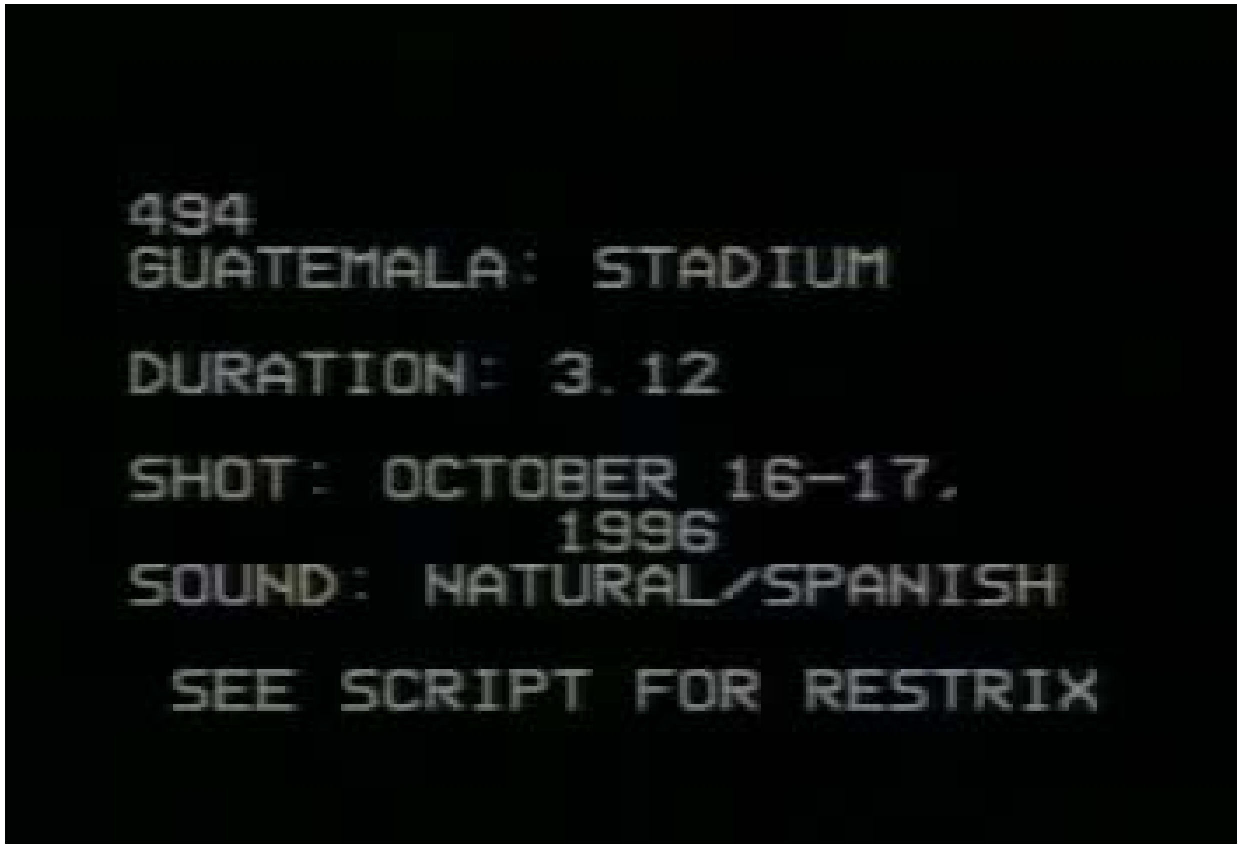
Simplest alignment model with hard core repulsion

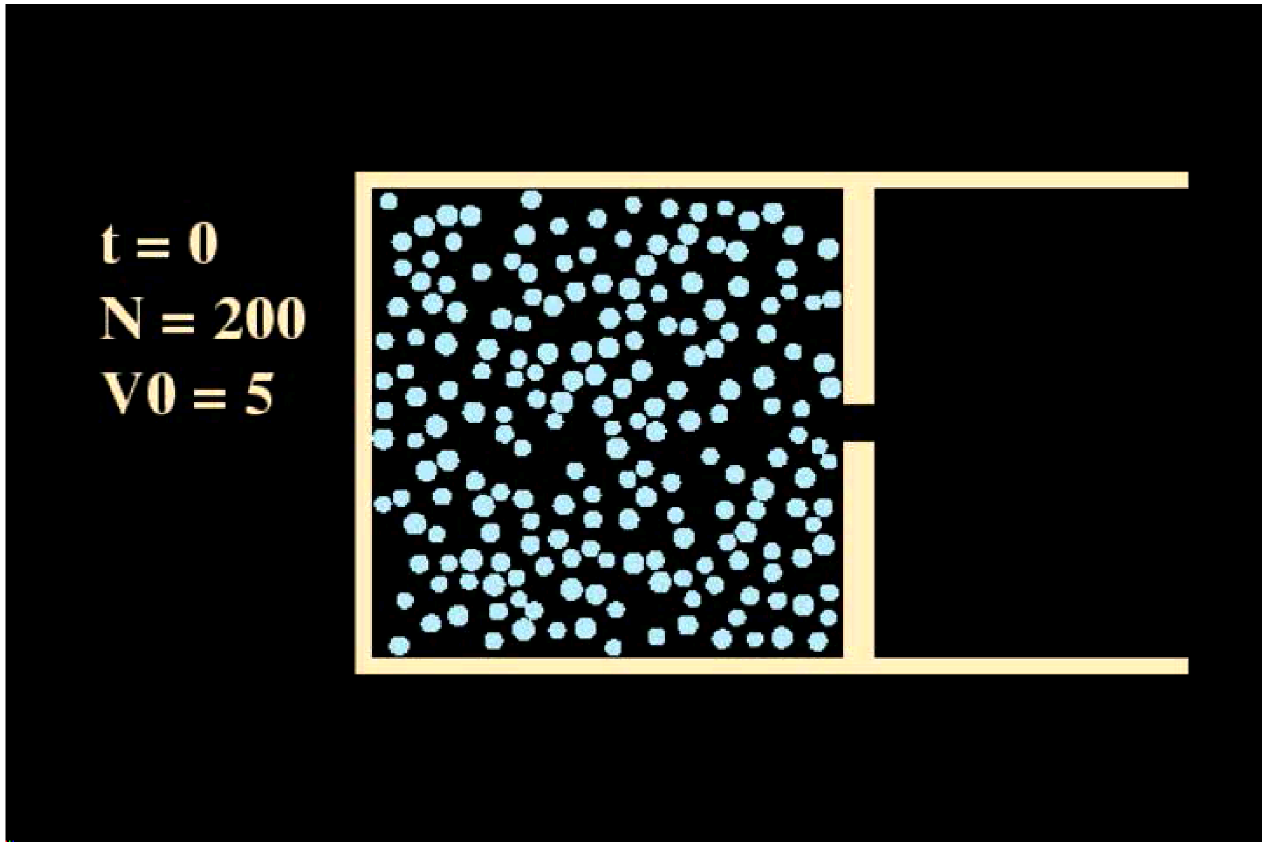


Motion of people in a crowd satisfies Newton's equations of motion with „desired" velocity + specific interaction rules

