CNR

Institute for Complex Systems

Collective change of state and transport of information in biological groups

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Rome, FloMat 2015

Collective behaviour in animal groups

movie by C. Carere - Starflag

movie by S. Melillo, SWARM

Flocks

Global order
Scale free correlations - Collective turns

Pnas 105 (2008), Pnas 107 (2010), Nature Phys 10 (2014), Jstat 2015

Swarms

No global order
Correlations – quasi critical behavior

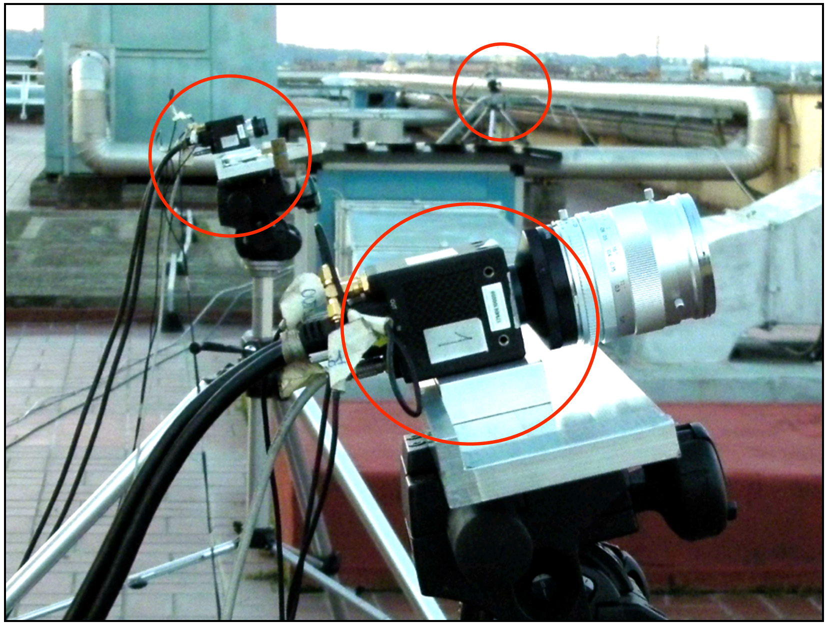
Plos Comp. Biol 10 (2014) . , Phys Rev Lett 113 (2014)

Collective Response

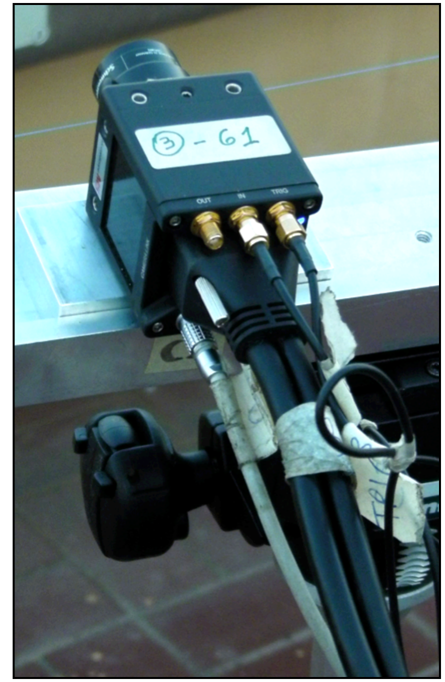
collective turns in flocks of birds

quick collective change of state
induced or spontaneous
fast mechanism for information propagation

