Information transfer in moving animal groups:
the case of turning flocks of starlings

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Flocks of starlings vs Physics

Typical flocking model:

e.g.Vicsek et al. 1995

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

Langevin equation: $$\frac{d\vec{v}_i}{dt} = -\frac{\partial H}{\partial \vec{v}_i} + \vec{\xi}_i$$

$$H = -J\sum_{<ij>}\vec{v}_i(t)\cdot\vec{v}_j(t)$$

Heisenberg ferromagnet

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Heisenberg ferromagnet

EMPIRICAL RESULTS

○ STATIC PROPERTIES:

- ✧ Topological interaction — BALLERINI ET AL., PNAS **105** 1232 (2008)
- ✧ Scale-free velocity correlations — CAVAGNA ET AL., PNAS **107** 11865 (2010)
- ✧ Maximum entropy model — BIALEK ET AL., PNAS **109** 4786 (2012)

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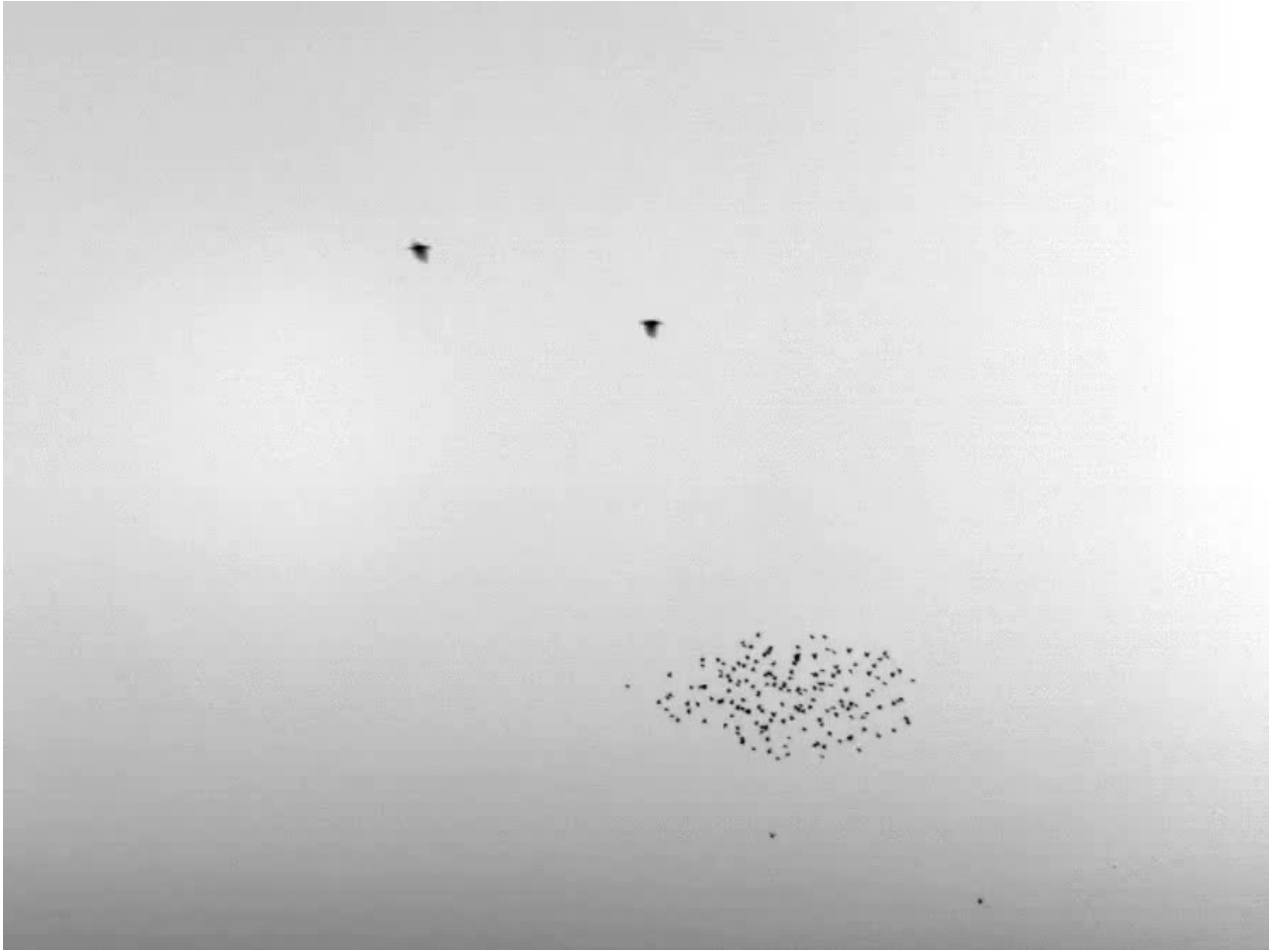
- DYNAMICS ?

Synchronized and rapid change of direction of the whole group – collective decision making ?



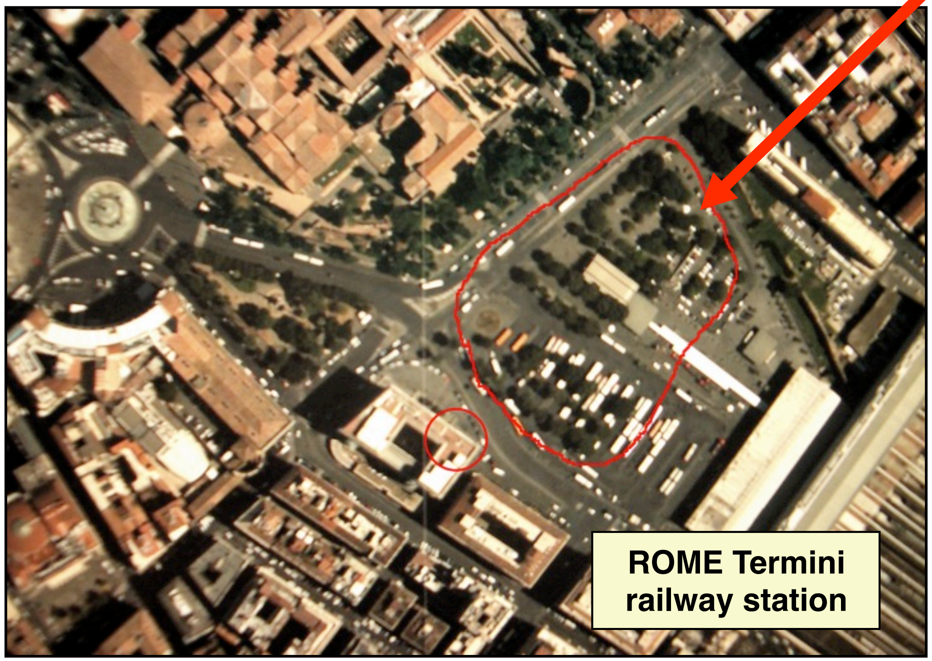
Questions about collective turns

- Is the turn instantaneous for all birds in the flock?
  - ✧ who starts the turn first, who second…?
- Where does the the turning decision start?
  - ✧ spatially localized or extended origin?
- How does the information spread across the flock?
  - ✧ what kind of propagation (dispersion) law?

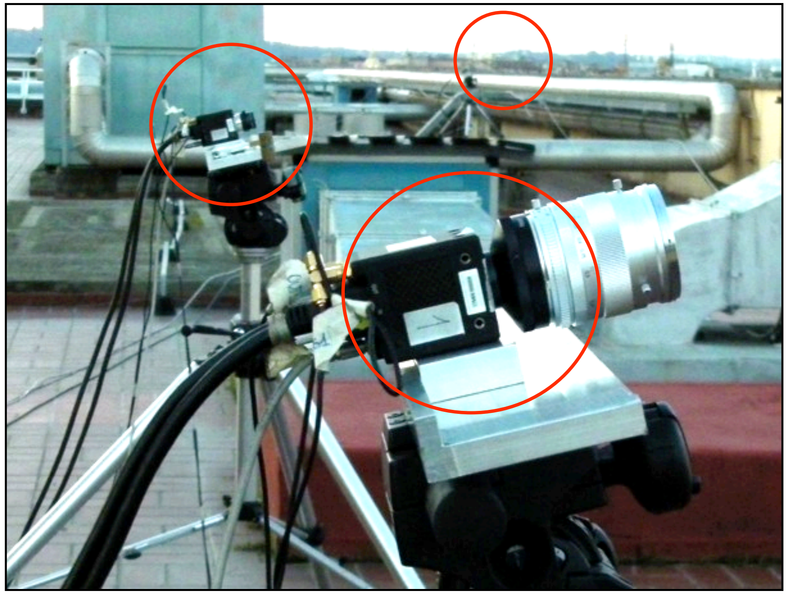
Experiments in Rome

GOAL:

- Turning flocks of starlings above a roosting place in Rome
- 3D trajectories of individual birds for the entire duration of a turning event (>5s)