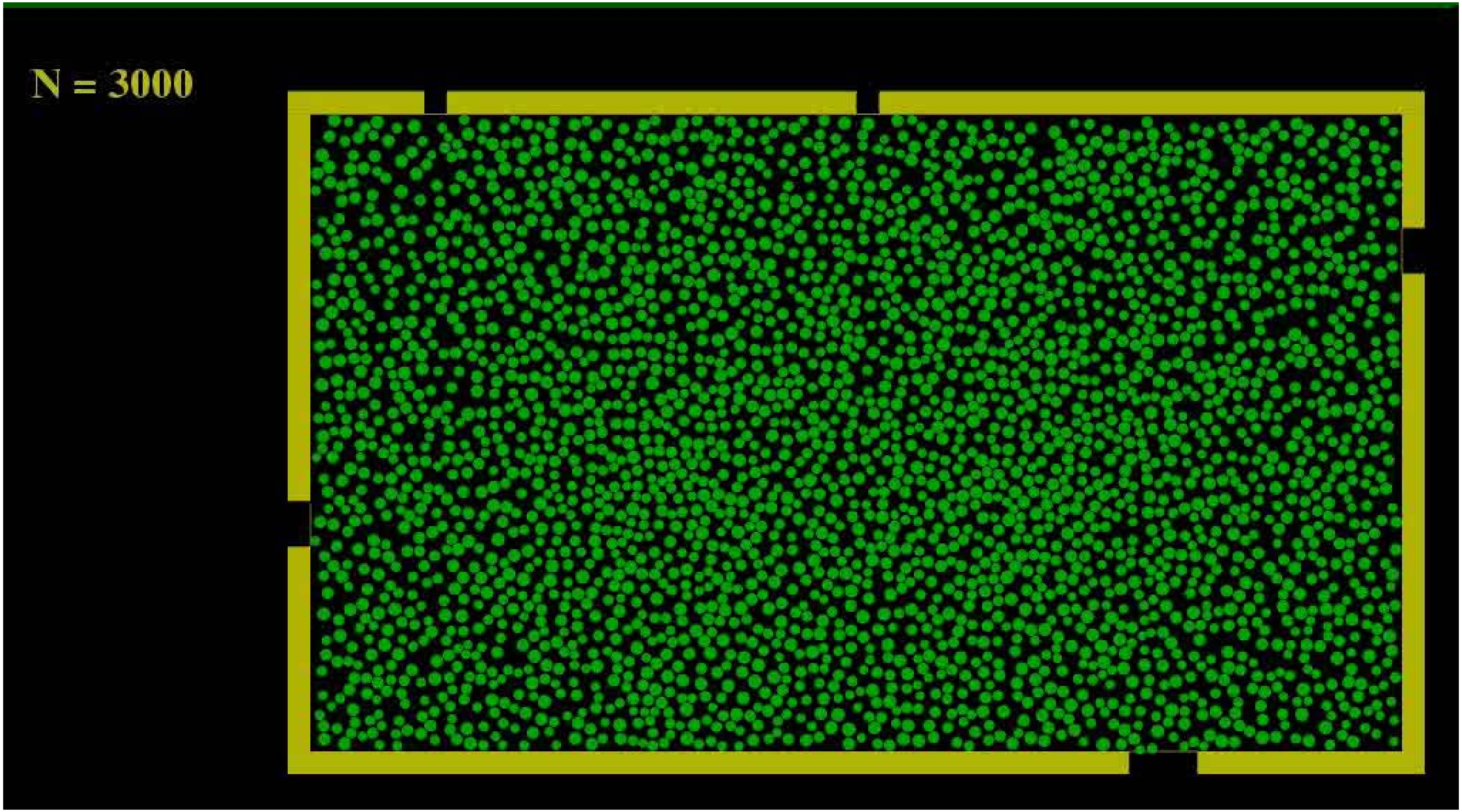
$$m_i \frac{d\vec{v}_i}{dt} = m_i \frac{v_i^0(t)\vec{e}_i^{\,0}(t) - \vec{v}_i(t)}{\tau_i} + \sum_{j \neq i} \vec{f}_{ij} + \vec{f}_{iW} \quad ,$$

$$\vec{f}_{ij} = \left[A_i \exp\left[\left(r_{ij} - d_{ij} \right) / B_i \right] + kg\left(r_{ij} - d_{ij} \right) \right] \vec{n}_{ij} + \kappa g\left(r_{ij} - d_{ij} \right) \Delta v_{ji}^{t} \vec{t}_{ij} \quad ,$$



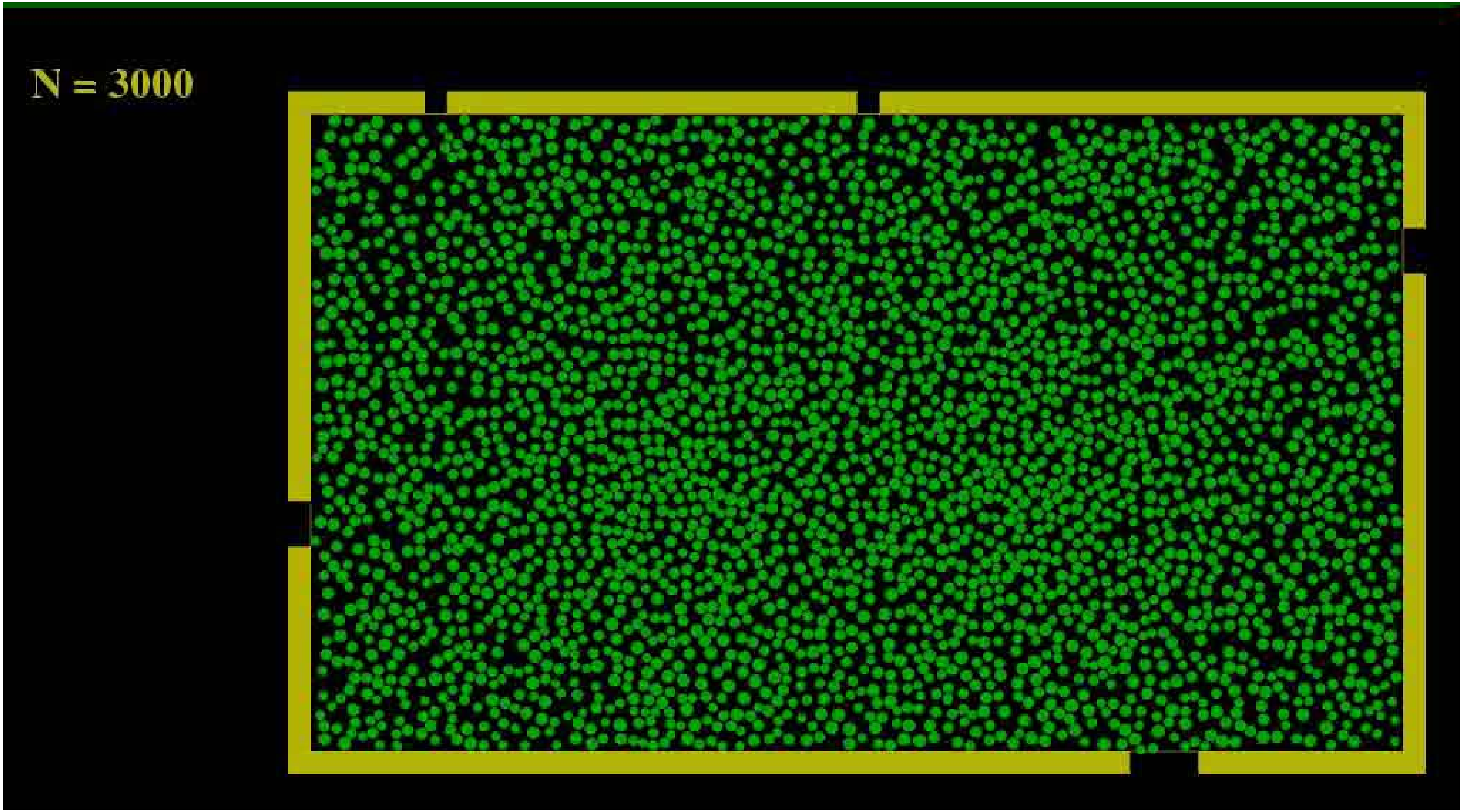


Escape: several doors, patient



Colour codes the level of pressure

Escape: several doors, unpatient



Colour codes the level of pressure

Overall escaping time 2 times shorter

On 7th January, 2020, 40 people died and several hundreds were injured before the planned funeral of a supreme Iranian commander (*the crowd was huge and the funeral had to be postponed*)

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)