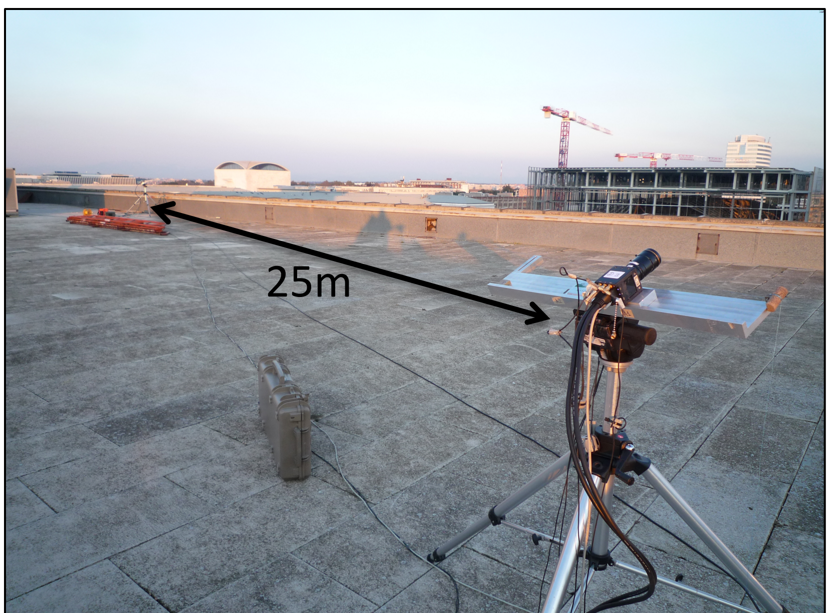
stereo experiments



trifocal system

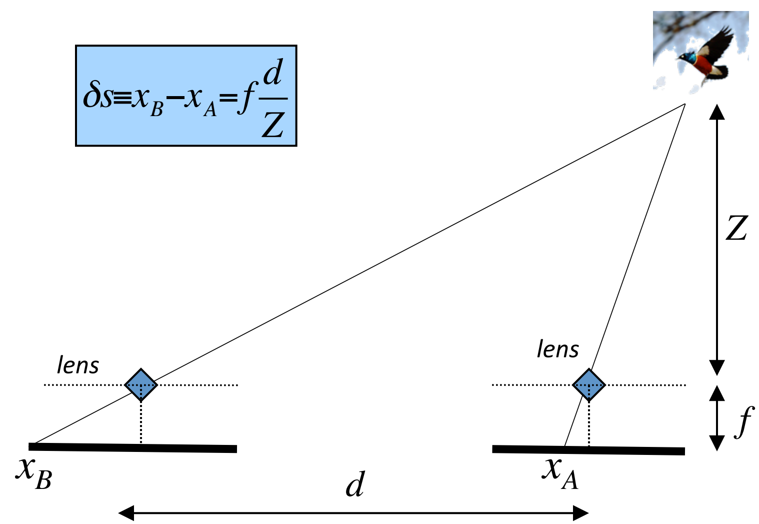


- IDT-Red Lake M5
- 4 Megapixel
- monochromatic
- 170 fps
- Schneider lenses



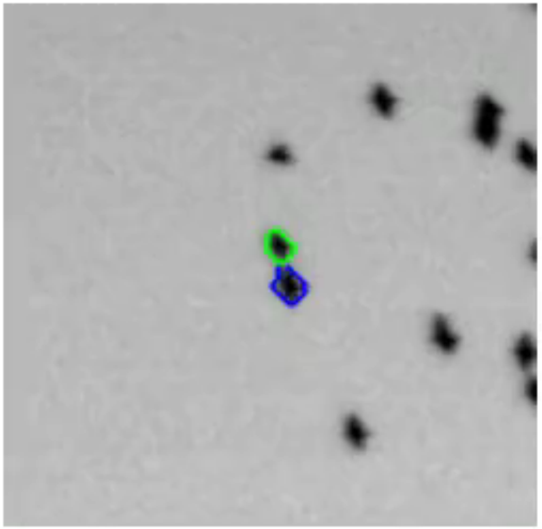
Stereometry

$$\delta s \equiv x_B - x_A = f\frac{d}{Z}$$

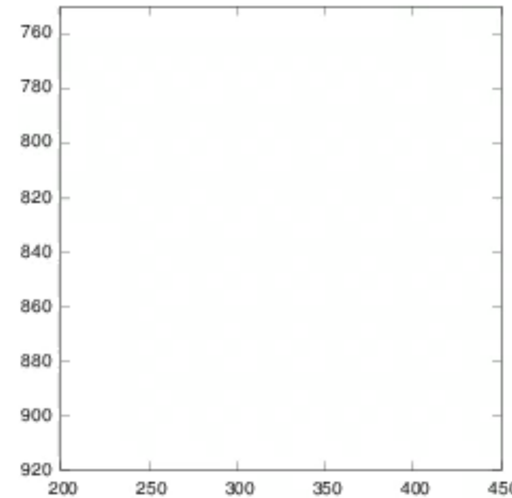


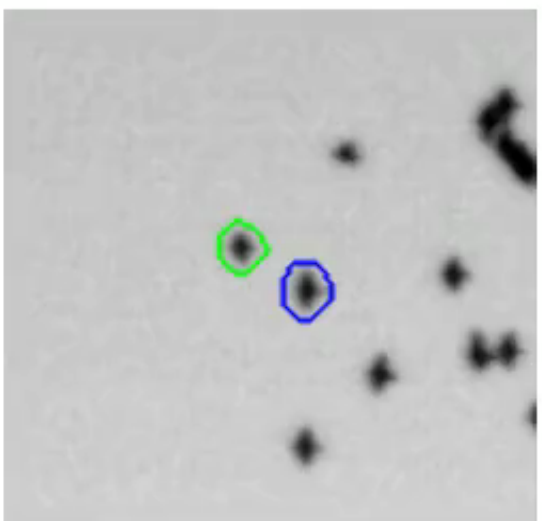
the real enemy: blobs

frame 1

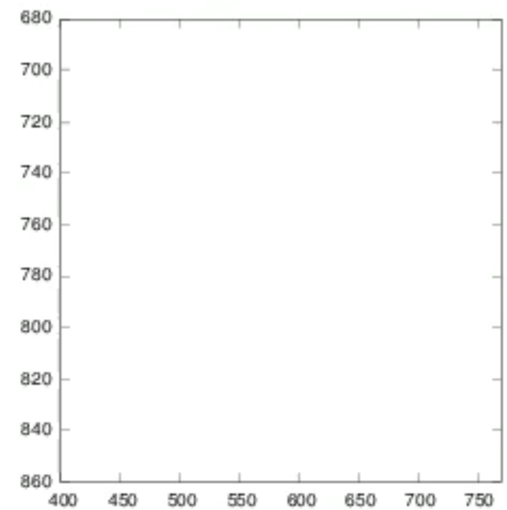


right camera

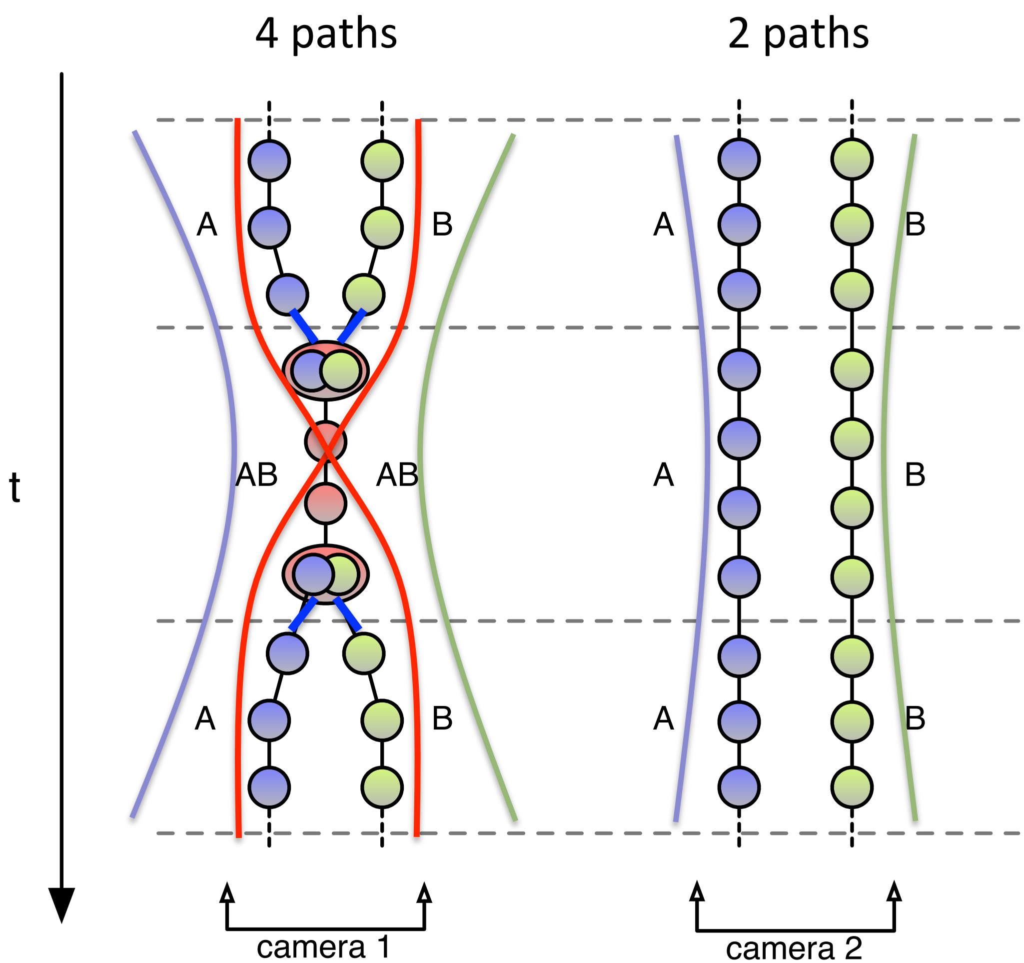




left camera



create all paths

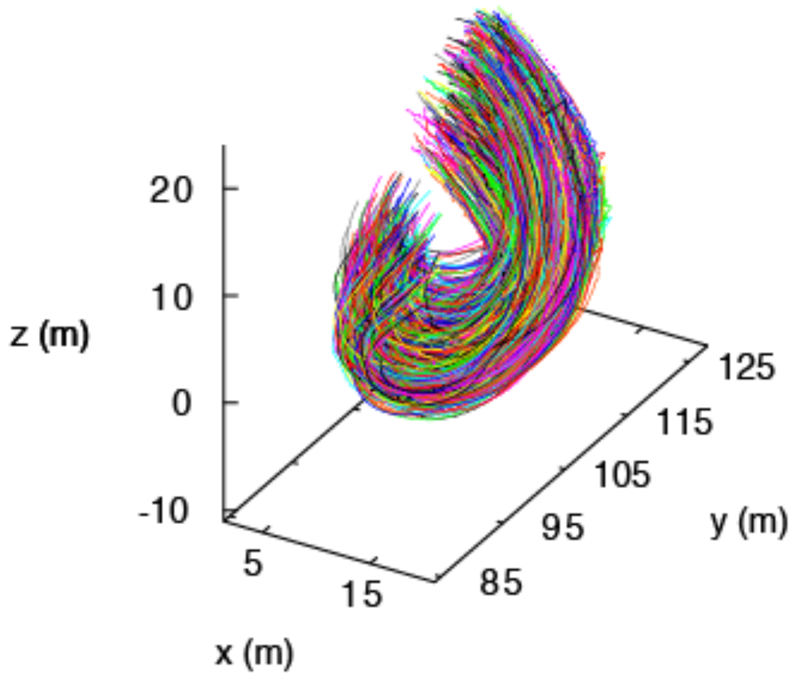


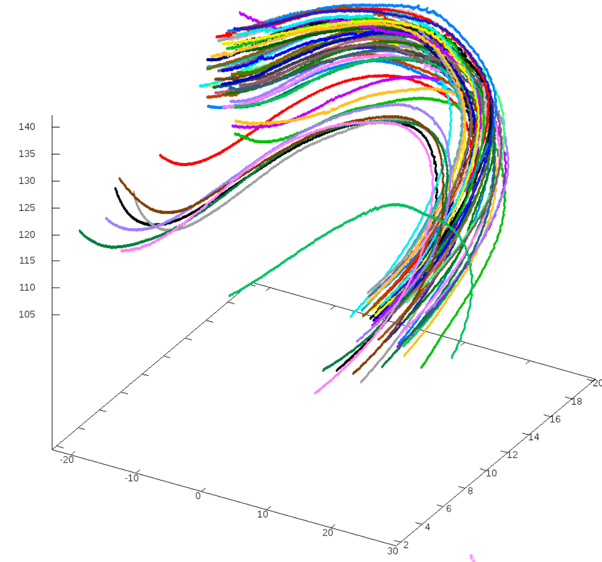
score matrix