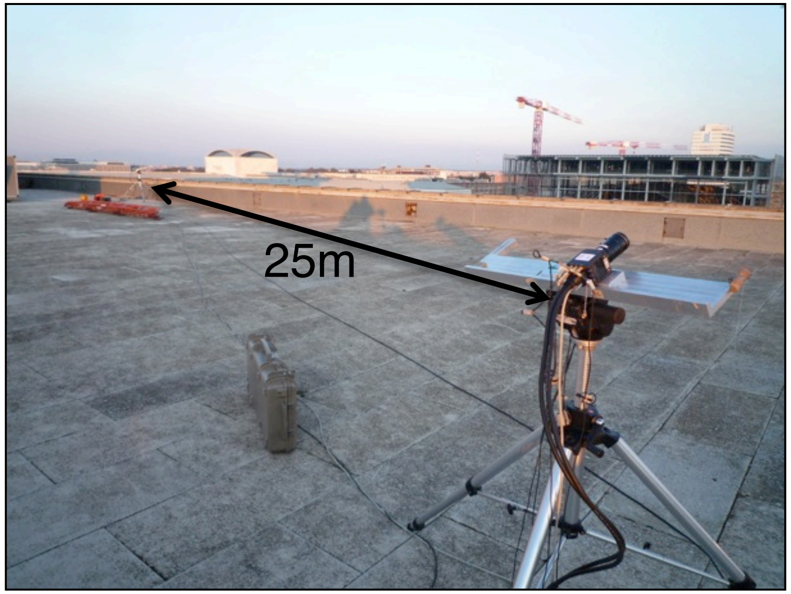
Experimental setup



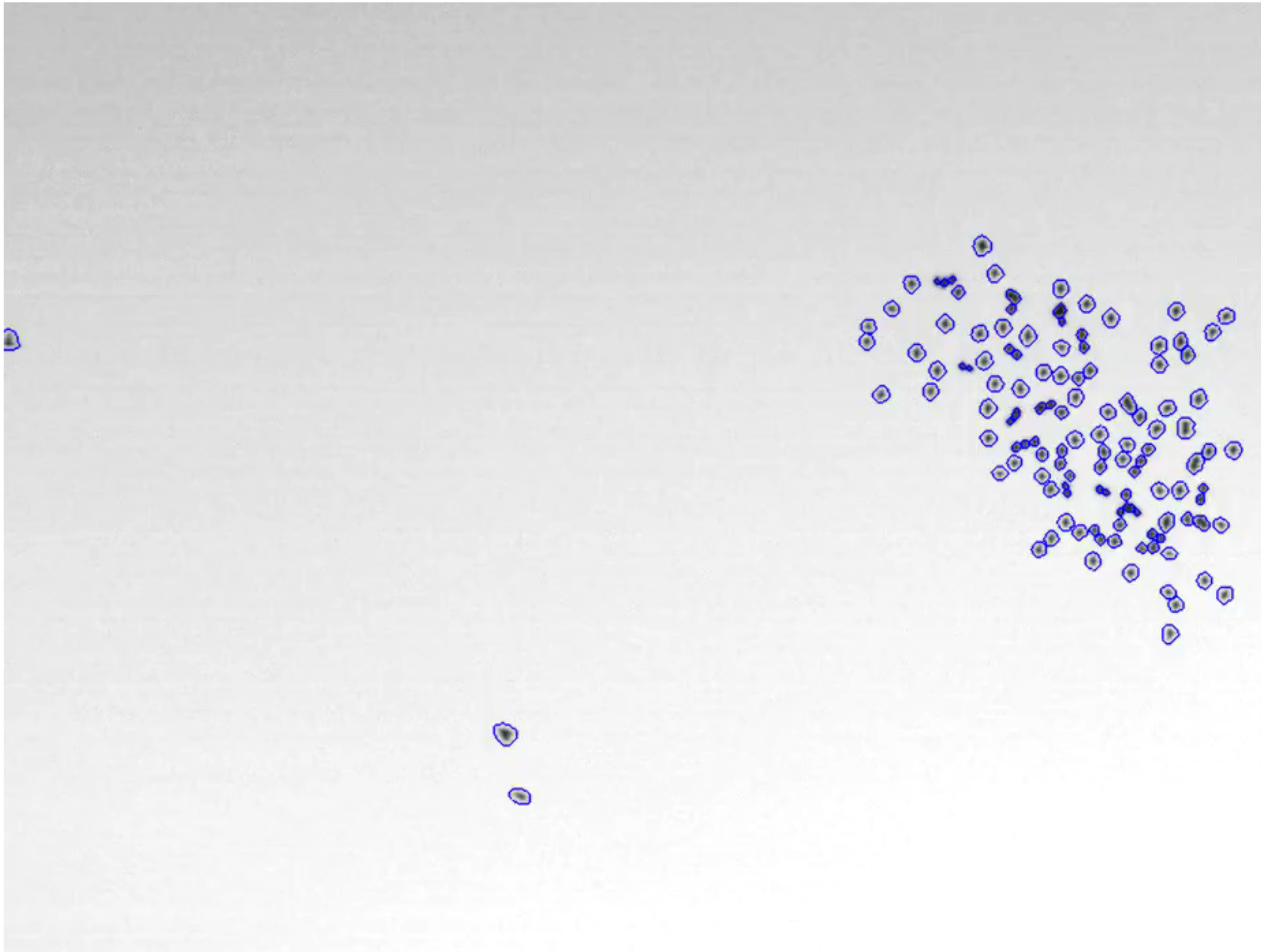
trifocal

system

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

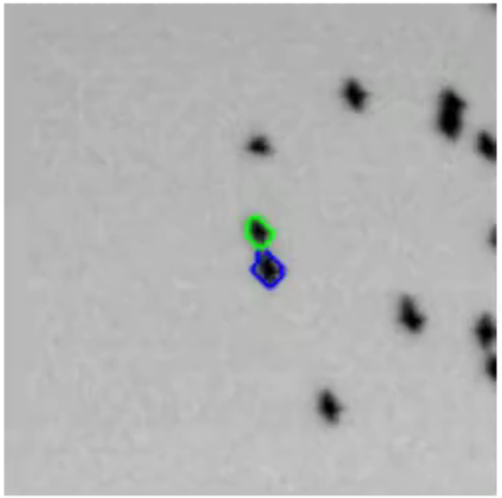


Tracking

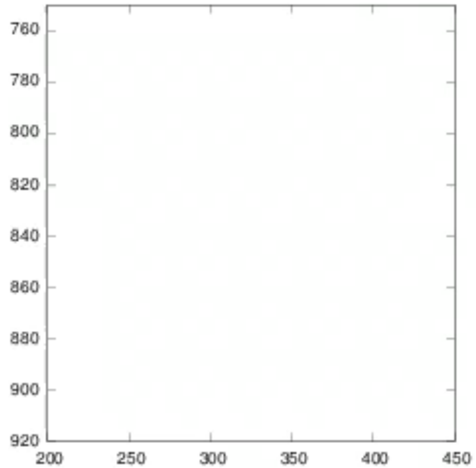


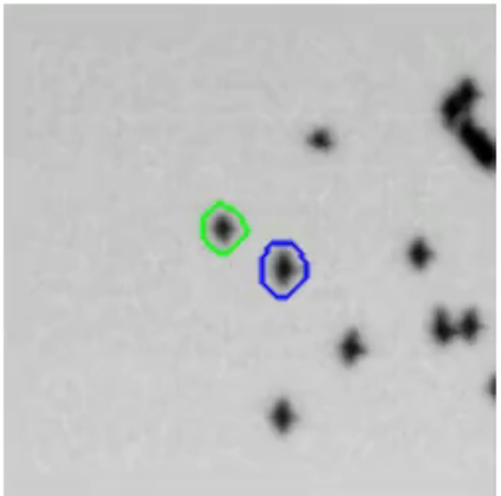
Tracking problems - blobs

frame 1



right camera





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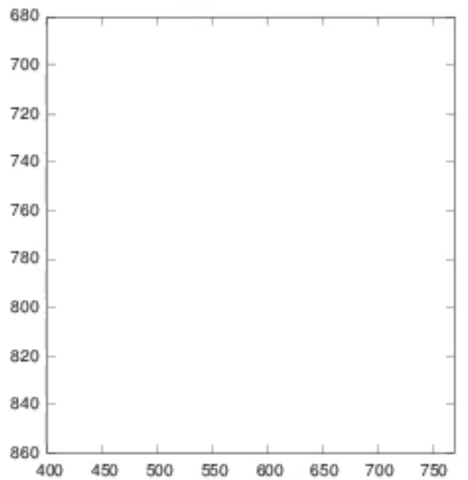
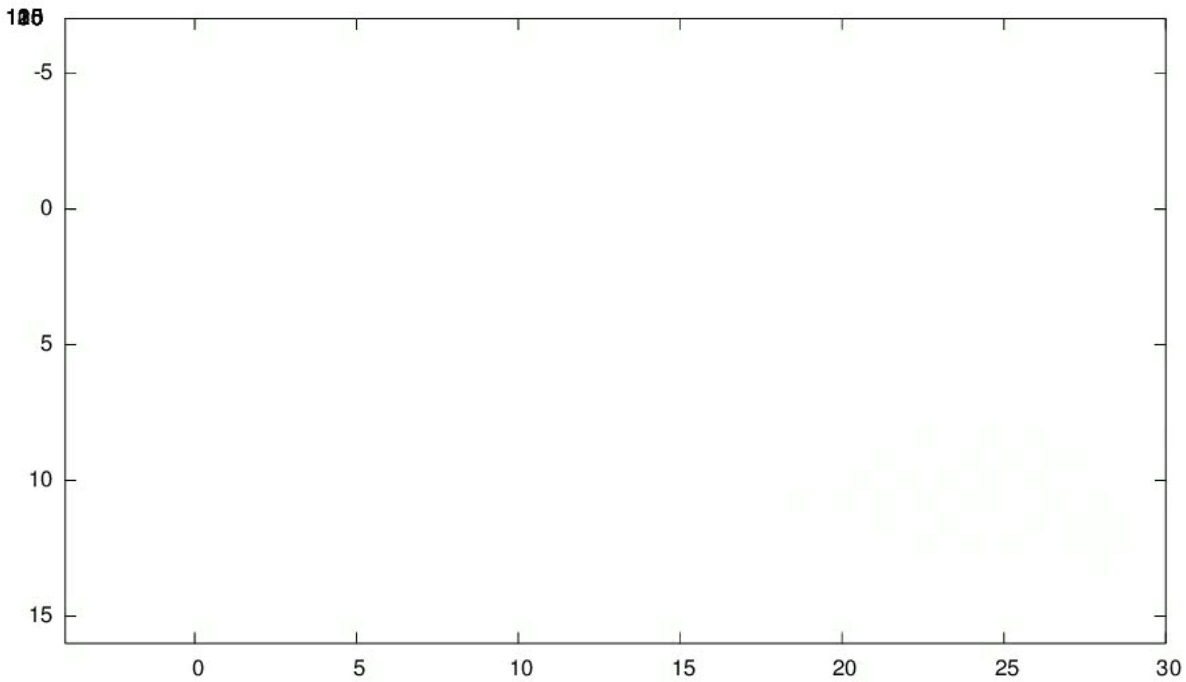


And finally… individual 3D trajectories

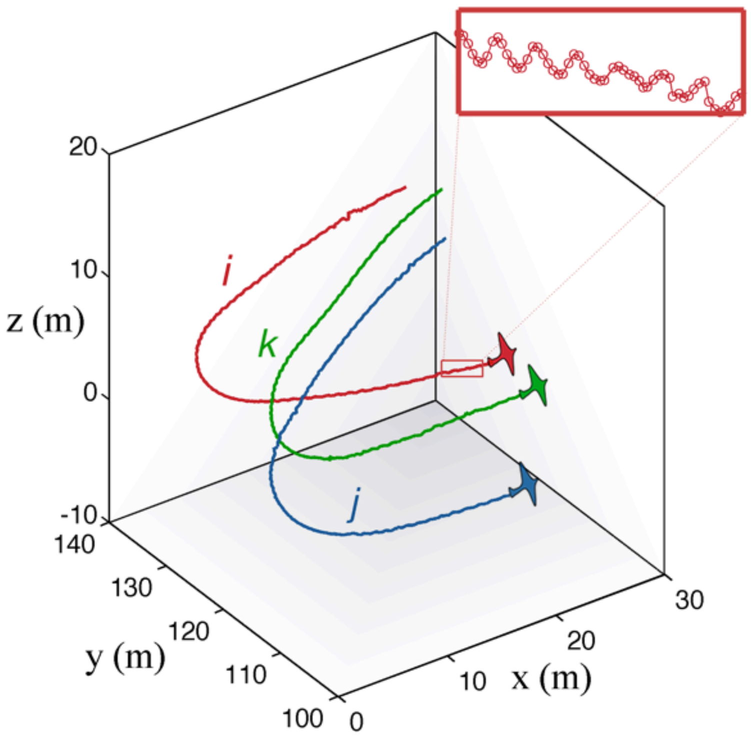
- 12 turning flocks of 50 to 600 starlings above a roosting place in Rome
- 3D trajectories of individual birds for the entire duration of a turning event (>5s)