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

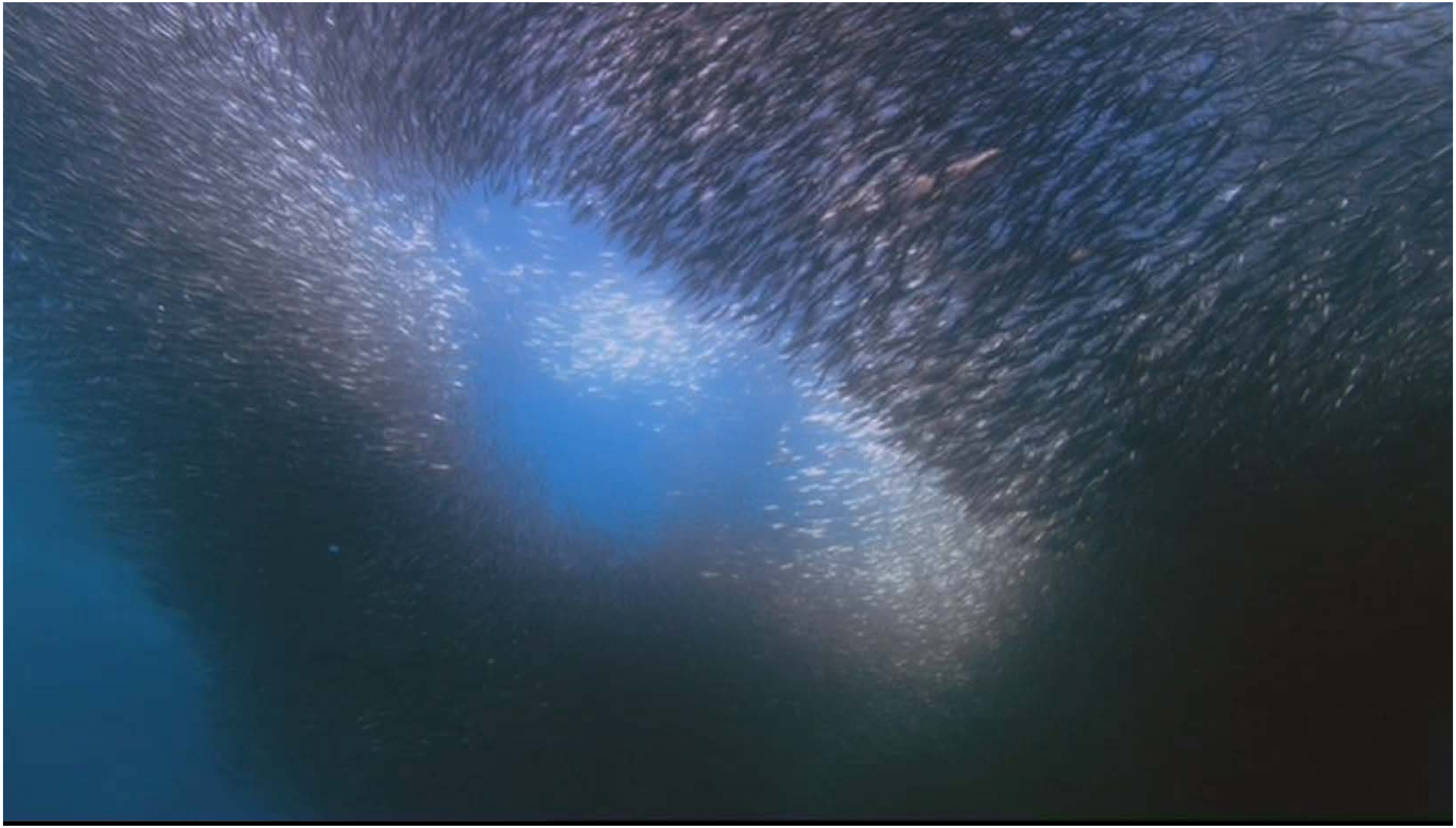
v) *Jamming*

Plus several more exotic phases

PART II

Selected recent applications

- The physics of group hunting (realistic simulation)
- Hiearachical leadership/dominance in pigeon flocks
- Flocking drones (quadcopters)



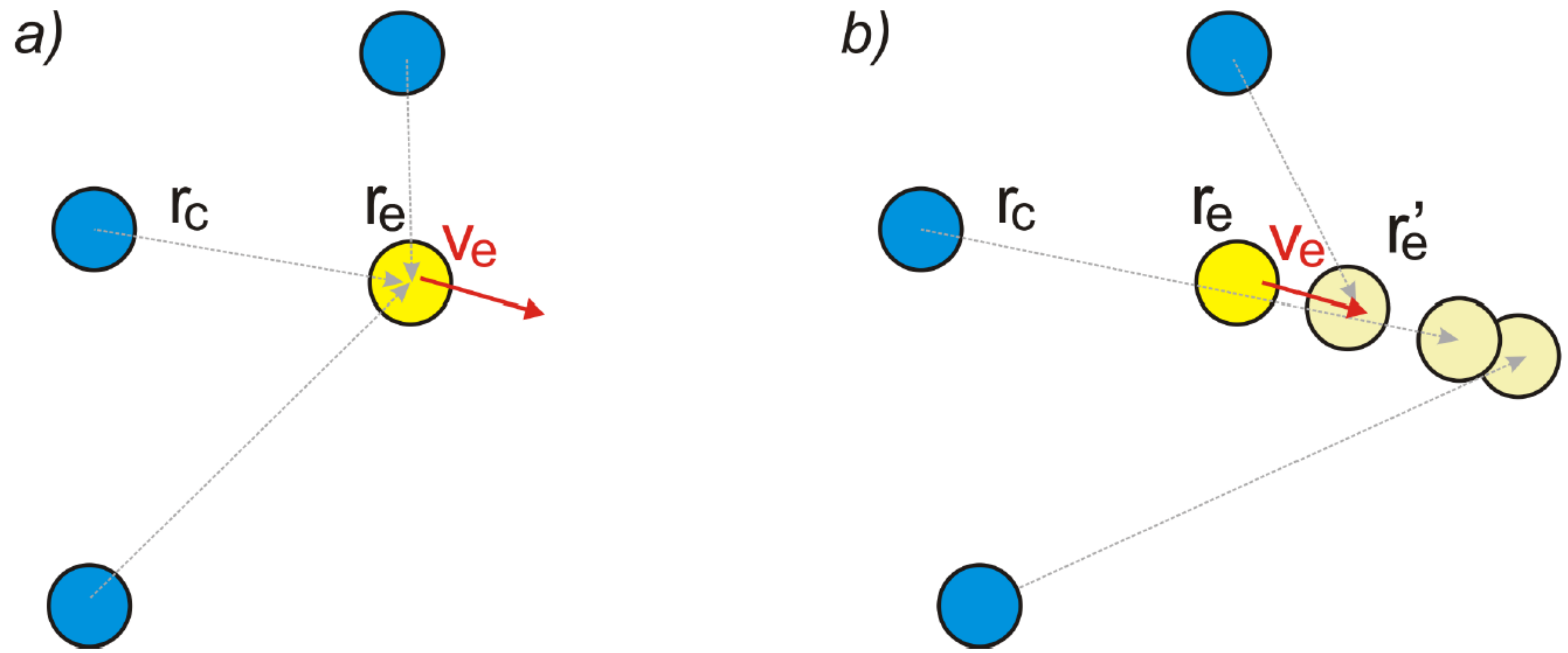
Several slower predators chase faster prey(s)
The case of collective hunting

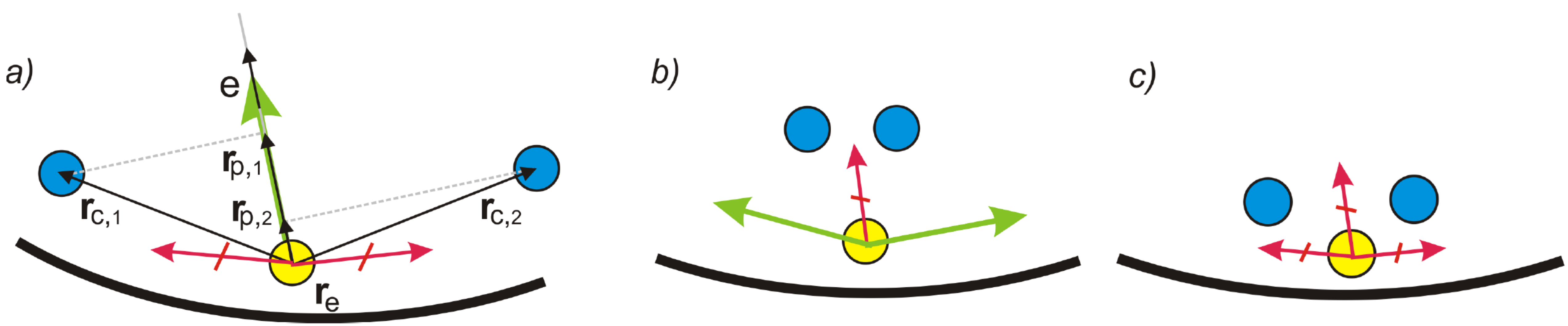
A complex set of equations, taking into account:

- **Instantaneous velocities**
- **Collision avoidance**
- **Predicted positions**
- **Delayed reactions**
- **Perturbations**
- **Boundary conditions**
- **Escaping tactics („zig-zag" running)**
- **Otimizing the parameters**
- **Etc.**