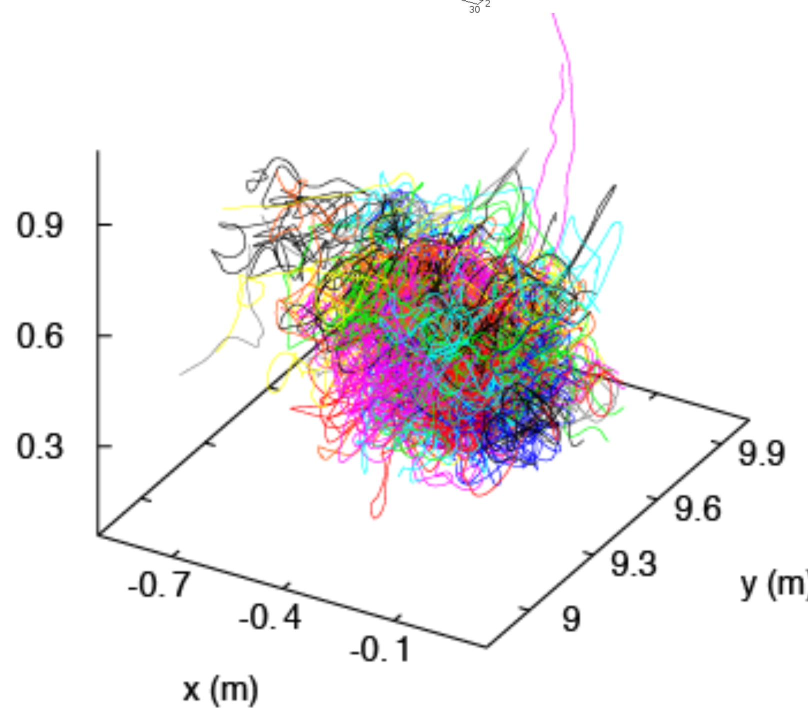
	A	B
AA	10	4
AB	7	7
BA	7	7
BB	4	10

2 real birds

global multi-path recursive algorithm







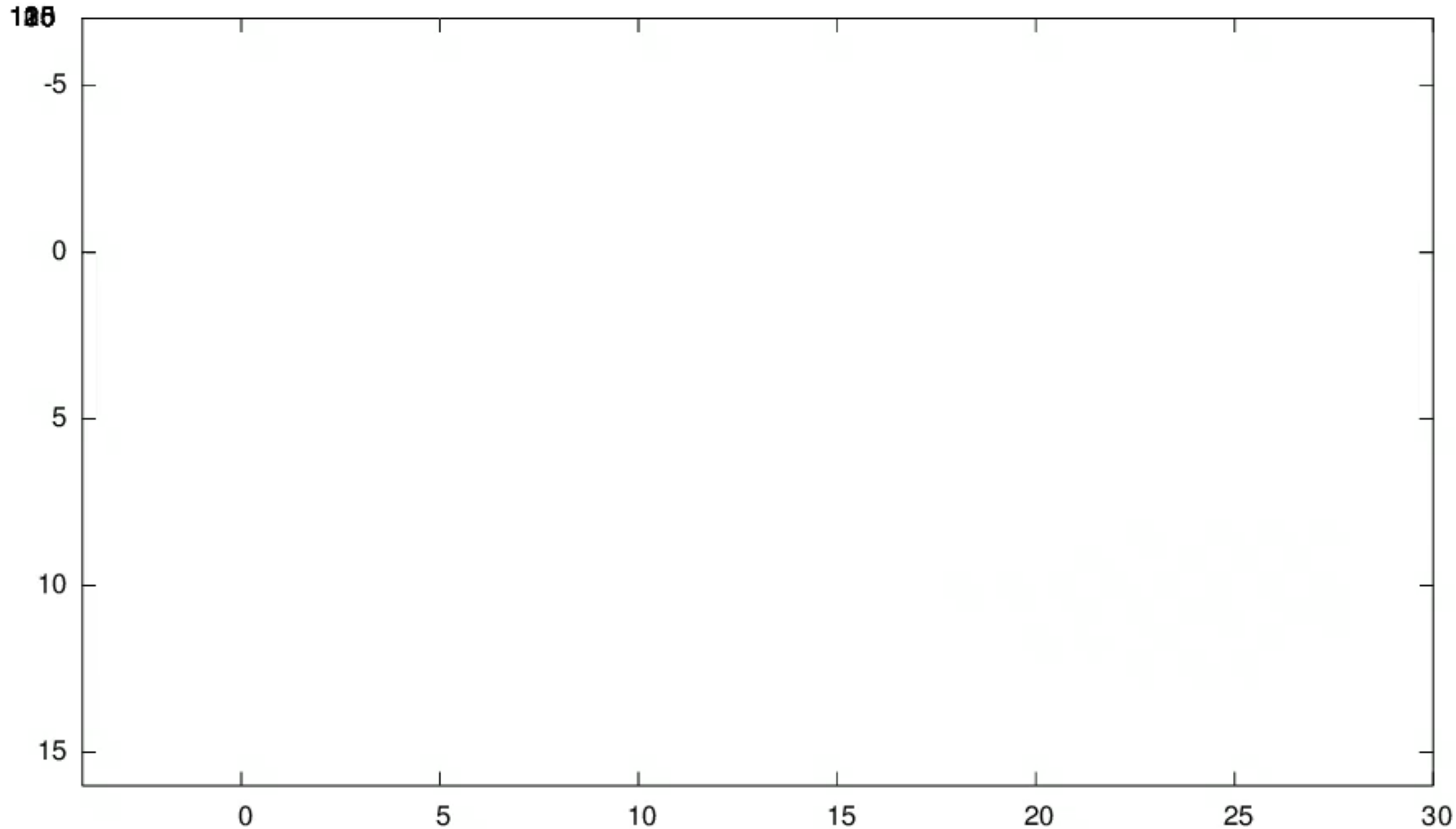
Attanasi et al, IEEE TPAMI (2015)

basic questions about collective turns

- what is the origin of the turn?
  - spatially localized or extended?
  - endogenous or exogenous?

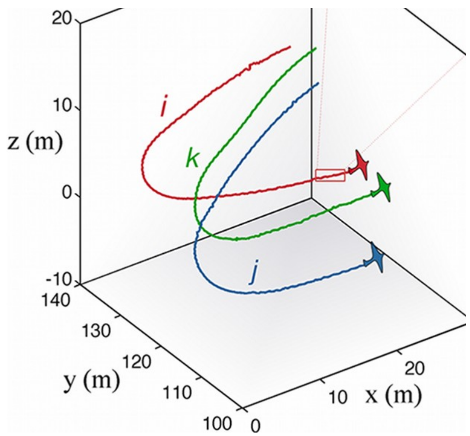
- how does the information spread across the flock?
  - what kind of propagation (dispersion) law?
  - damped or undamped propagation?

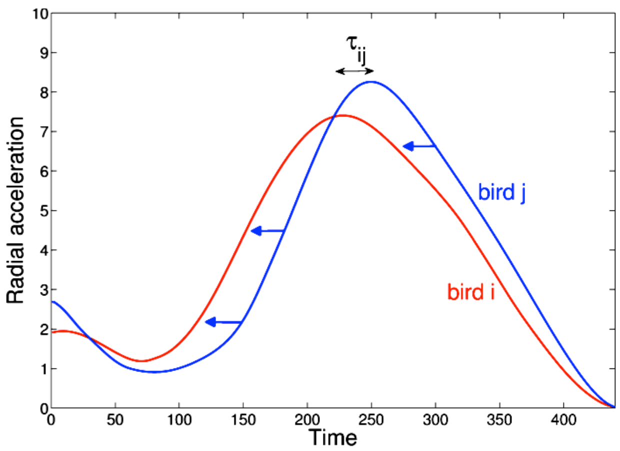
effective decision-making crucially depends on these last two issues