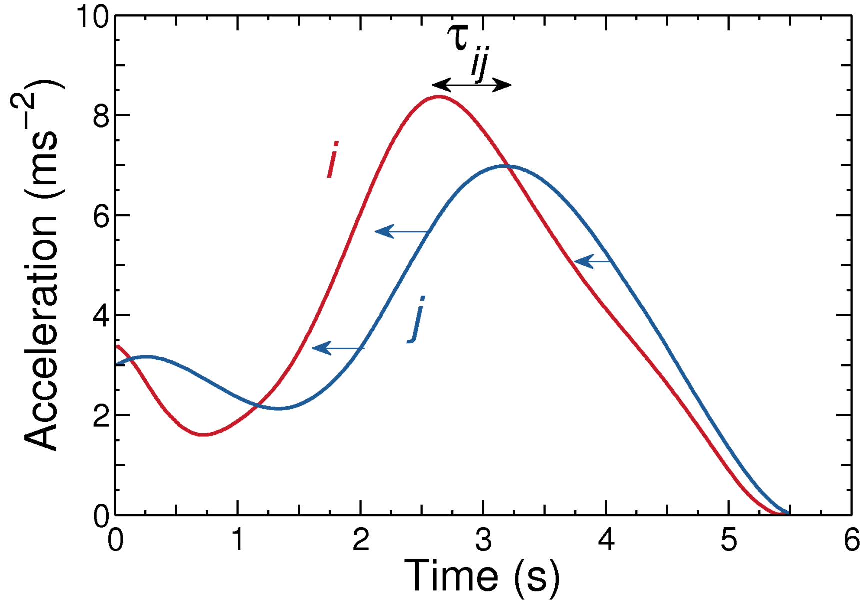
flock_20110208_ACQ3_N176

ATTANASI ET AL. ARXIV:1305.1495

Mutual time delays



bird i turns before bird j



find the delay τ_{ij} that maximizes the overlap between the two accelerations

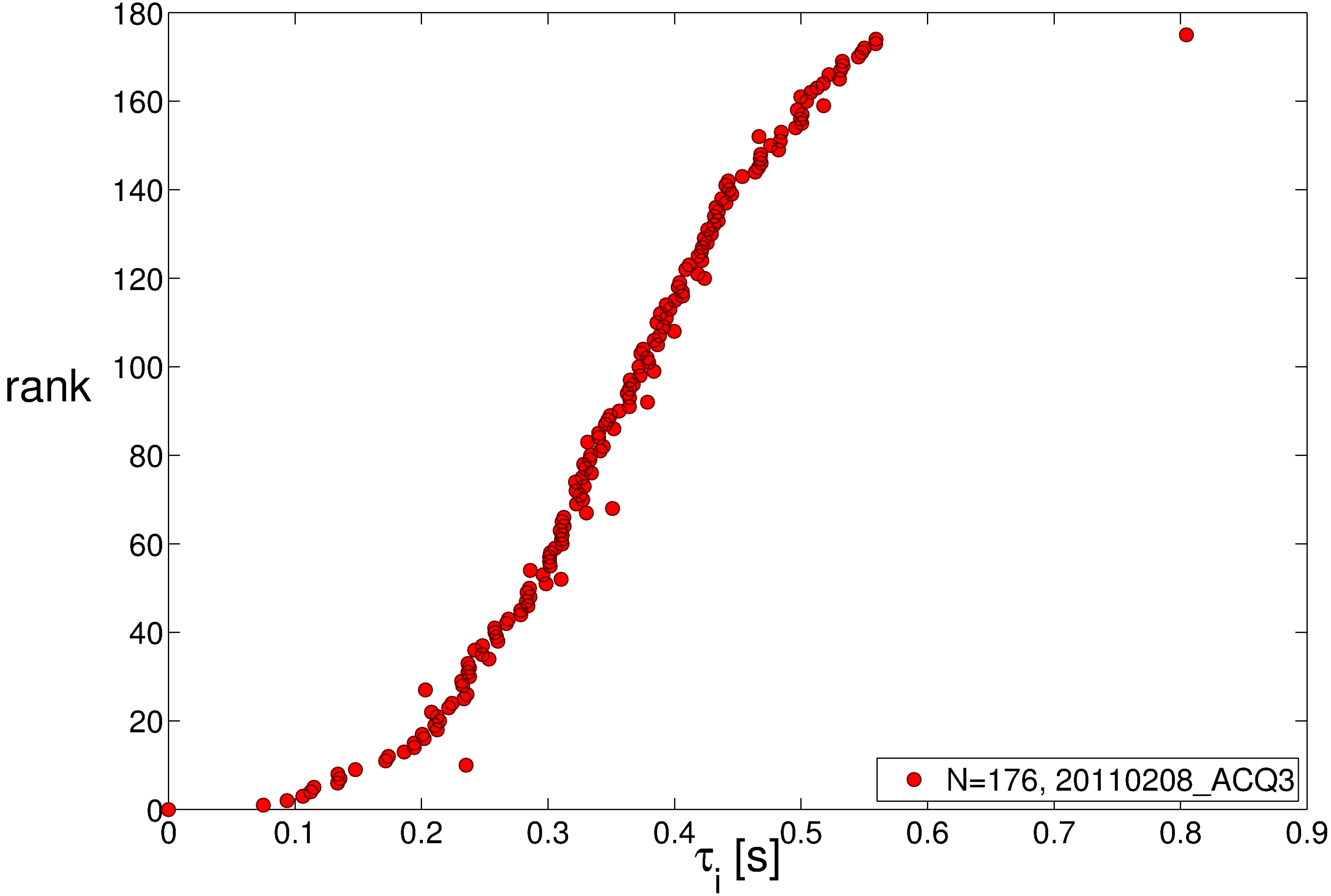
Birds ranking

Rank birds according to their mutual delays τ_{ij}