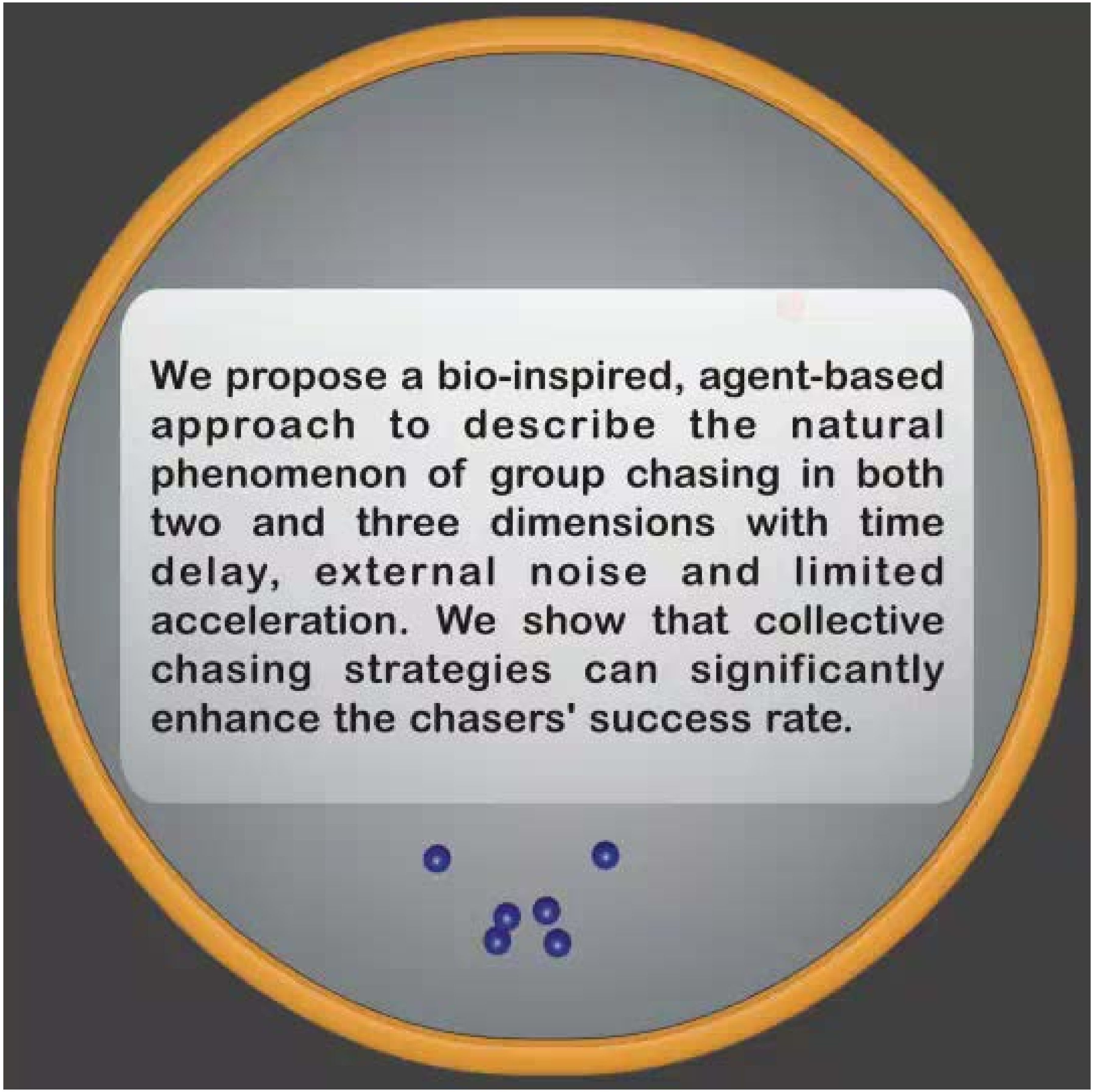
Example: prediction

of chaser





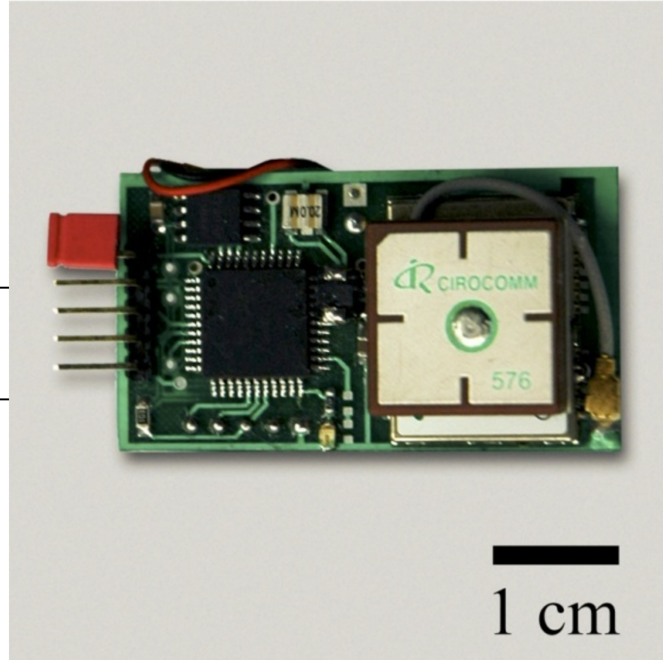
of escaper


We propose a bio-inspired, agent-based approach to describe the natural phenomenon of group chasing in both two and three dimensions with time delay, external noise and limited acceleration. We show that collective chasing strategies can significantly enhance the chasers' success rate.

Hierarchical group dynamics in pigeon flocks

A group of homing pigeons: paradigm of making collective decisions about choosing the right answer

Studies of pigeon flocks have a history

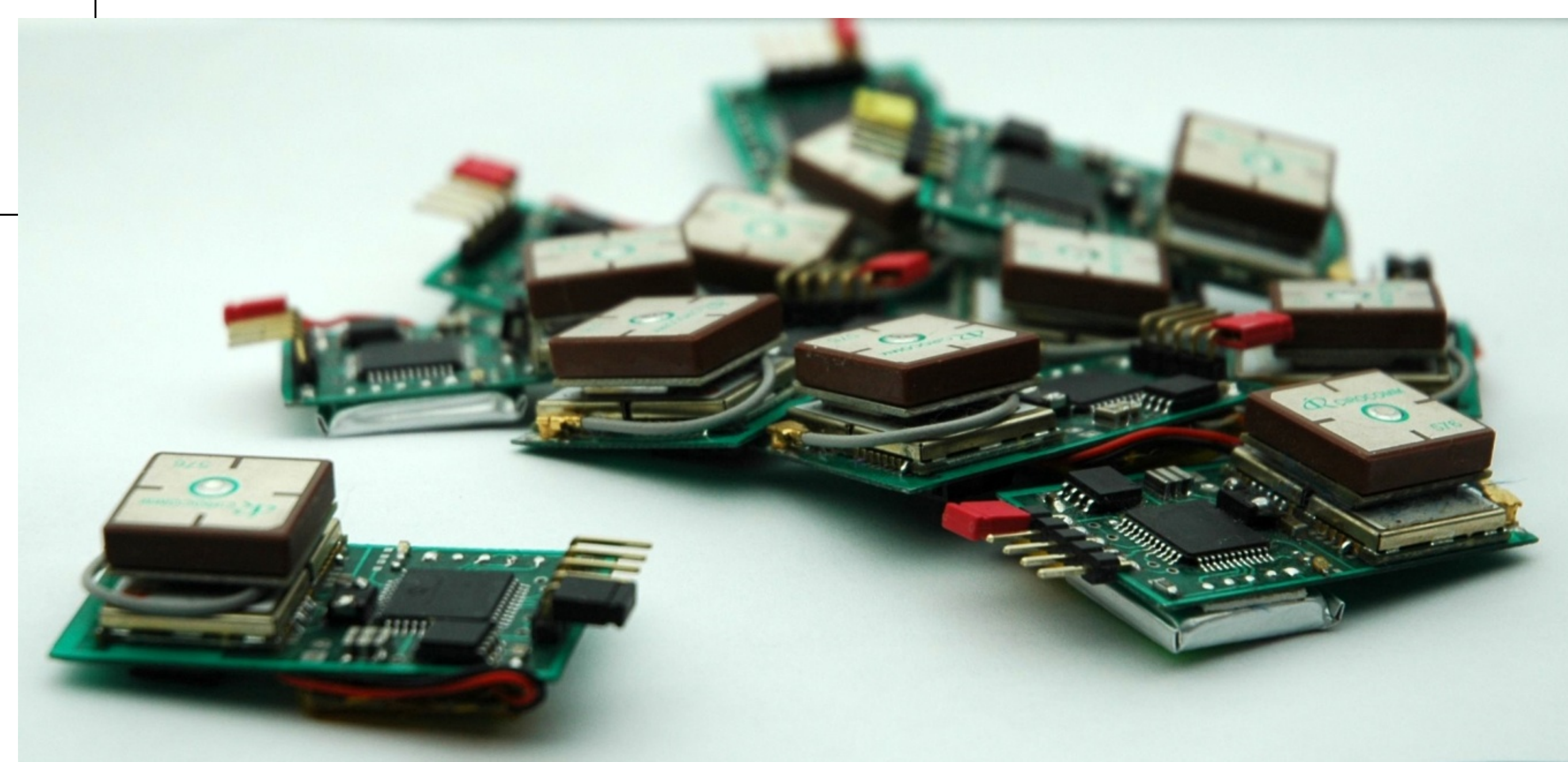


GPS module: Switzerland, U-blox, (17 X 22 mm, 2,1g), 5Hz (2,5 Hz)

antenna, Ireland, Taoglas

accumulator : lipoly 2,9g (100mAh)