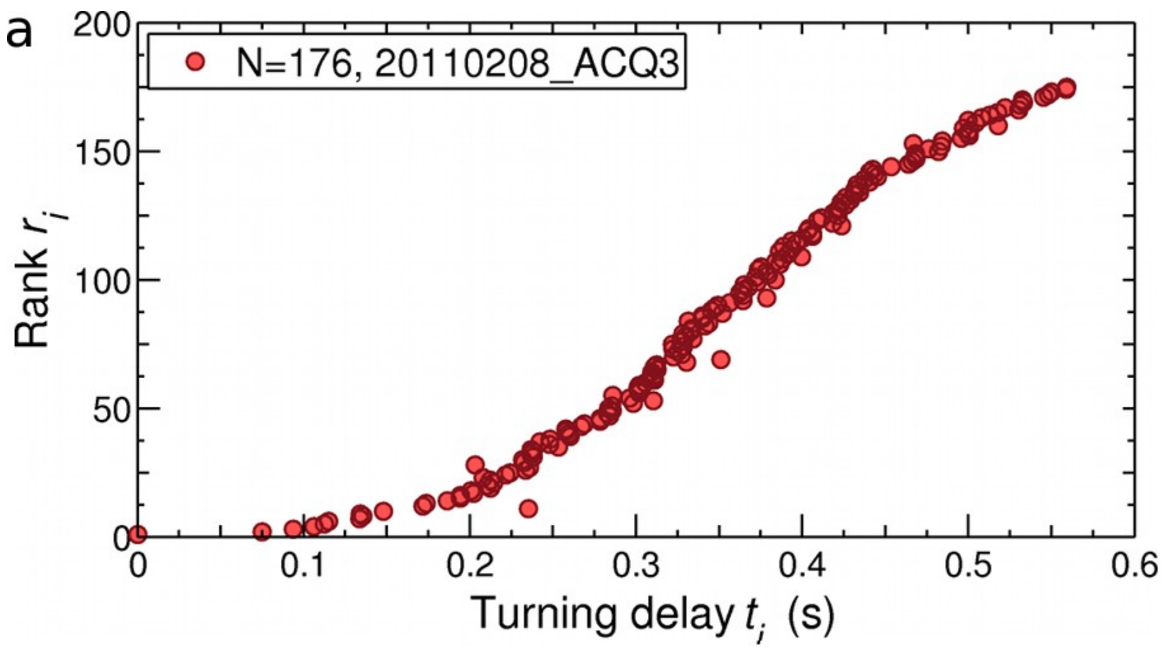


-5
0
5
10
15
0
5
10
15
20
25
30

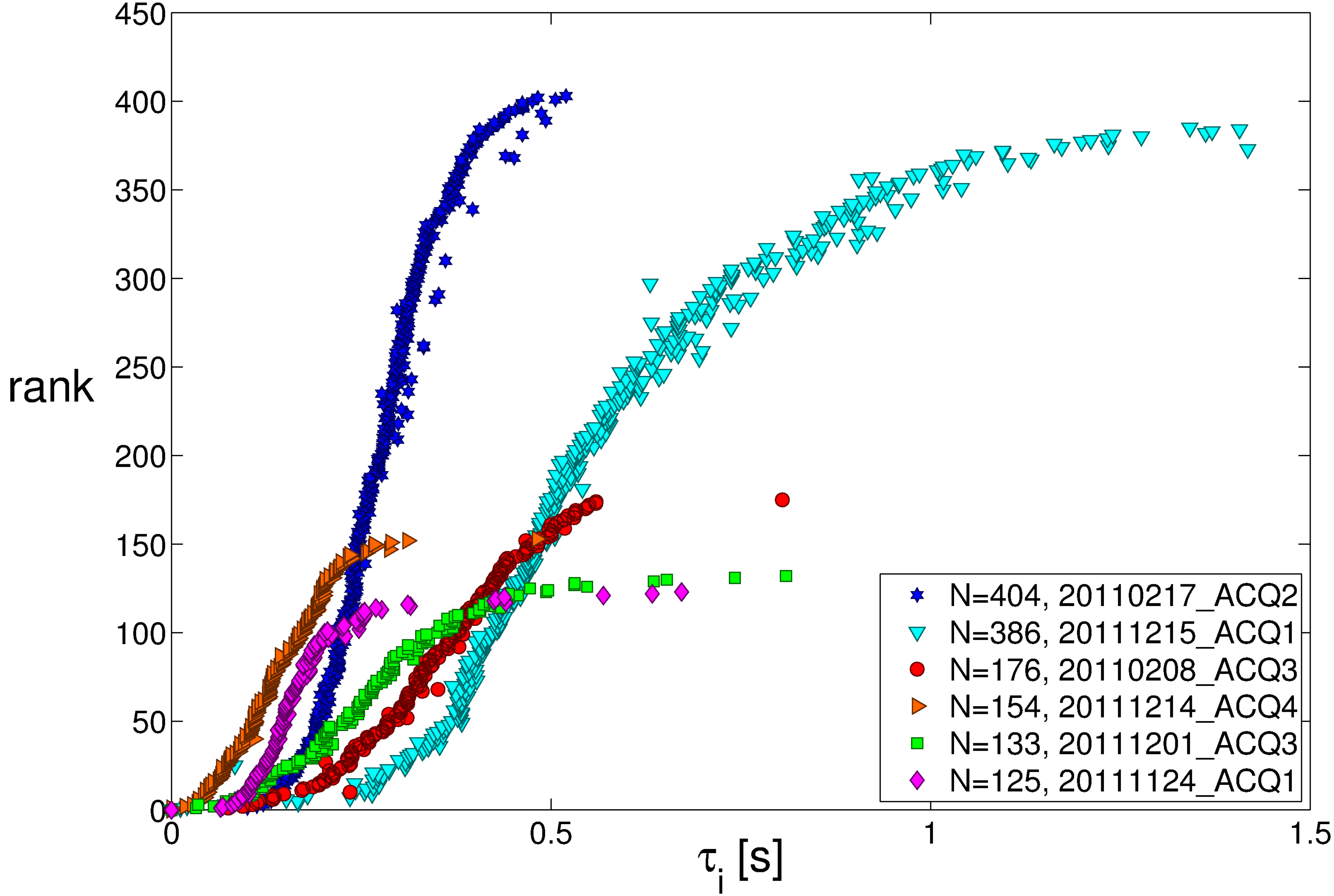
mutual delay τ_{ij} and ranking



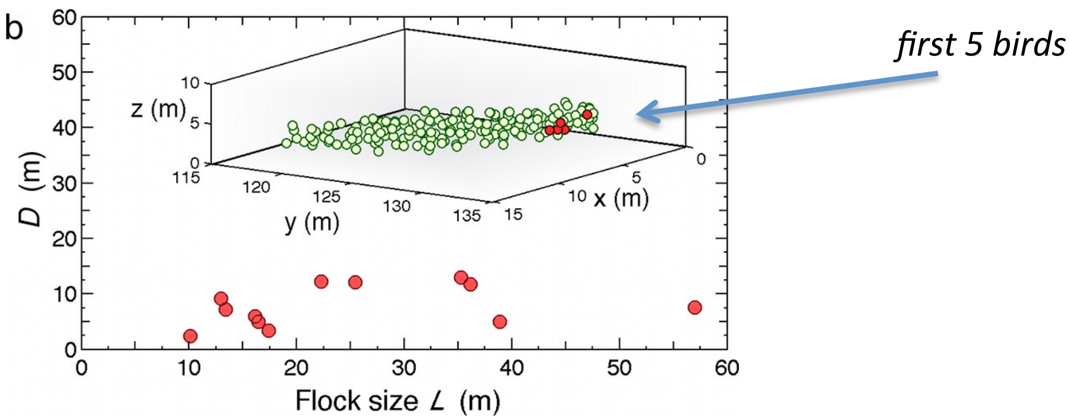


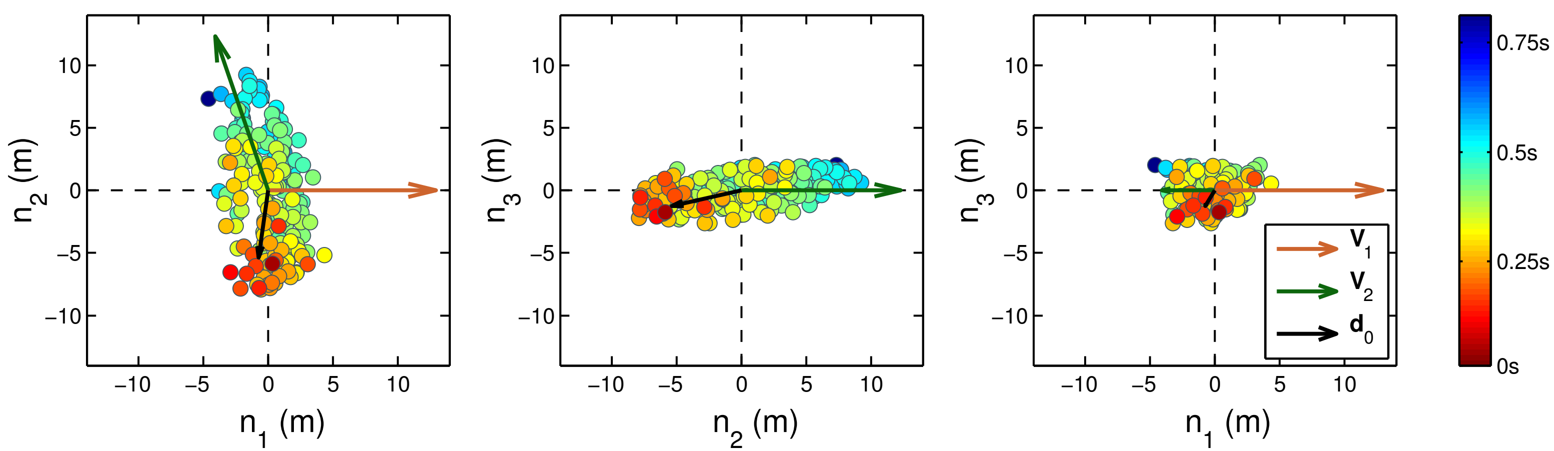


ranking curve



localized start of the turn



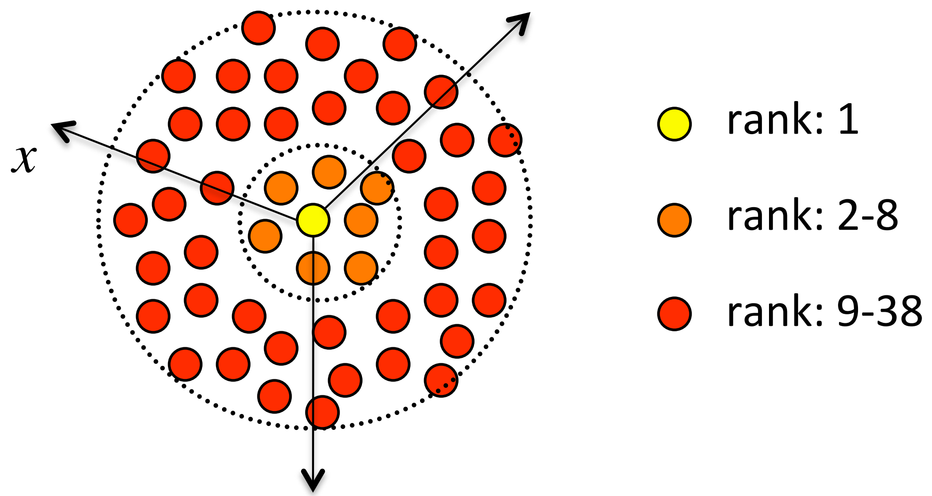


the turn starts localized at the edges and then it propagates across the flock

ranking and propagation

if the turn starts localized then:

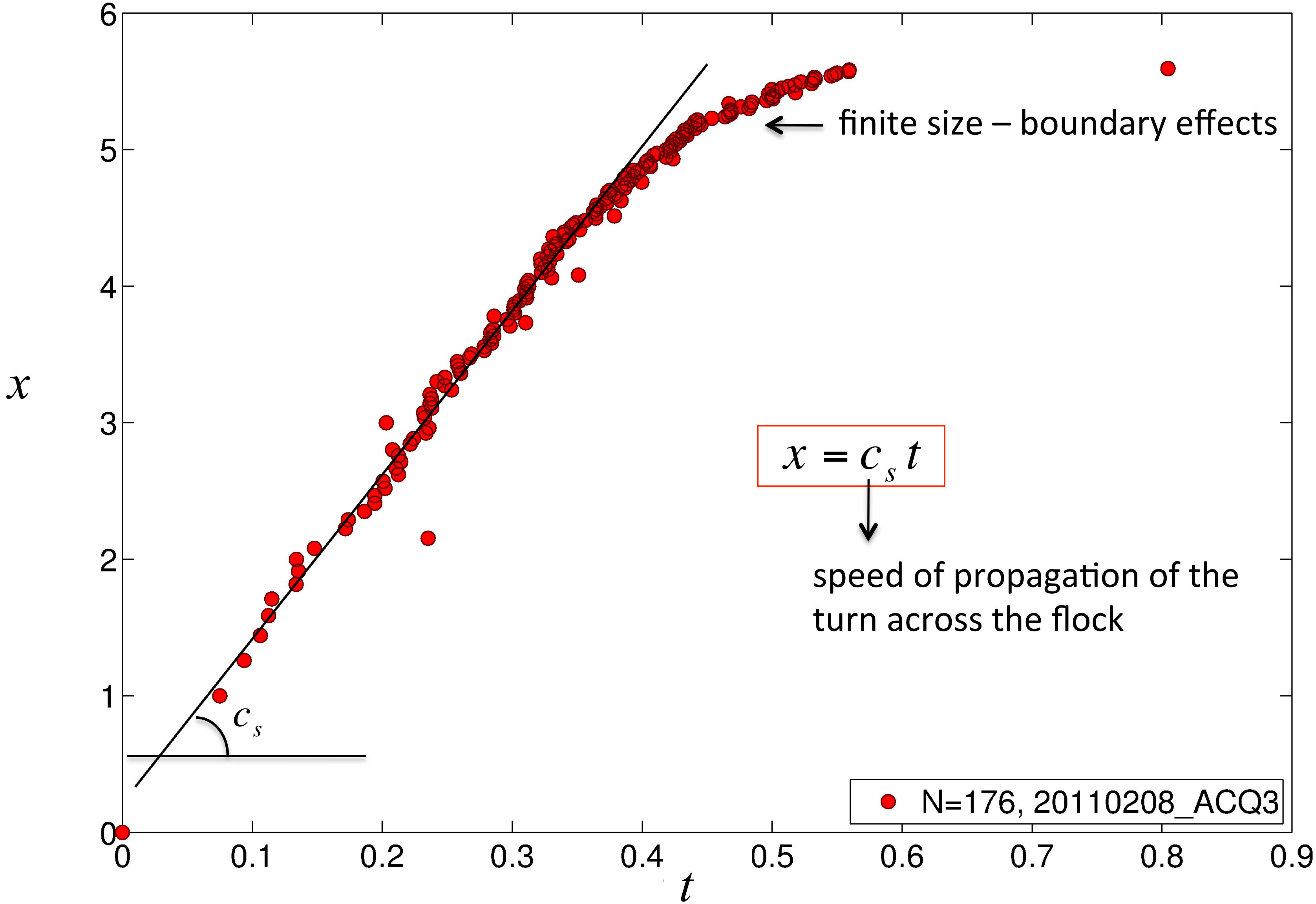
rank = (density ρ) x (space traveled by the turn x)^3



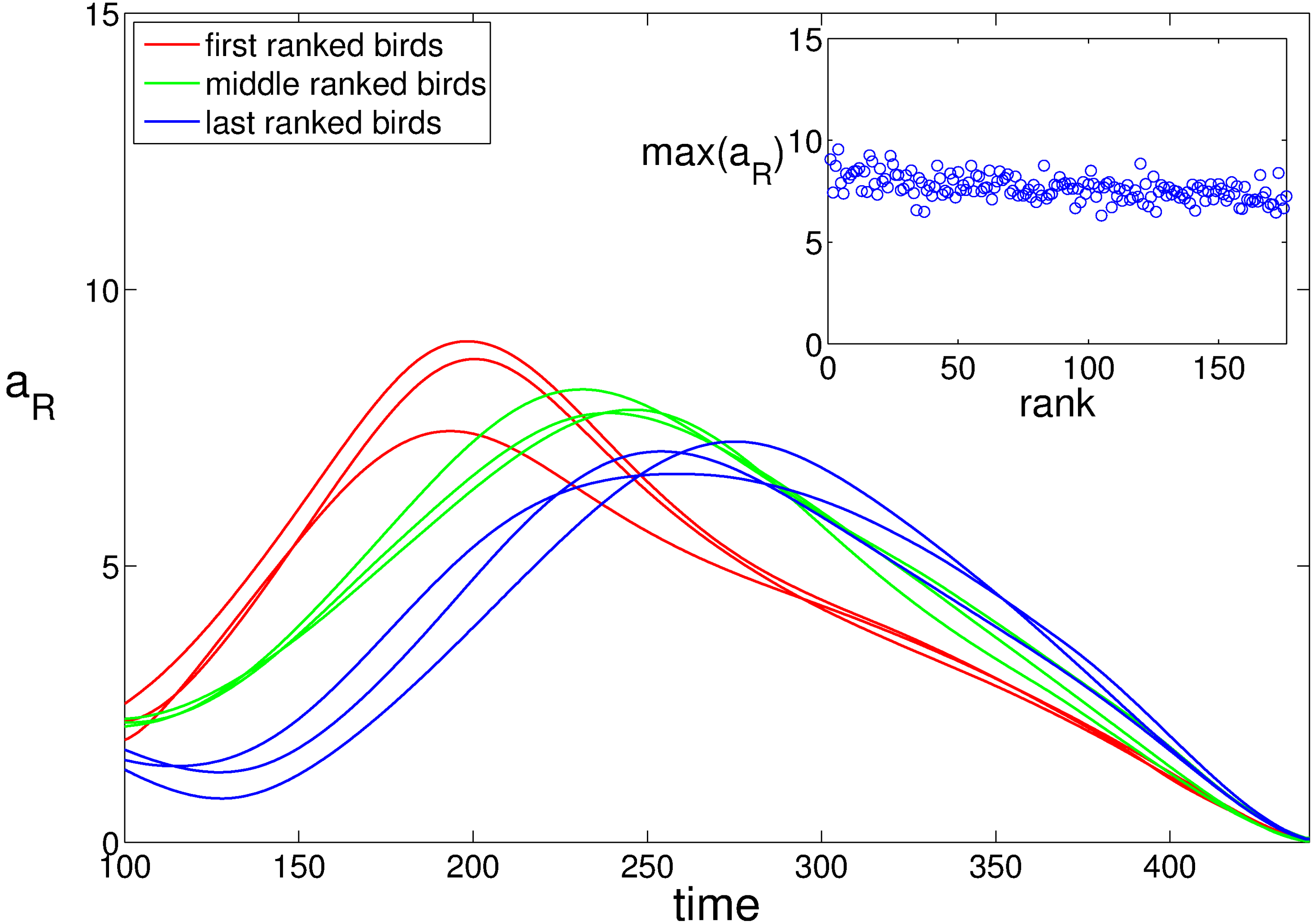
$$x(t) = \left[\frac{r(t)}{\rho}\right]^{1/3}$$