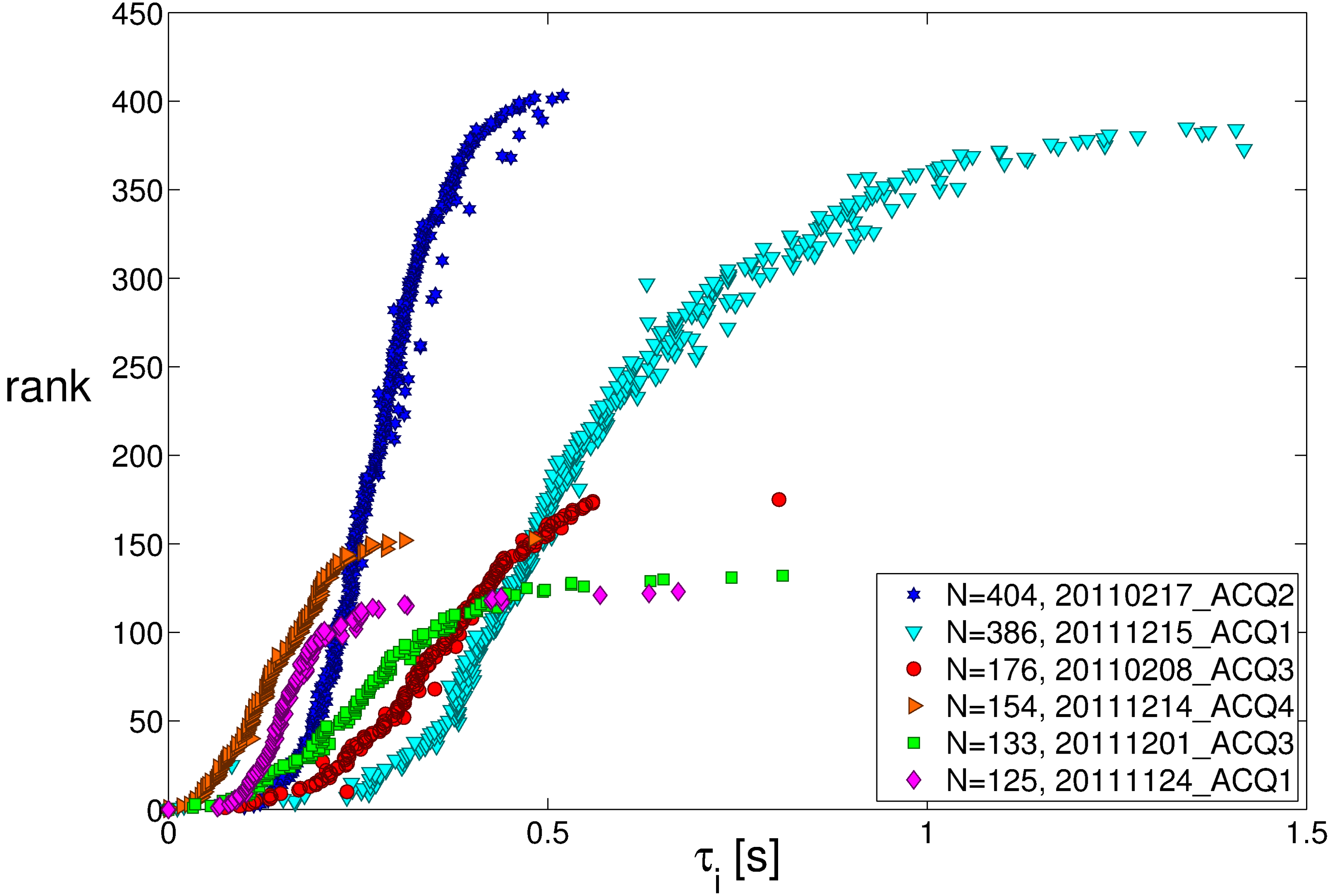
rank	turning time delay
1	0 ms – first bird to turn
2	35 ms
3	44 ms
4	50 ms
5	52 ms
6	54 ms
7	63 ms
8	64 ms
9	68 ms
…	…

flock_20110208_ACQ3_N176

Ranking curve



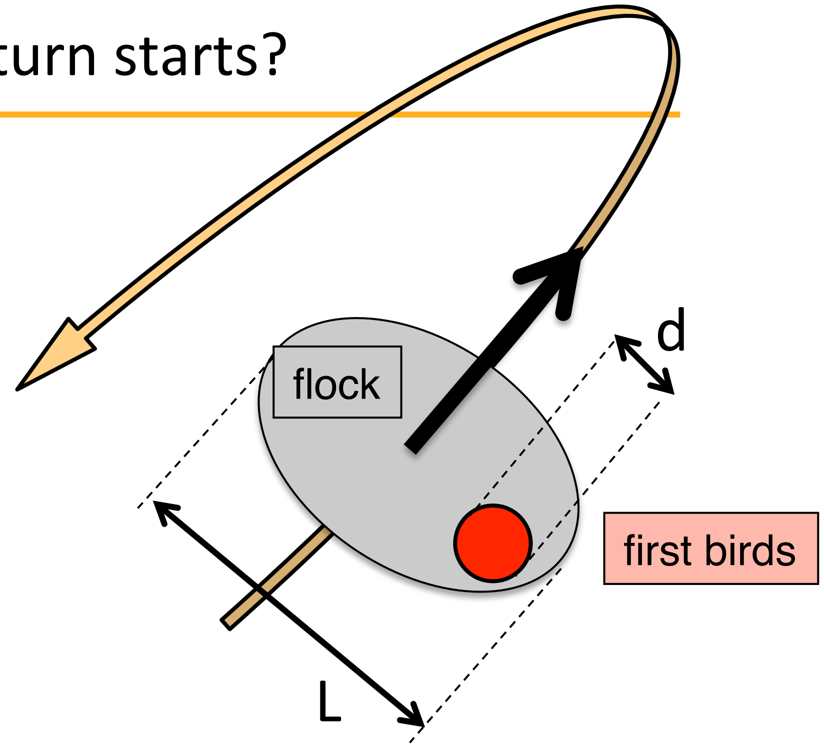
Ranking curve

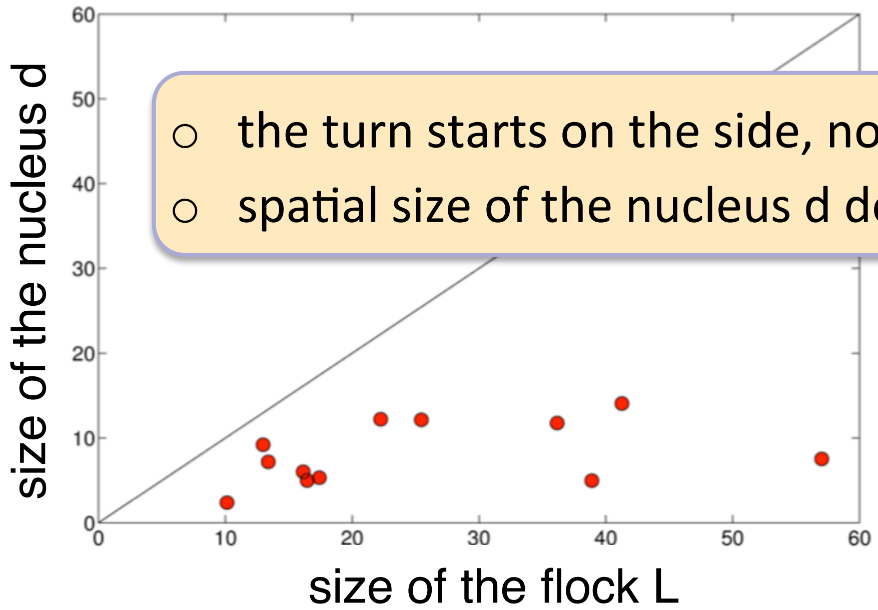


Where the turn starts?