Weight: 13g



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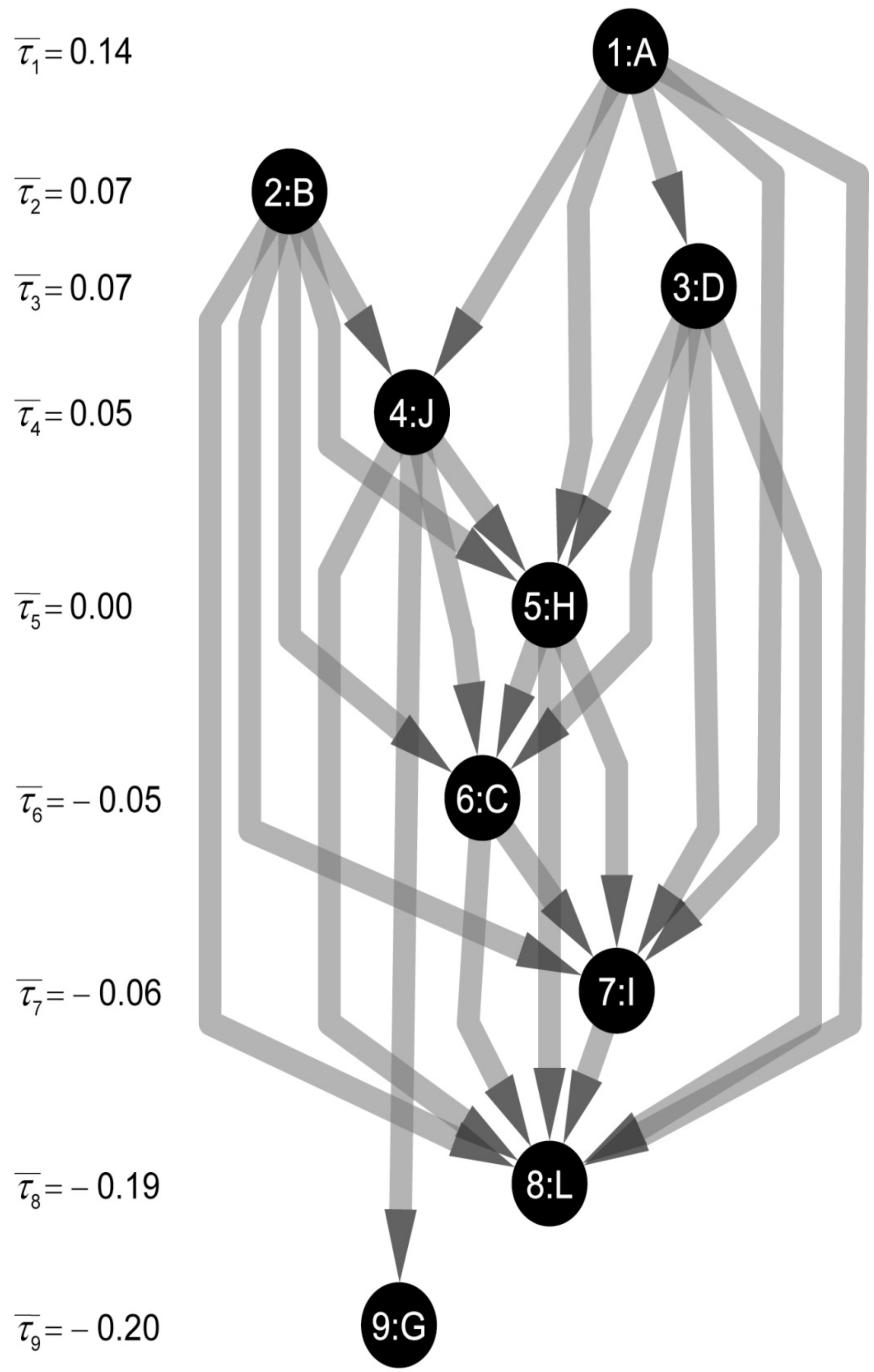


$\overline{\tau}_1 = 0.14$
$\overline{\tau}_2 = 0.07$
$\overline{\tau}_3 = 0.07$
$\overline{\tau}_4 = 0.05$
$\overline{\tau}_5 = 0.00$
$\overline{\tau}_6 = -0.05$
$\overline{\tau}_7 = -0.06$
$\overline{\tau}_8 = -0.19$
$\overline{\tau}_9 = -0.20$
1:A
2:B
3:D
4:J
5:H
6:C
7:I
8:L
9:G

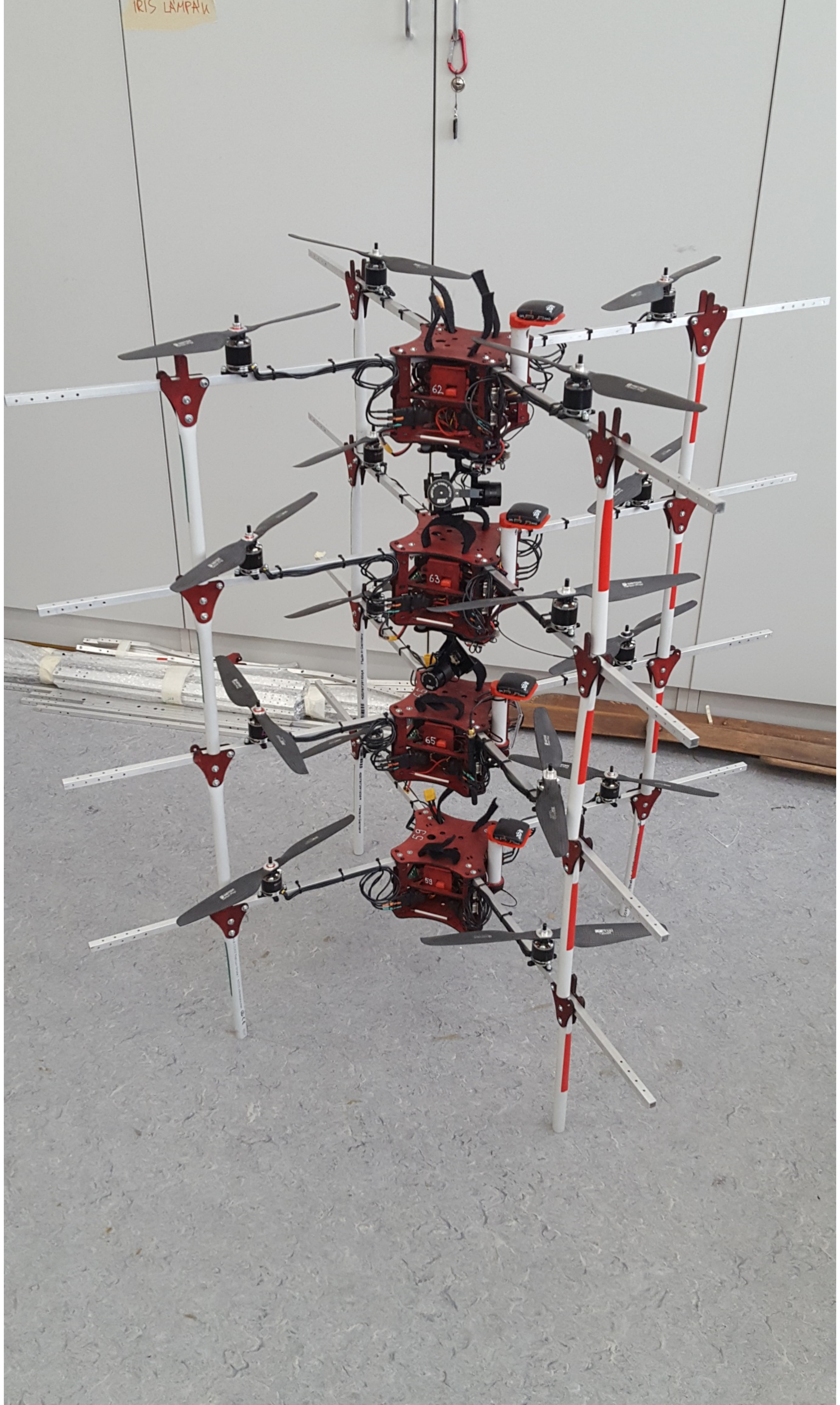
B

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

Technology and life are intimately related...