linear dispersion law

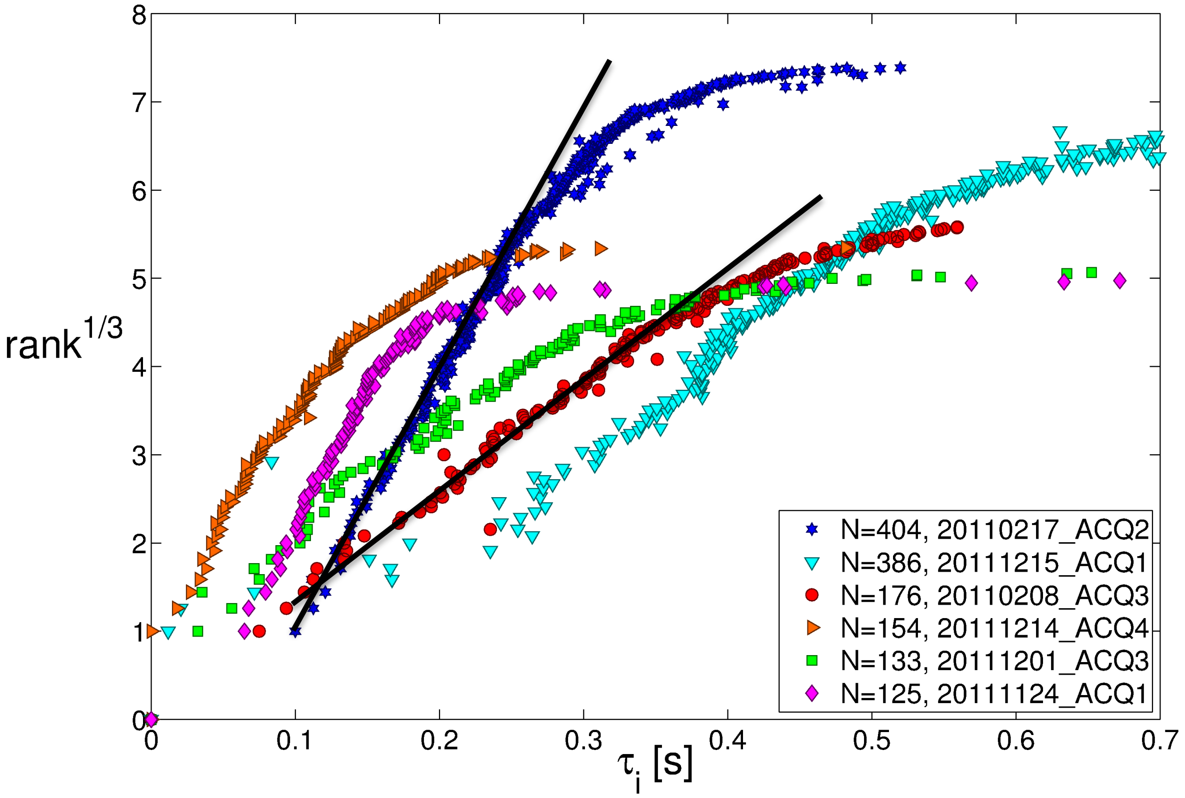
$x \sim \text{rank}^{1/3}$



very weak attenuation



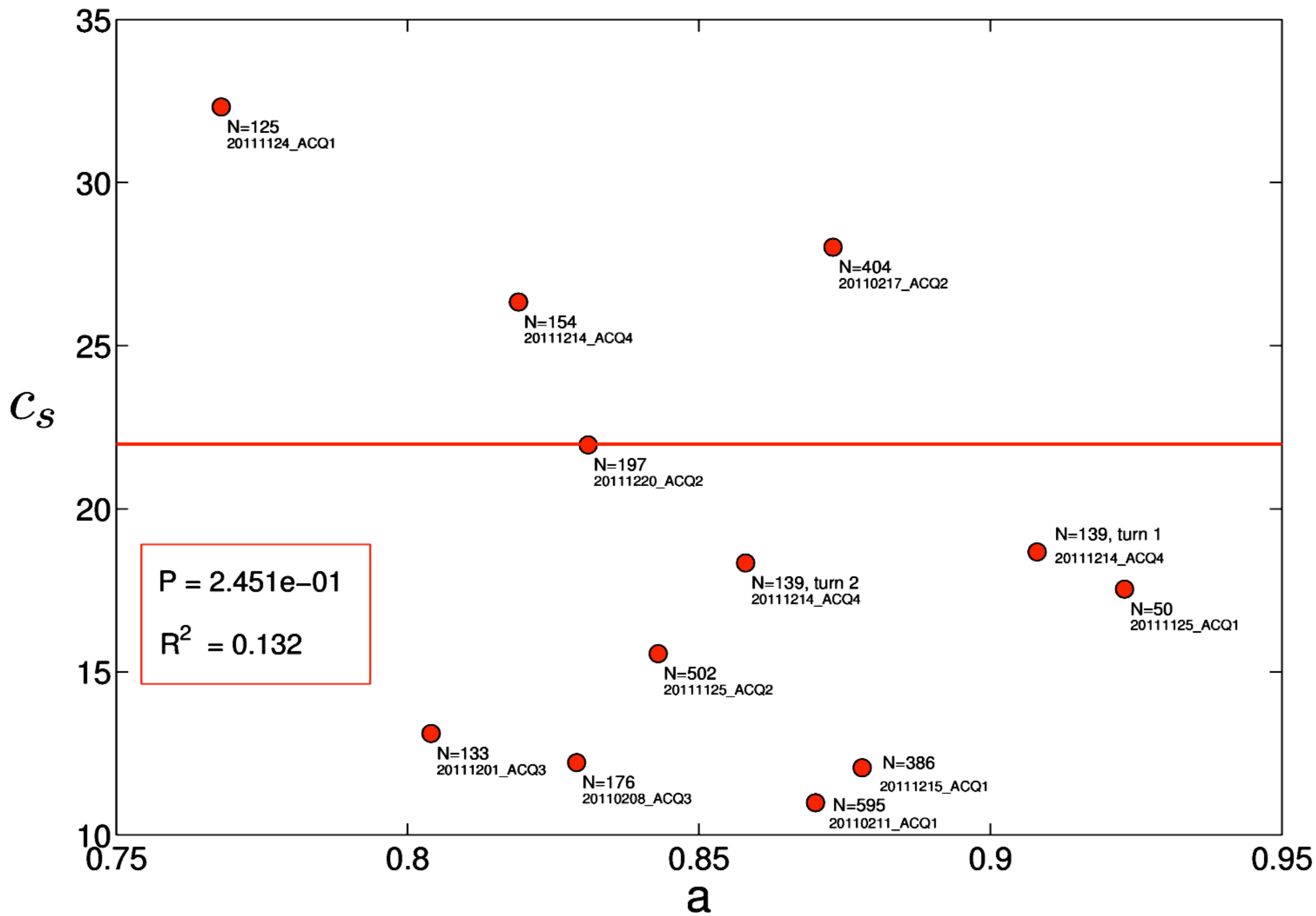
flock-to-flock variability of c_s



c_s is ~ 4 time larger than the birds speed

c_s does NOT depend on density, nor on system size

making sense of the variability of c_s attempt #1



nearest neighbours distance

questions

propagation

- why a linear propagation law?

  orientation waves, not density waves

- why a very weak attenuation?
- how to make sense of the variability of c_s ?

start

- why turns occur spontaneously ?
- what triggers the start of the turn ?
- why initiators are on the edges ?

standard theory of flocking

$$\vec{v}_i(t+1) = \vec{v}_i(t) + J\sum_{k\in i}\vec{v}_k(t) + \vec{\xi}_i$$

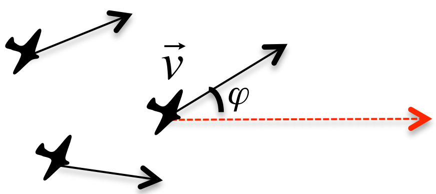
alignment force

typical flocking model (Vicsek model)

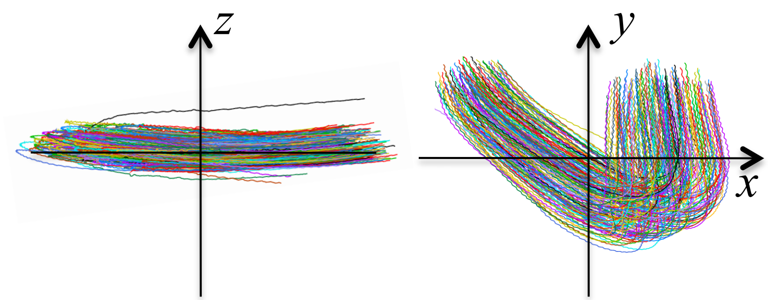
$$|\vec{v}_i| = v = const$$

active nature

- planar order parameter:



$$v_i^x + iv_i^y = v\,e^{i\varphi_i}$$



- high polarization: $\varphi \sim 0$

$$\frac{\partial\varphi}{\partial t} = J\nabla^2\varphi + \xi$$

alignment

$$\omega = iJk^2$$

$$x \sim \sqrt{t}$$

- damping ✗
- diffusive propagation ✗

What is missing ?