`nucleus' = first 5 birds in the rank

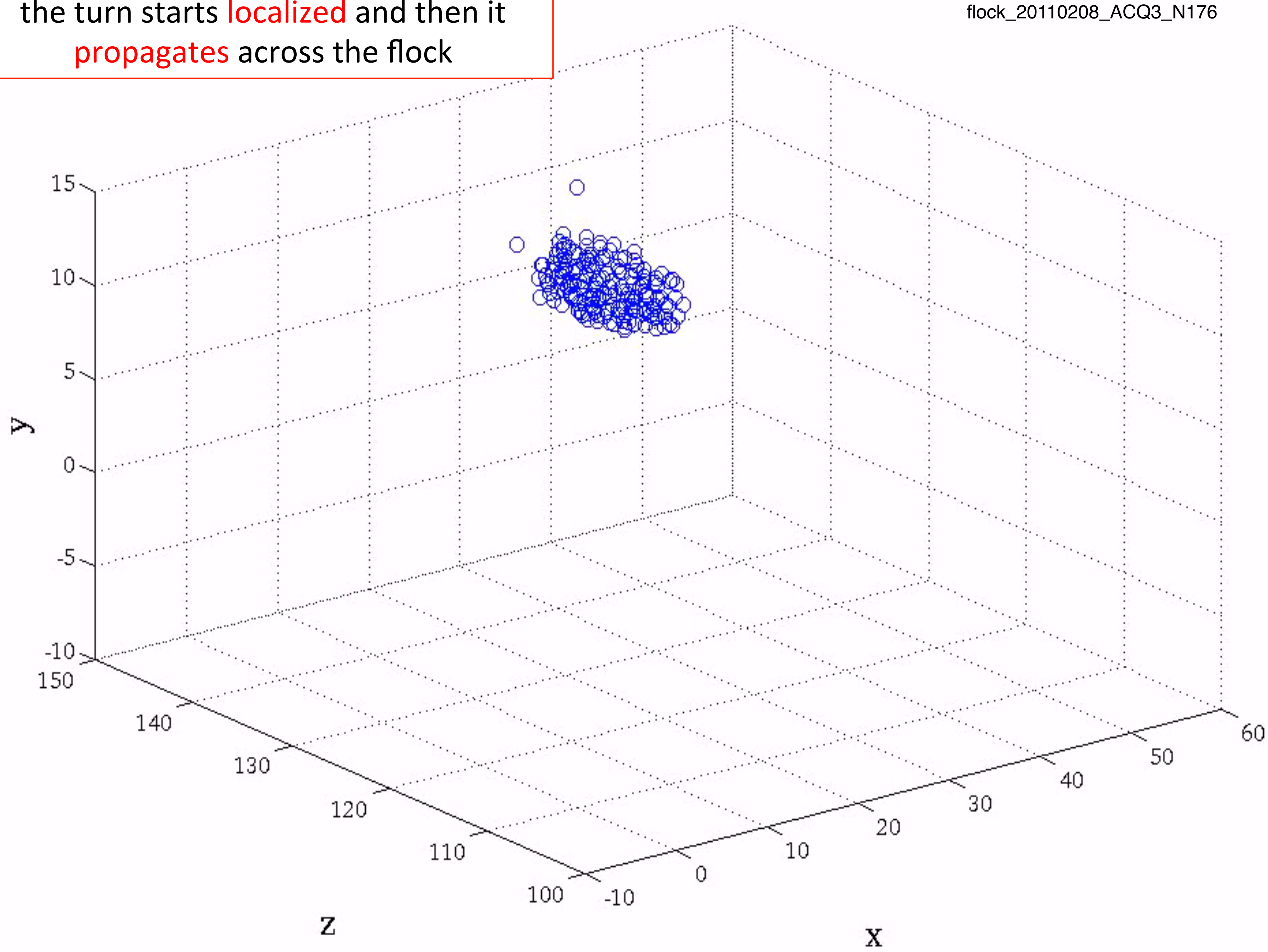
rank	delay
1	0 ms
2	35ms
3	44 ms
4	50 ms
5	52 ms
6	54 ms
7	63 ms
8	64 ms
9	68 ms
10	70 ms
11	71 ms
...	...





- the turn starts on the side, not at the front
- spatial size of the nucleus d does not scale with L

the turn starts localized and then it propagates across the flock



Ranking and propagation in space

if the turn starts localized then:

rank	delay
1	0 ms
2	35ms
3	44 ms
4	50 ms
5	52 ms
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7	63 ms
8	64 ms
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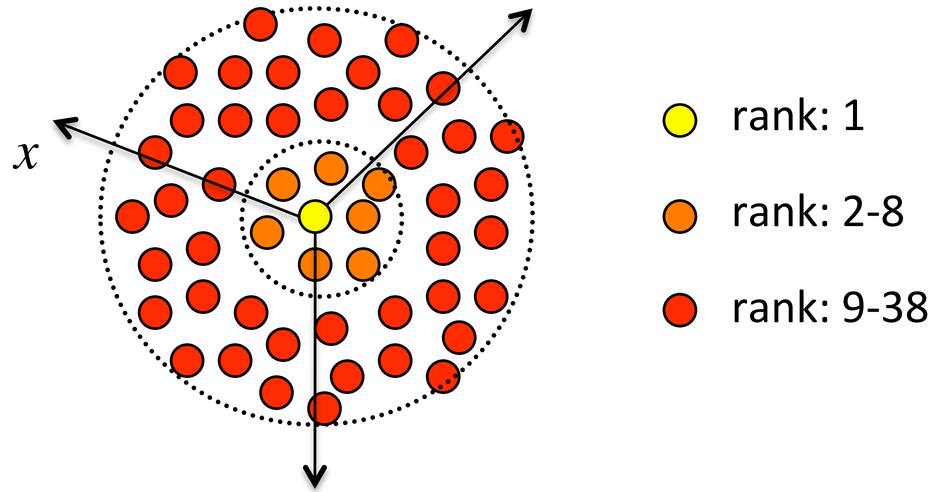
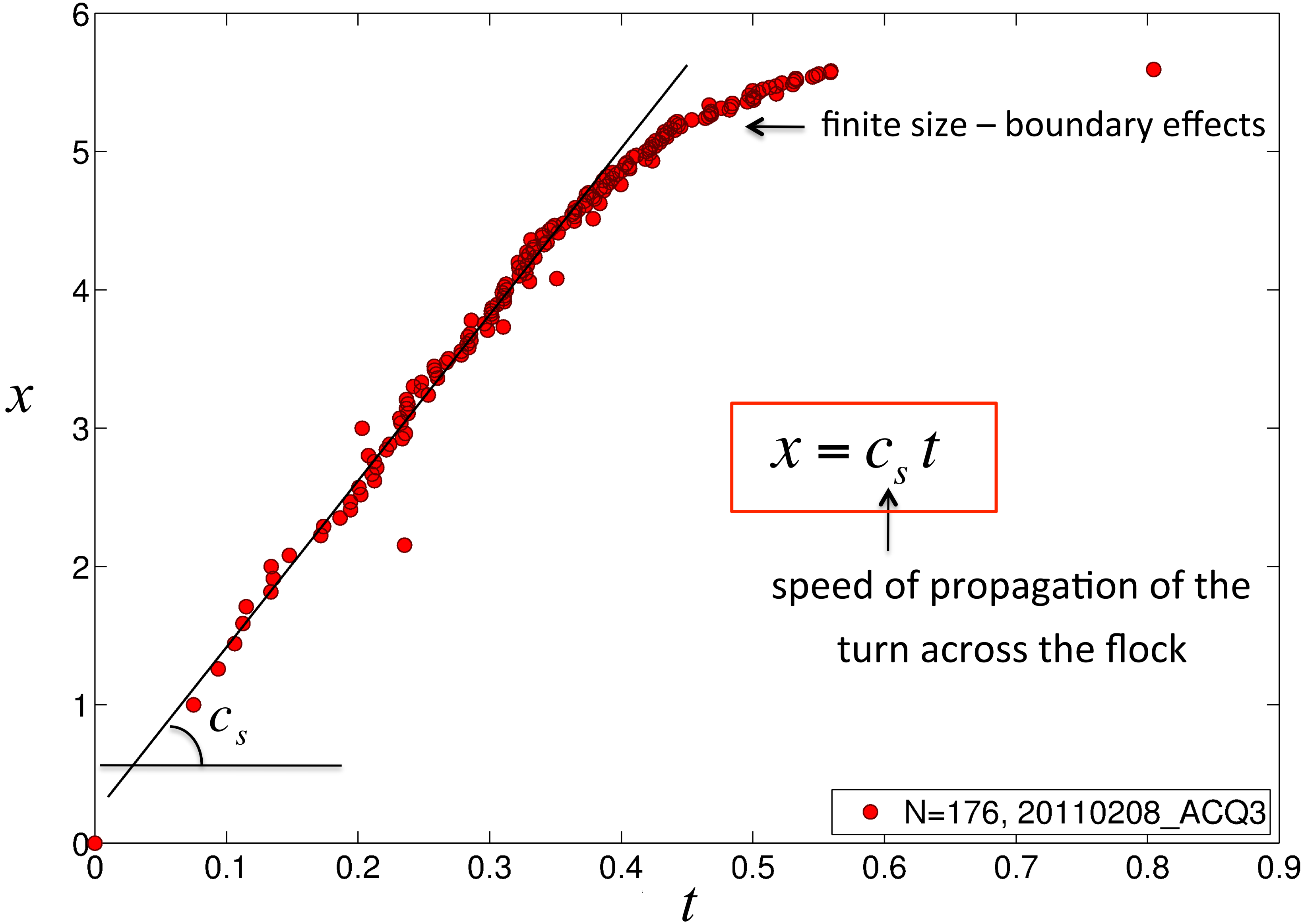
11	71 ms
...	...