Robethology

The collective behaviour of autonomous quadcopters (NO central computer, communication only between the robots)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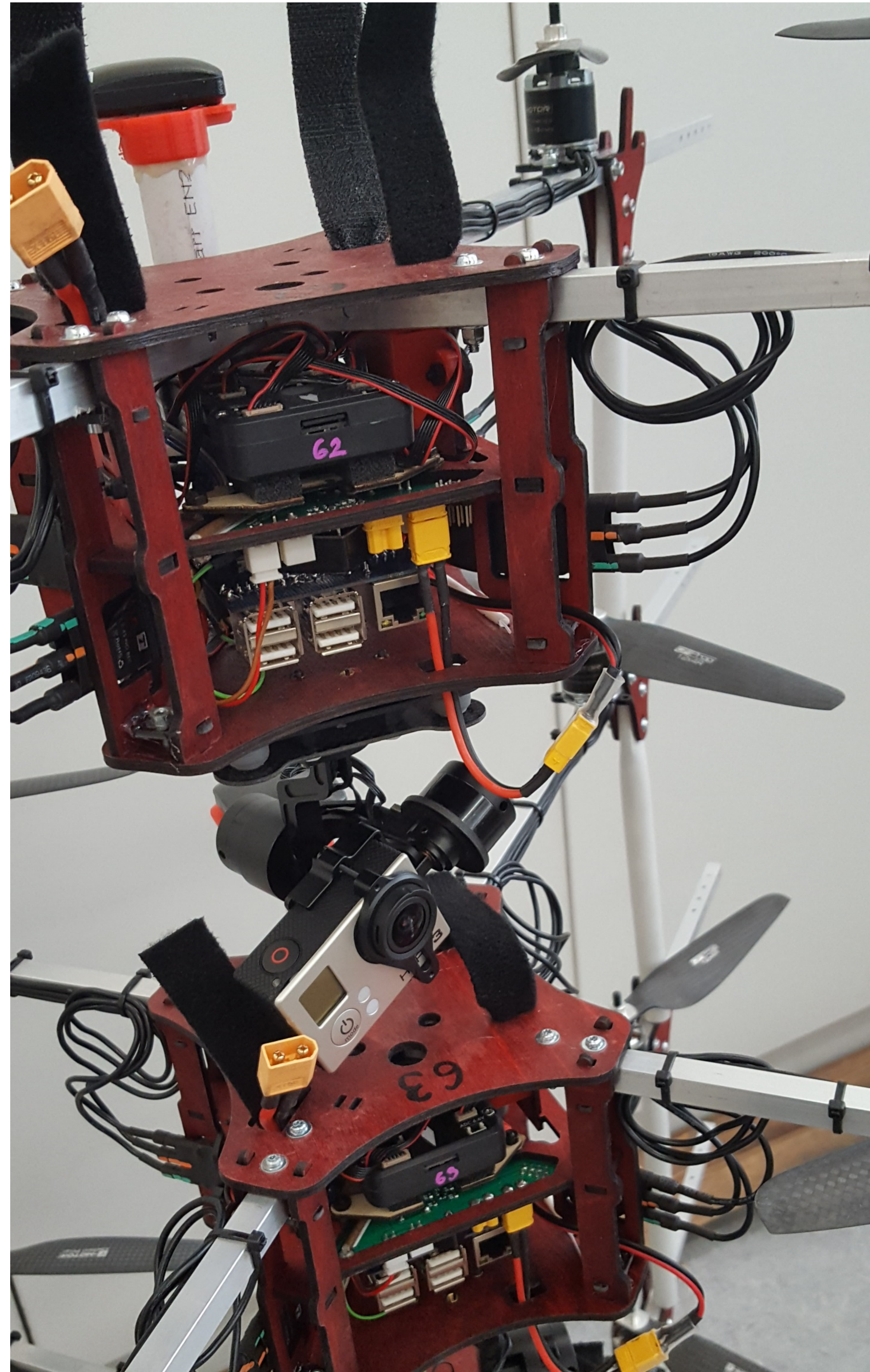
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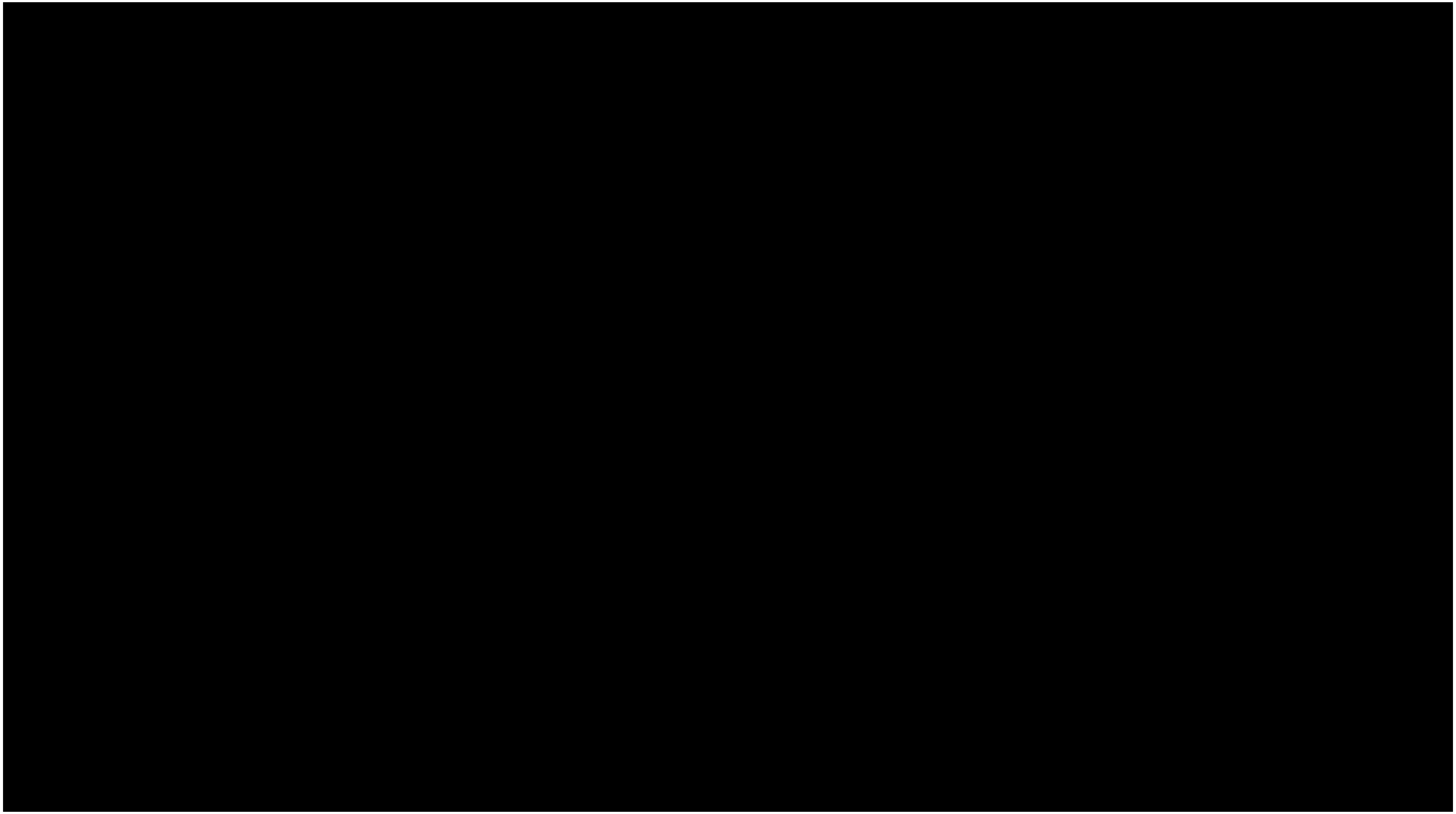
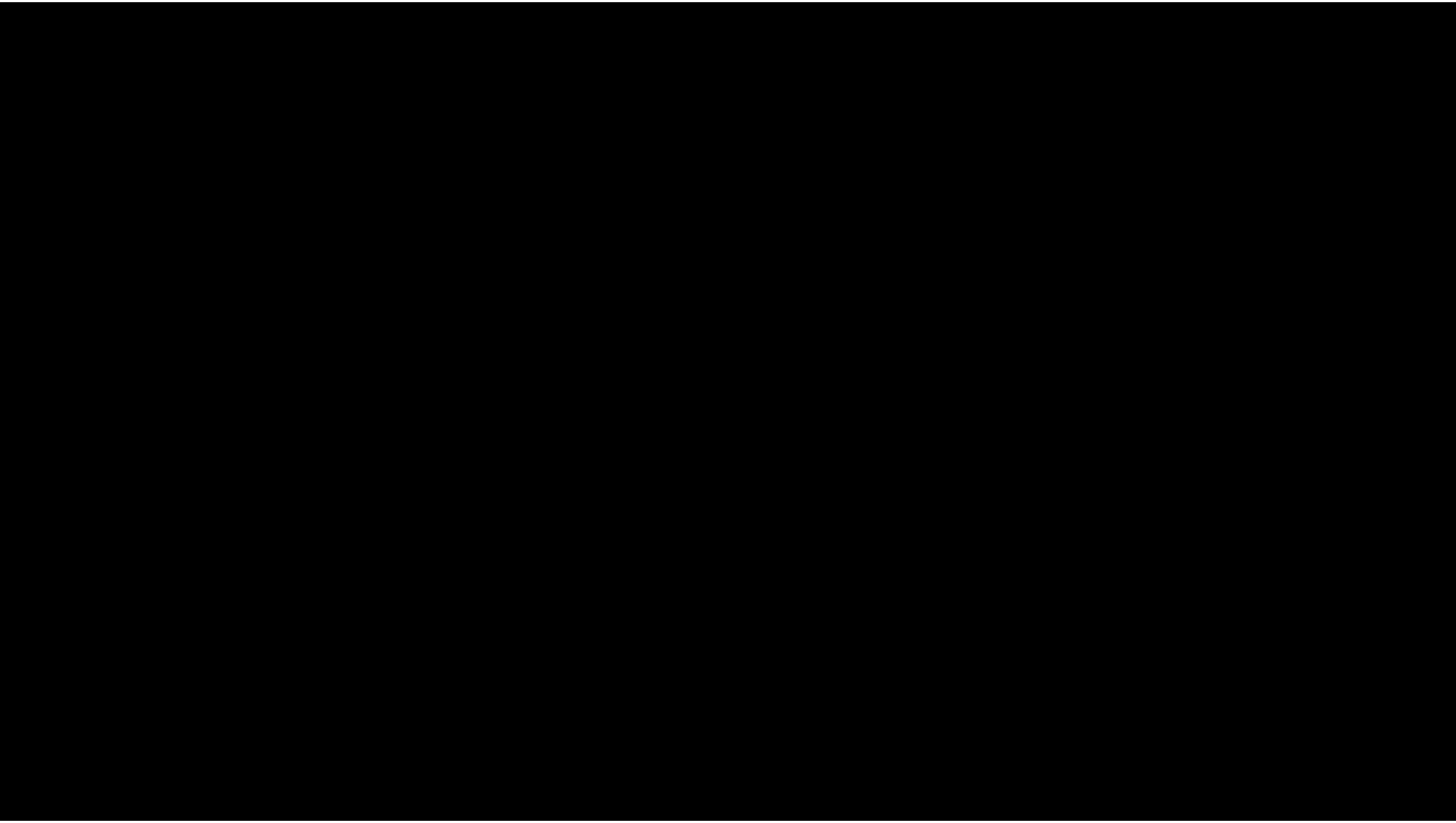
Interaction of a dancer with a flock of <u>autonomous</u> drones