$$\frac{\partial \varphi}{\partial t} = J\nabla^2 \varphi + \xi = -\frac{\delta H}{\delta \varphi} + \xi$$

force

The force acts on the velocity
NO rotational inertia - overdamping

but turns are smooth

There is a global continuous symmetry (rotation of velocities),
it has strong consequences on correlations *Cavagna et al. Pnas 107 (2010)*
Implications on the dispersion law ?

direction AND curvature propagate in turns – turns occur on the short scales

Hamiltonian structure of equations

Inertia + global continuous symmetry

CONSERVATION LAW

$$\begin{cases} \dfrac{\partial \varphi}{\partial t} = \dfrac{1}{\chi} s \\ \dfrac{\partial s}{\partial t} = J a^2 \nabla^2 \varphi \end{cases}$$

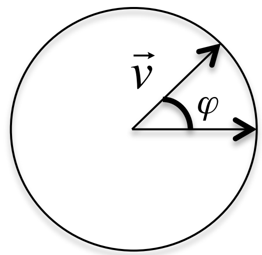
Hamiltonian description ?

Active nature of individuals $|\vec{v}_i| = v = const$ *not Hamiltonian in* $(\vec{r}_i, \vec{v}_i)$ *!!!!*

$\vec{v}_i = v\, e^{i\varphi_i}$ + rotational symmetry → *Hamiltonian in* (φ_i, s_i)

$$H = \int \frac{d^3x}{a^3}\left[\frac{1}{2}Ja^2\left(\vec{\nabla}\varphi\right)^2 + \frac{s^2}{2\chi}\right]$$

Rotational inertia



φ Parameterizes rotations of $\vec{v}$

s Generates rotations (SPIN)

Like circular motion BUT in internal space

canonical equations:

$$\begin{cases} \dfrac{\partial\varphi}{\partial t} = \dfrac{\delta H}{\delta s} = \dfrac{1}{\chi}s \\[2ex] \dfrac{\partial s}{\partial t} = -\dfrac{\delta H}{\delta\varphi} = Ja^2\,\nabla^2\varphi \end{cases}$$

conservation law:

$$\frac{\partial s}{\partial t} + \vec{\nabla}\cdot\vec{j} = 0$$

with: $\vec{j} = -Ja^2\,\vec{\nabla}\varphi$

s ~ curvature

Excess curvature cannot be dissipated but propagate !

Predictions

Model F (Hohenberg-Halperin 1977)

planar ferromagnet

lattice model for superfluid He2

$$\begin{cases} \dfrac{\partial \varphi}{\partial t} = \dfrac{1}{\chi} s \\ \dfrac{\partial s}{\partial t} = Ja^2 \nabla^2 \varphi \end{cases} \Rightarrow \frac{\partial^2 \varphi}{\partial t^2} - \frac{Ja^2}{\chi} \nabla^2 \varphi = 0$$

linear dispersion law: $\omega = c_s k$ $\quad x = c_s t$ ✓

speed of propagation: $c_s = \sqrt{\dfrac{Ja^2}{\chi}}$

the coupling J can be measured through the polarization Φ :

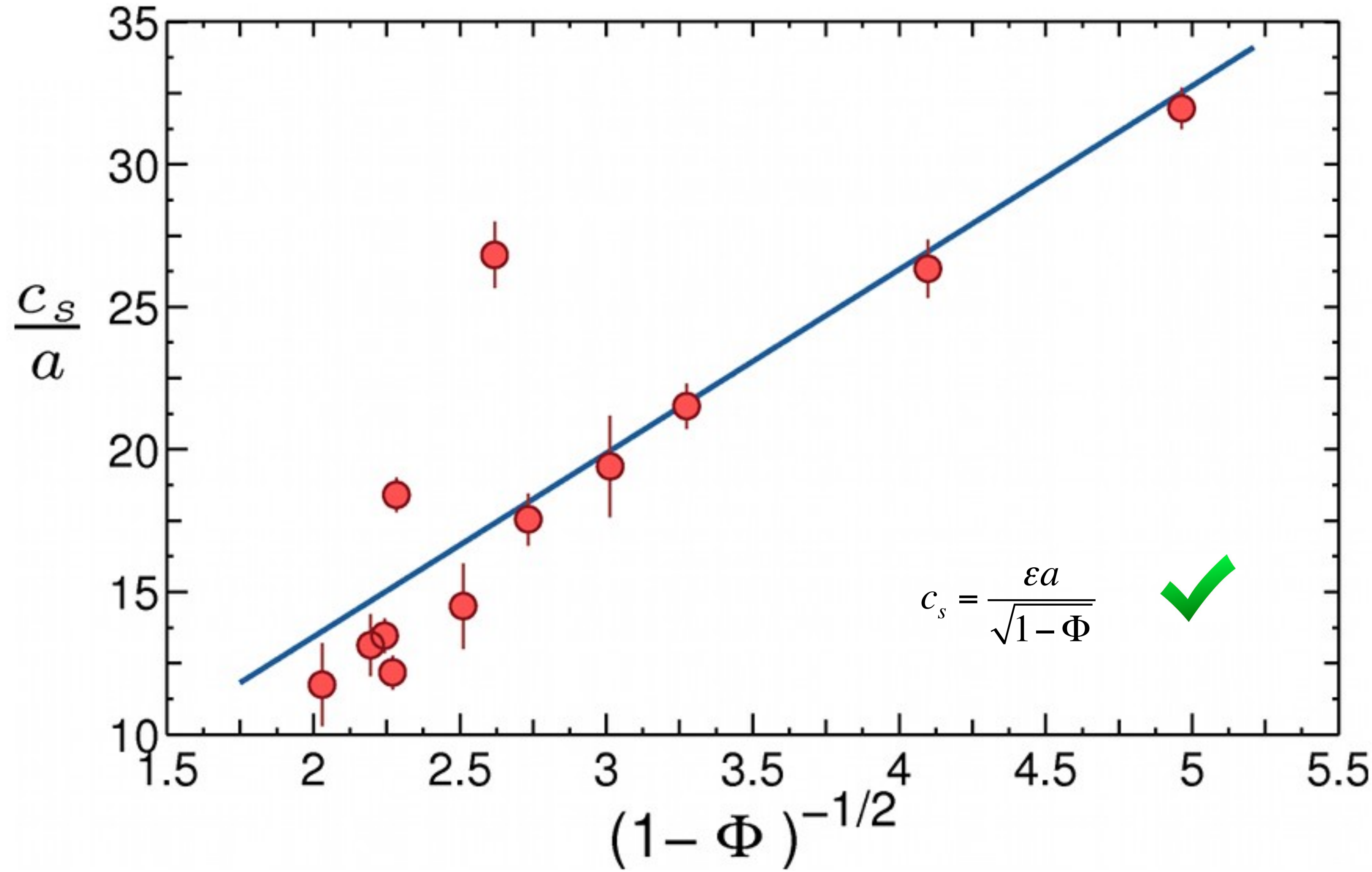
$$J = \frac{\varepsilon}{1 - \Phi} \qquad \Phi = \left\| \frac{1}{N} \sum_i \frac{\vec{v}_i}{\|\vec{v}_i\|} \right\|$$