rank = *(density ρ)* x *(distance traveled by the turn x)* ^{3}

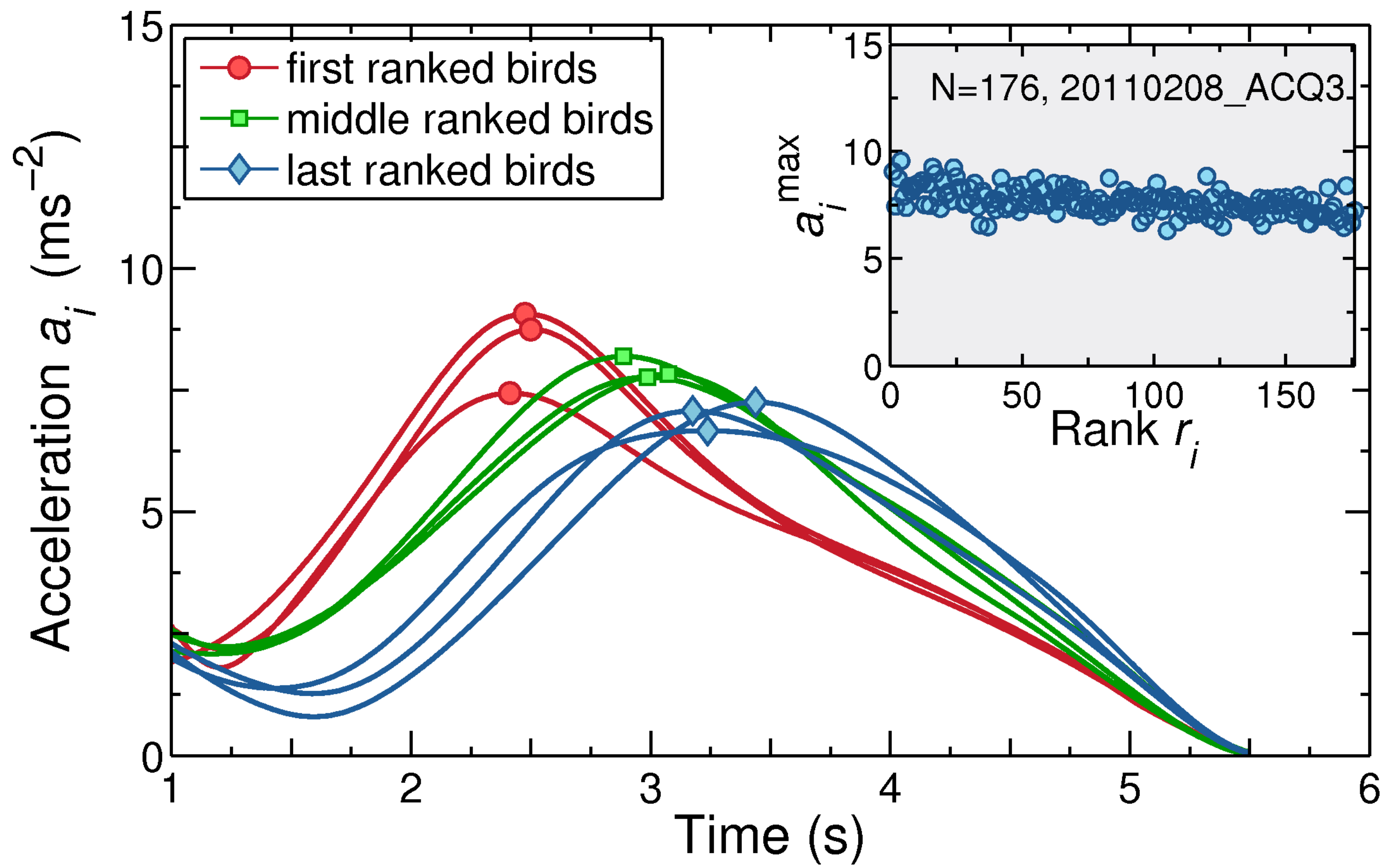


$$x(t) = \left[\frac{rank(t)}{\rho}\right]^{1/3}$$

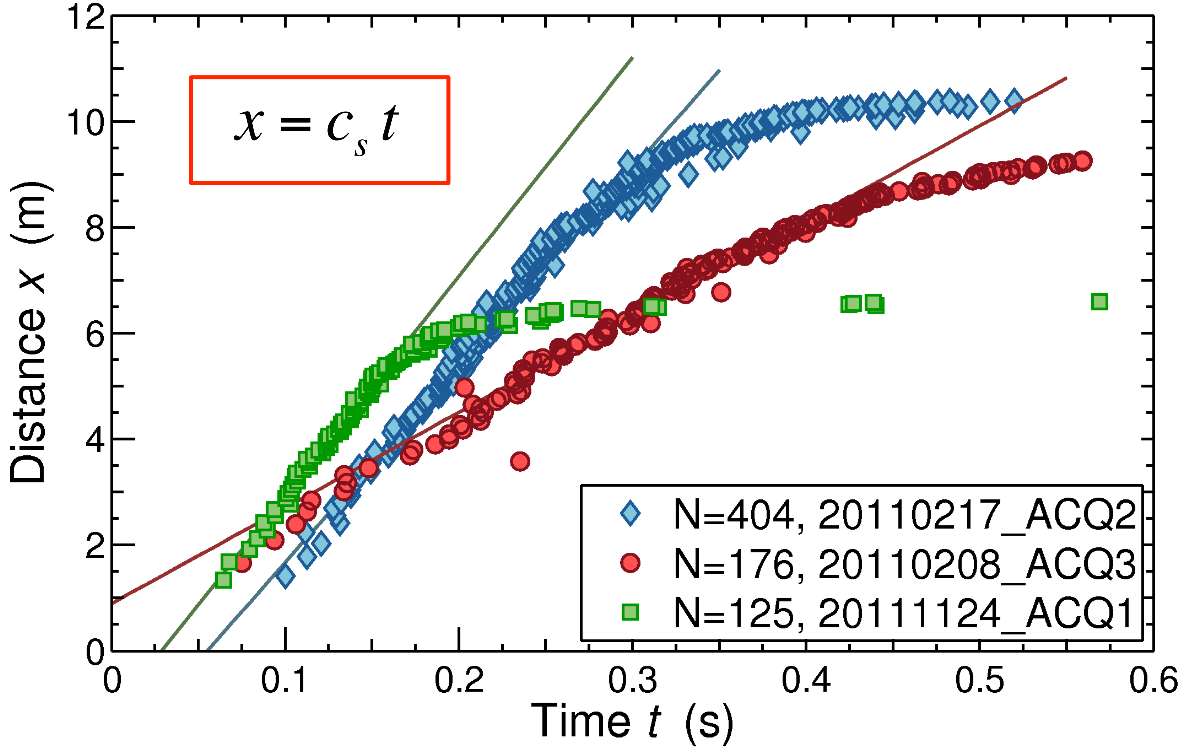
Linear propagation (dispersion law) of the turn



Very weak attenuation – no damping

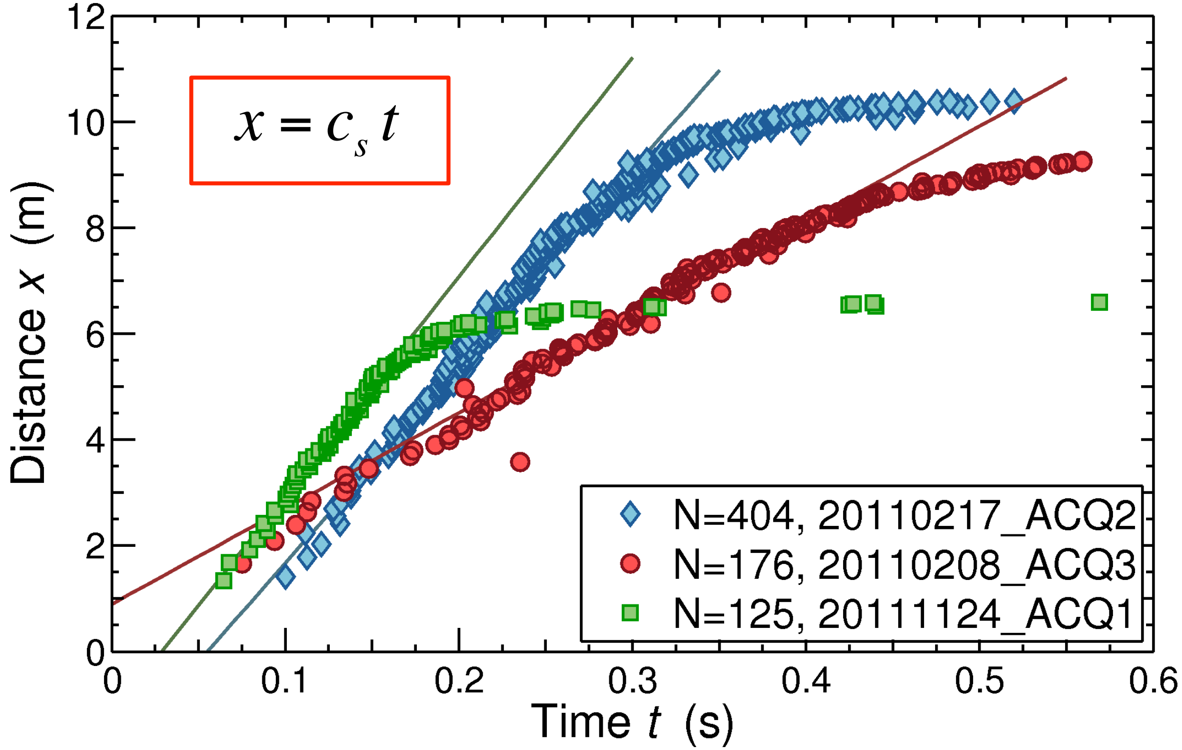


Flock-to-flock variability of c_s



What does c_s depend on?