(equations in the spirit of the chase and escape project)



Autonomuous chasing by drones
(Viceland, Canada, Teaser, Dec, 2016)

Collective target tracking in the dark…



Long exposure fun photos

Many thanks are due to my collaborators

Principal collaborators:

Zsuzsa Ákos
Kunal Bhattacharya
Dóra Biró (Oxford)
Máté Nagy
Tamás Nepusz
Benj Pettit (Oxford)
Gergely Somorjai
Gábor Vásárhelyi
+ many more

Support: Hungarian Science Foundation (OTKA)
EU FP6 Starflag project
EU ERC COLLMOT project

Thank you for your attention


Thank you for your attention!
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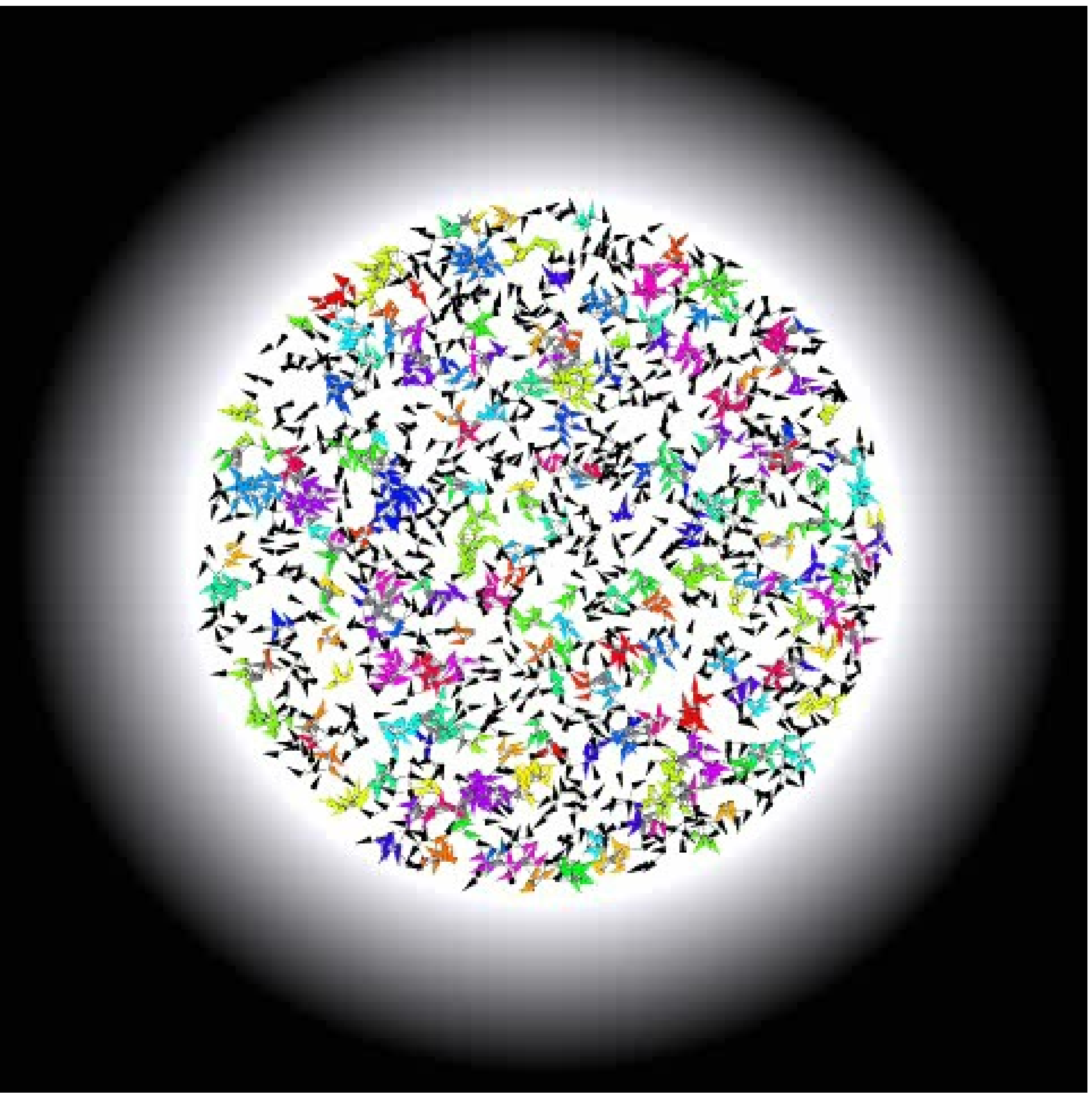
Dynamics of *k*-clique clusters