Φ is experimentally accessible

$$\boxed{c_s = \frac{a\varepsilon}{\sqrt{1 - \Phi}}}$$

the speed of propagation of the turn across the flock must be larger in more ordered flocks

experimental test of the theory



Nature Phys 10 (2014), Jstat 2015

why turns occur spontaneously

standard Heisenberg on a lattice

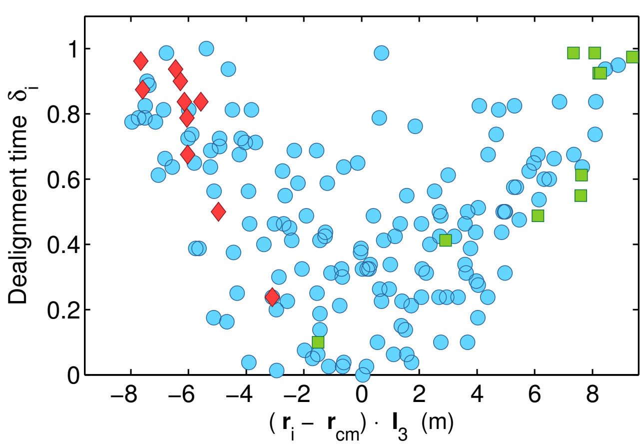
$$\tau^{rel} \sim L^{d-2}$$

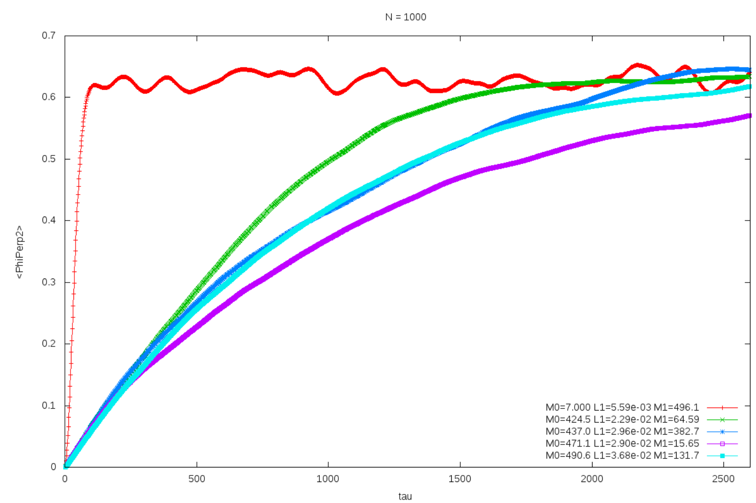
the system changes global state on large scales

what is different in flocks ?

the network is random
interactions are NOT symmetric

→ peripheral clusters more sensitive to noise





conclusions

- high order in the group (large stiffness) grants a more efficient propagation of information

  impact on collective dynamical response

- current dynamical models of flocking lack an essential term

- a new model including inertial terms and conservation laws is able to explain all known features of flocking

  new dynamical properties of the ordered phase

- non symmetric random interaction network + inertial dynamics can produce spontaneous changes of collective state on short scales

COBBS group

Massimiliano Viale
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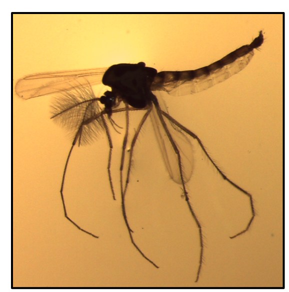
Alessandro Attanasi
Ed Shen
Lorenzo Del Castello
Asja Jelic
Oliver Pohl
Edmondo Silvestri
Leonardo Parisi
Agnese D'Orazio

and… the Red Van

Andrea Cavagna

Irene Giardina



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The inertial spin model

model G

from phases to velocities:

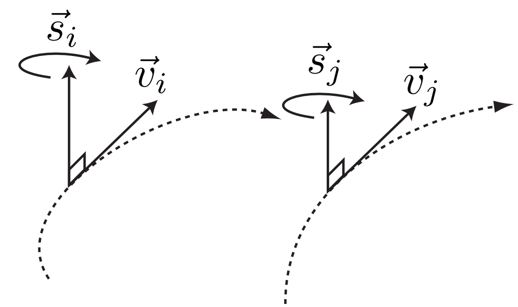
$$\frac{d\vec{v}_i}{dt} = \frac{1}{\chi}\vec{s}_i \times \vec{v}_i$$

$$\frac{d\vec{s}_i}{dt} = \vec{v}_i \times \left[J\sum_{j\sim i}\vec{v}_j - \eta\frac{d\vec{v}_i}{dt} + \vec{\xi}_i \right]$$

$$\frac{d\vec{r}_i}{dt} = \vec{v}_i$$

rotational dissipation

noise $\left\langle \vec{\xi}_i(t)\bullet\vec{\xi}_j(t')\right\rangle = 2d\eta T\delta_{ij}\delta(t-t')$



$$\chi\frac{d^2\vec{v}_i}{dt^2} + \chi\left(\frac{d\vec{v}_i}{dt}\right)^2 + \eta\frac{d\vec{v}_i}{dt} = J\left(\sum_{j\sim i}\vec{v}_j\right)^{\perp} + \vec{\xi}_i^{\perp}$$

inertial term *centripetal term* *dissipation* *social force* *noise*

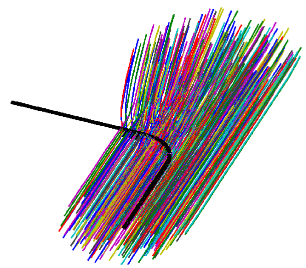
the Vicsek model is recovered in the overdamped limit

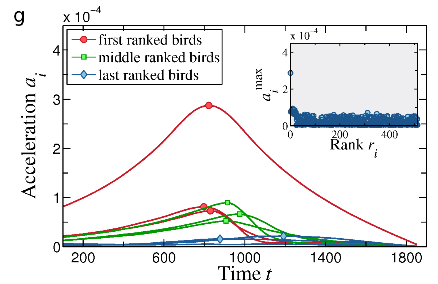
General dispersion relations

$$\omega = i\frac{\eta}{\chi} + c_s k\sqrt{1 - {k_0^2}/{k^2}} \qquad\qquad k_0 = \frac{\eta}{2\sqrt{Ja^2\chi}}$$

- overdamped regime

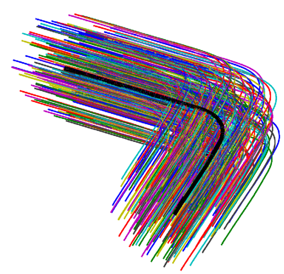
$$k_0 = \frac{\eta}{2\sqrt{Ja^2\chi}} >> \frac{1}{L}$$

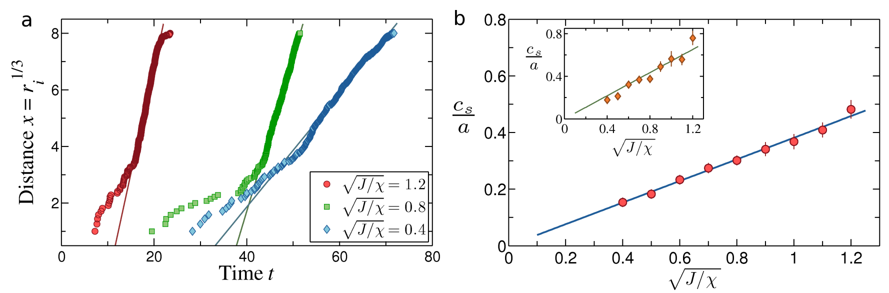




- underdamped regime

$$k_0 = \frac{\eta}{2\sqrt{Ja^2\chi}} << \frac{1}{L}$$

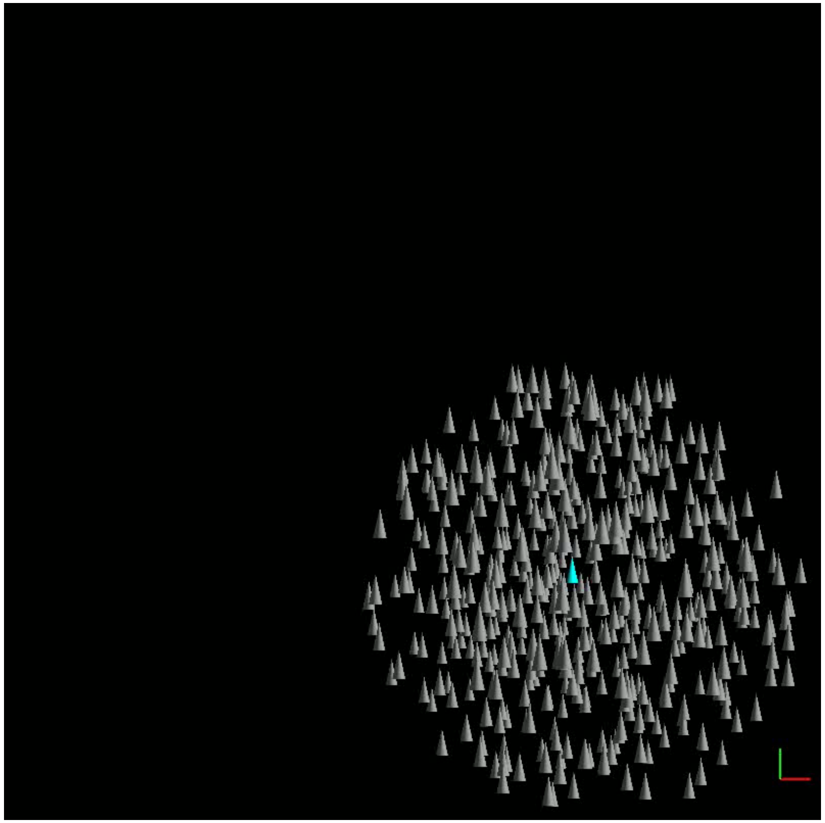




some small dissipation does NOT affect the linear propagation

Birds are in the underdamped regime

overdamped



underdamped