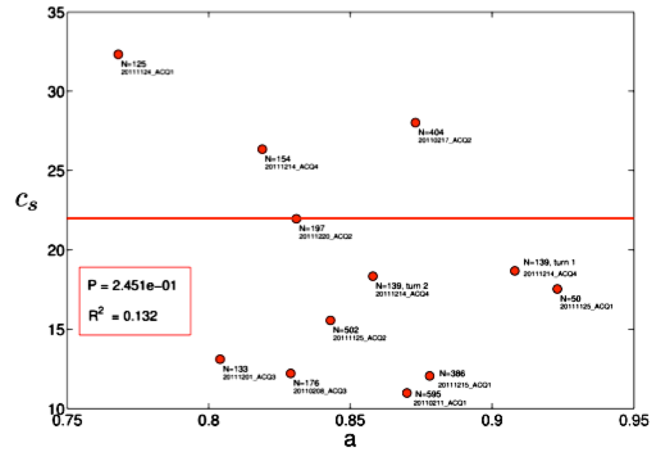
Flock-to-flock variability of c_s



What does c_s depend on?

Density ?

c_s



nearest neighbours distance

Experimental results to be explained

- Linear (sound-like) propagation of the turn

  These are orientation waves, not density waves

- Very weak attenuation of the turning signal – no damping

- Variability of the speed of propagation c_S (20-40 ms^{-1})

  Not explained by the difference in density of the flocks, i.e. not a standard sound wave

  Typical velocity of a bird/flock is 10 ms^{-1}

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Typical velocity of a bird/flock is 10 ms^{-1}

Do current theories of collective motion account for such an efficient transport of information ?

Standard theory of flocking

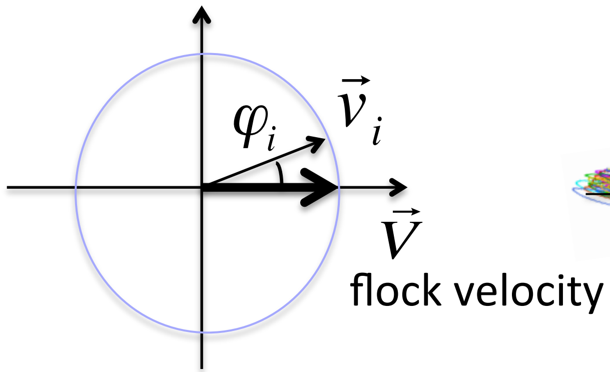
$$\vec{v}_i(t+1) = \vec{v}_i(t) + J\sum_{k\in i}\vec{v}_k(t) + \vec{\xi}_i$$

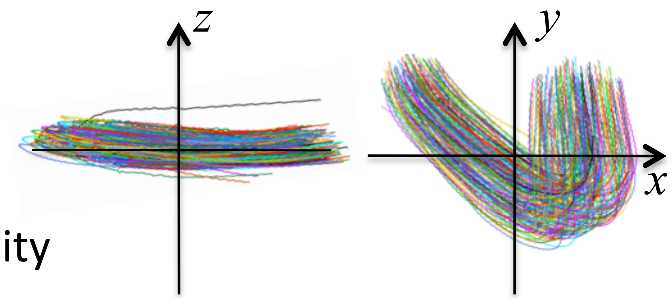
typical flocking model

$$\frac{d\vec{v}_i}{dt} = -\frac{\partial H}{\partial \vec{v}_i} + \vec{\xi}_i \qquad H = -J\sum_{<ij>}\vec{v}_i(t)\cdot\vec{v}_j(t)$$

- Planar order parameter:

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





- High polarization (low T) – spin wave expansion:

$$\varphi \sim 0 \quad \Rightarrow \quad H = \frac{1}{2}J\sum_{<ij>}(\varphi_i - \varphi_j)^2 = \frac{1}{2a}J\int d^3x\left[\vec{\nabla}\varphi(x,t)\right]^2$$

a = lattice spacing

$$\frac{\partial \varphi}{\partial t} = -\frac{\delta H}{\delta \varphi} = a^2 J\,\nabla^2\varphi \quad \Rightarrow$$

$x \sim \sqrt{t}$ — diffusive propagation ✗

$\omega = ik^2$ — damping ✗

What is wrong?

1) Missing conservation law

Rotational symmetry of the Hamiltonian $v_i = v\, e^{i\varphi_i}$ $\quad \varphi_i \rightarrow \varphi_i + d\varphi$

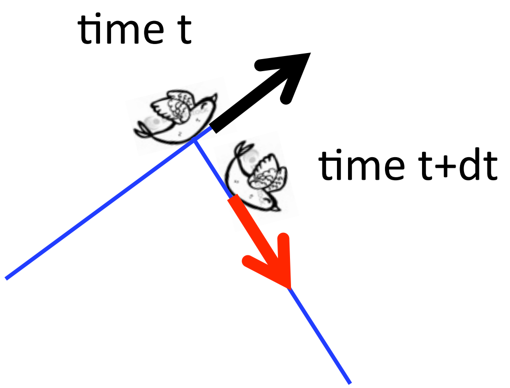
(all flight directions are equivalent)

⇨ Conservation law $\dfrac{\partial s_z}{\partial t} + \vec{\nabla} \cdot \vec{j}_z = 0$ which affects the dynamics !

2) No inertia

- Standard theory: $\dfrac{\partial \varphi}{\partial t} = a^2 J\, \nabla^2 \varphi$

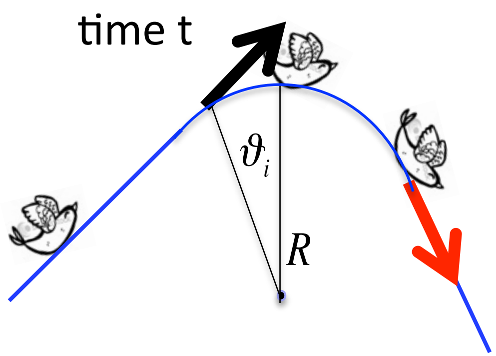
  Bird can turn instantaneously !



Paradox!

- Real bird:

  To change direction, the bird has some constraints: mass, size, wings, etc.



New (superfluid) theory of flocking

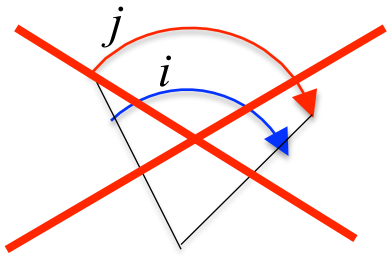
$$H = \int \frac{d^3x}{a^3} \left\{ \frac{1}{2} \rho_S \left[\vec{\nabla}\varphi(x,t) \right]^2 + \frac{s_z^2(x,t)}{2\chi} \right\}$$

$\rho_S \equiv a^2 J$: rescaled alignment coupling

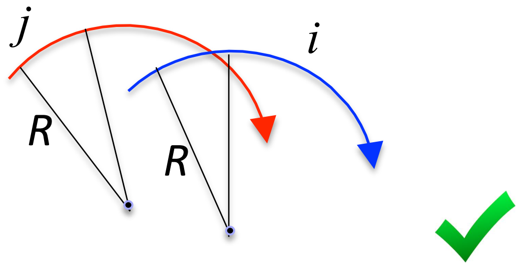
$s_z(x,t)$ = momentum conjugated to $\varphi(x,t)$, i.e. generator of the rotations around z-axis

χ = generalized moment of inertia

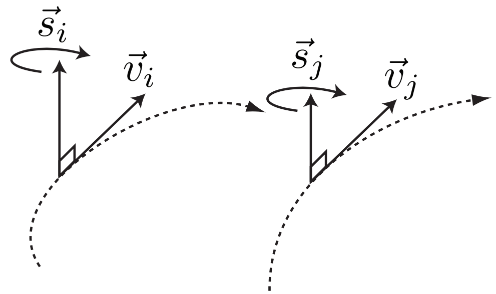
$$\vec{v} = v_x + i v_y = v e^{i\varphi} \qquad \{\vec{v}, s_z\} = \frac{\partial \vec{v}}{\partial \varphi} = i\vec{v}$$



parallel paths trajectories



equal radius trajectories



$R \approx$ const.

$v \approx$ const.