Two nodes belong to the same cluster if there is connected path of neighbouring *k*-cliques (overlapping cluster analysis of the underlying graph)

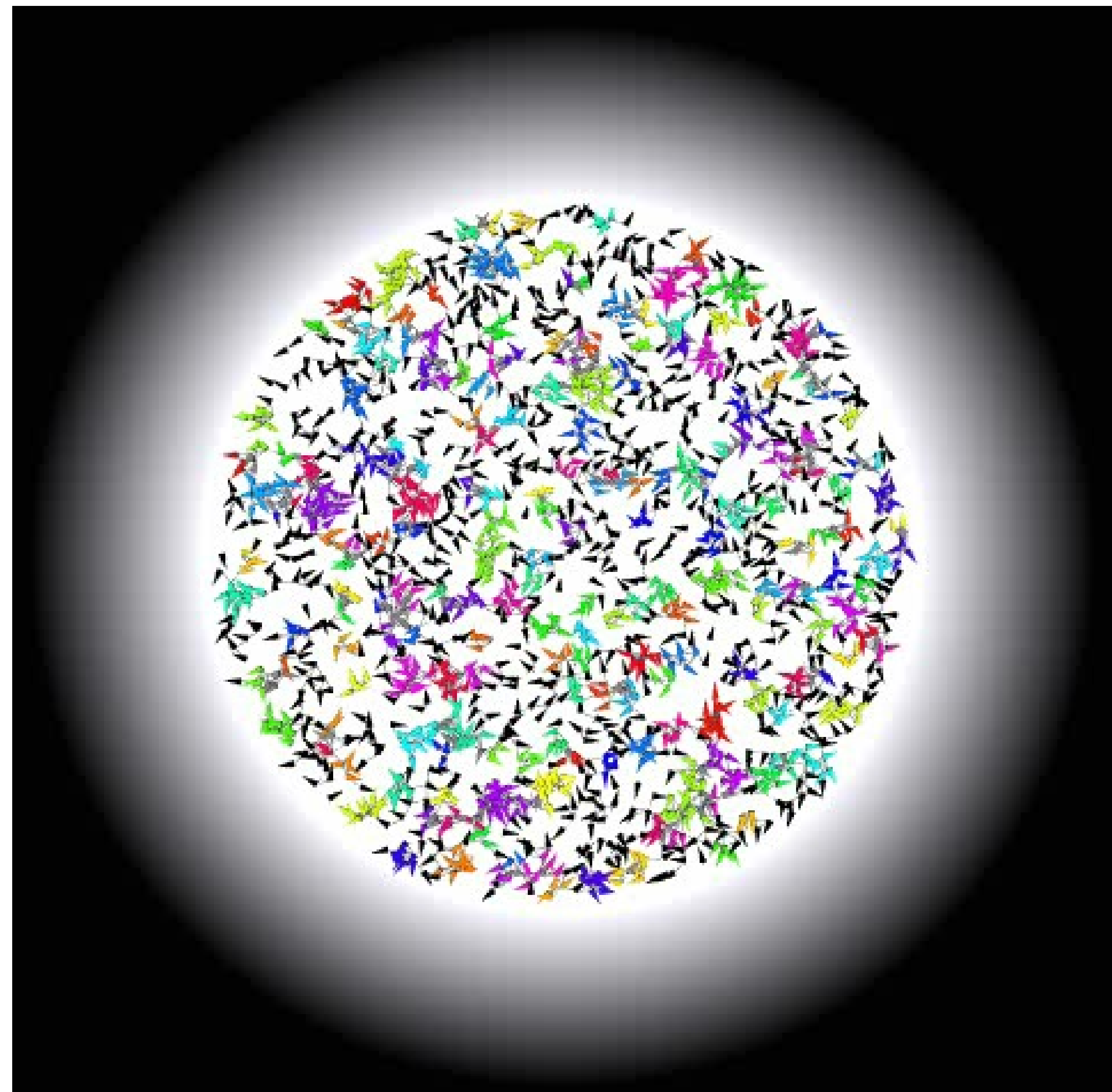
Here: $k = 4$

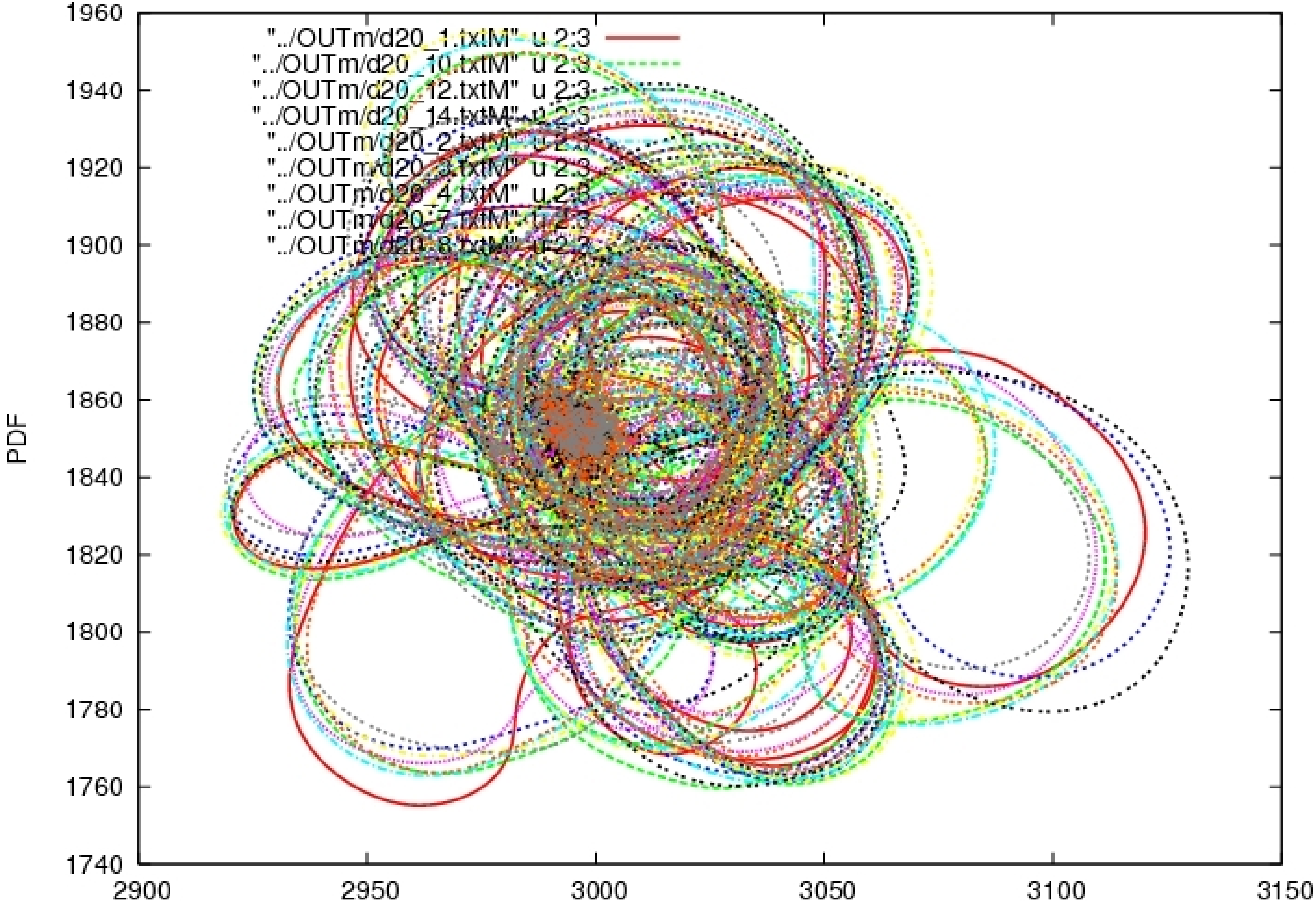
Method after Palla, Barabasi and T.V, *Nature*, 2007

□= 0.4



□= 0.3





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