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Equations of motion:

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

New (superfluid) theory of flocking

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Equations of motion:

$$\frac{\partial \varphi}{\partial t} = \frac{\delta H}{\delta s_z} = \frac{1}{\chi} s_z$$

$$\frac{\partial s_z}{\partial t} = -\frac{\delta H}{\delta \varphi} = \rho_s \nabla^2 \varphi$$

Conservation law:

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

with: $\vec{j}_z = -\rho_s \vec{\nabla} \varphi$

current of directional information

$$\frac{\partial^2 \varphi}{\partial t^2} - \frac{\rho_s}{\chi} \nabla^2 \varphi = 0$$

equation for the orientation angle change during the turn

Predictions of the superfluid theory

$$\frac{\partial^2 \varphi}{\partial t^2} - c_s^2 \nabla^2 \varphi = 0$$

equation for the orientation angle change during the turn

$x = c_s t$ ○ linear propagation ✓

$\omega = c_s k$ ○ no damping ✓

Speed of propagation: $c_s = \sqrt{\dfrac{a^2 J}{\chi}}$

The alignment coupling J has been related to the polarization Φ

Bialek et al. PNAS (2012)

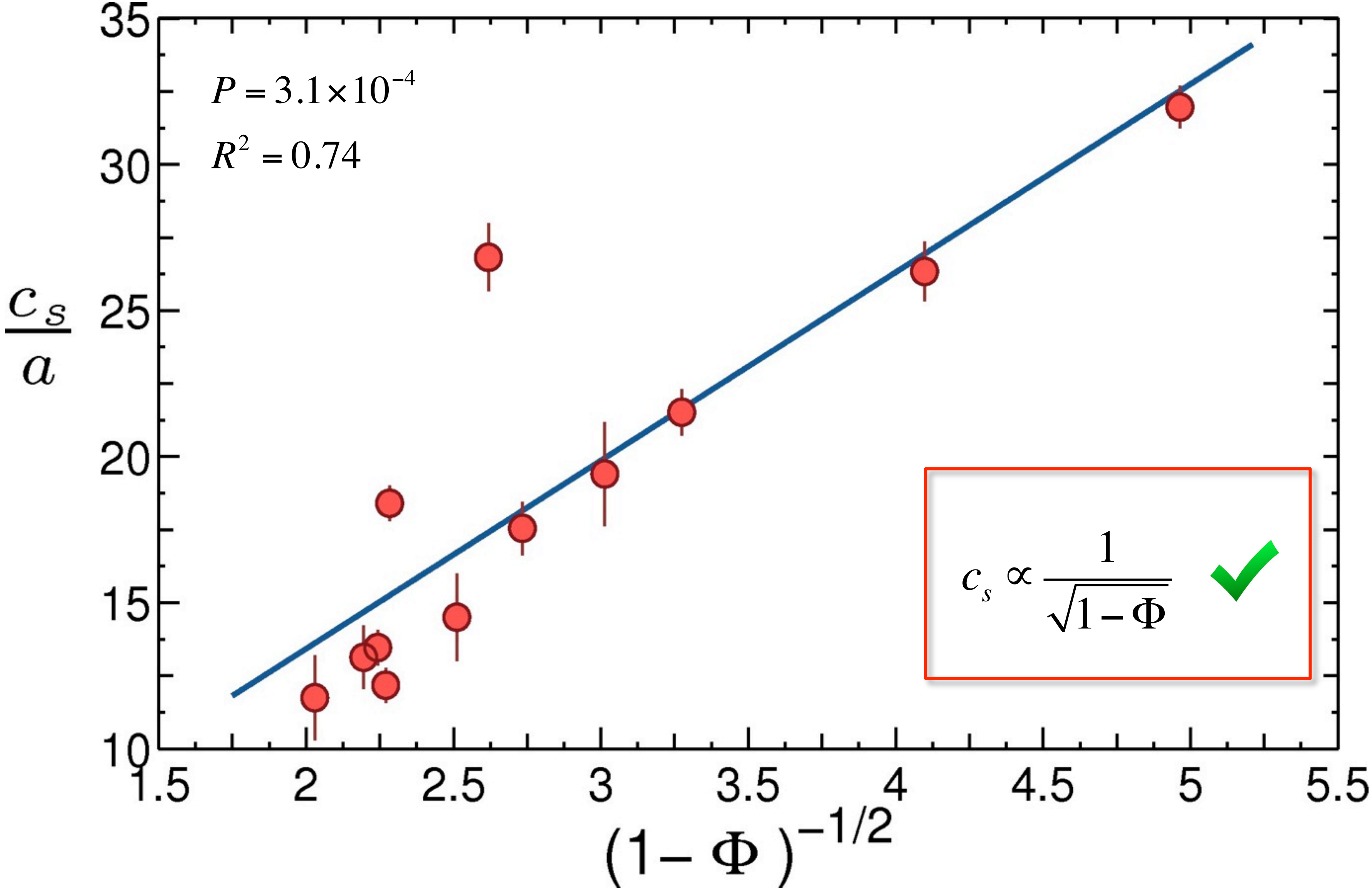
$$J \propto \frac{1}{1-\Phi} \qquad \Phi = \left\| \frac{1}{N} \sum_i \frac{\vec{v}_i}{\|\vec{v}_i\|} \right\|$$

Φ is experimentally accessible

$$c_s \propto \frac{1}{\sqrt{1-\Phi}}$$

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

Experimental test of the prediction



Superfluid theory of flocking

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easy plane ferromagnet ⟺ superfluid liquid He II

MATSUBARA & MATSUDA 1956

$\psi = |\psi| e^{i\varphi}$ = Bose wave function

s_z = Bose particle density

Model F dynamics in the Halperin-Hohenberg classification

$$\frac{\partial^2 \varphi}{\partial t^2} - c_S^2 \nabla^2 \varphi = 0$$

2nd sound

$x = c_s t$ ○ linear dispersion law ✓

$\omega = c_s k$ ○ no damping ✓

We do not have density waves (1st sound), but the orientation waves (2nd sound)!

c_s depends on :

- flocks: polarization
- superfluid He II: temperature

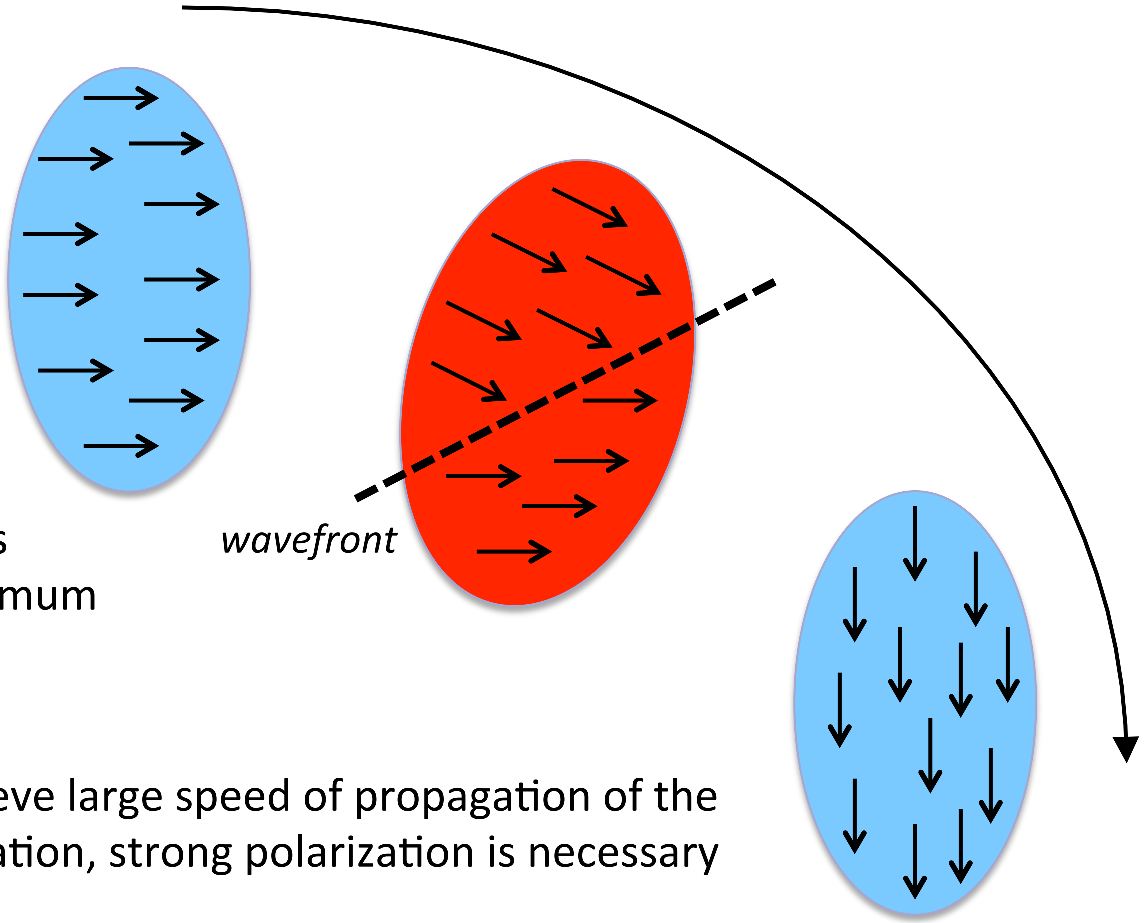
Collective turns - conclusions

- Turns start localized, then spread through the flock fast and accurate
    - linear propagation of orientational information, no damping
- New superfluid theory for turns
    - includes conservation laws/symmetries and inertia
- High order in the group grants a more efficient propagation of information
    - why natural groups are so polarized?

polarization around 0.98

Why natural groups are so polarized?

The group is fragile
during the decision



fast information transfer keeps
group's decoherence to a minimum

$$c_s \propto \frac{1}{\sqrt{1-\Phi}}$$

to achieve large speed of propagation of the
information, strong polarization is necessary

The link between swift decision-making and large polarization may be the evolutionary
drive behind the strong ordering observed in many living groups

Based on

- ✧ Information transfer and behavioural inertia in starling flocks

  Nature Physics, 2014 September issue

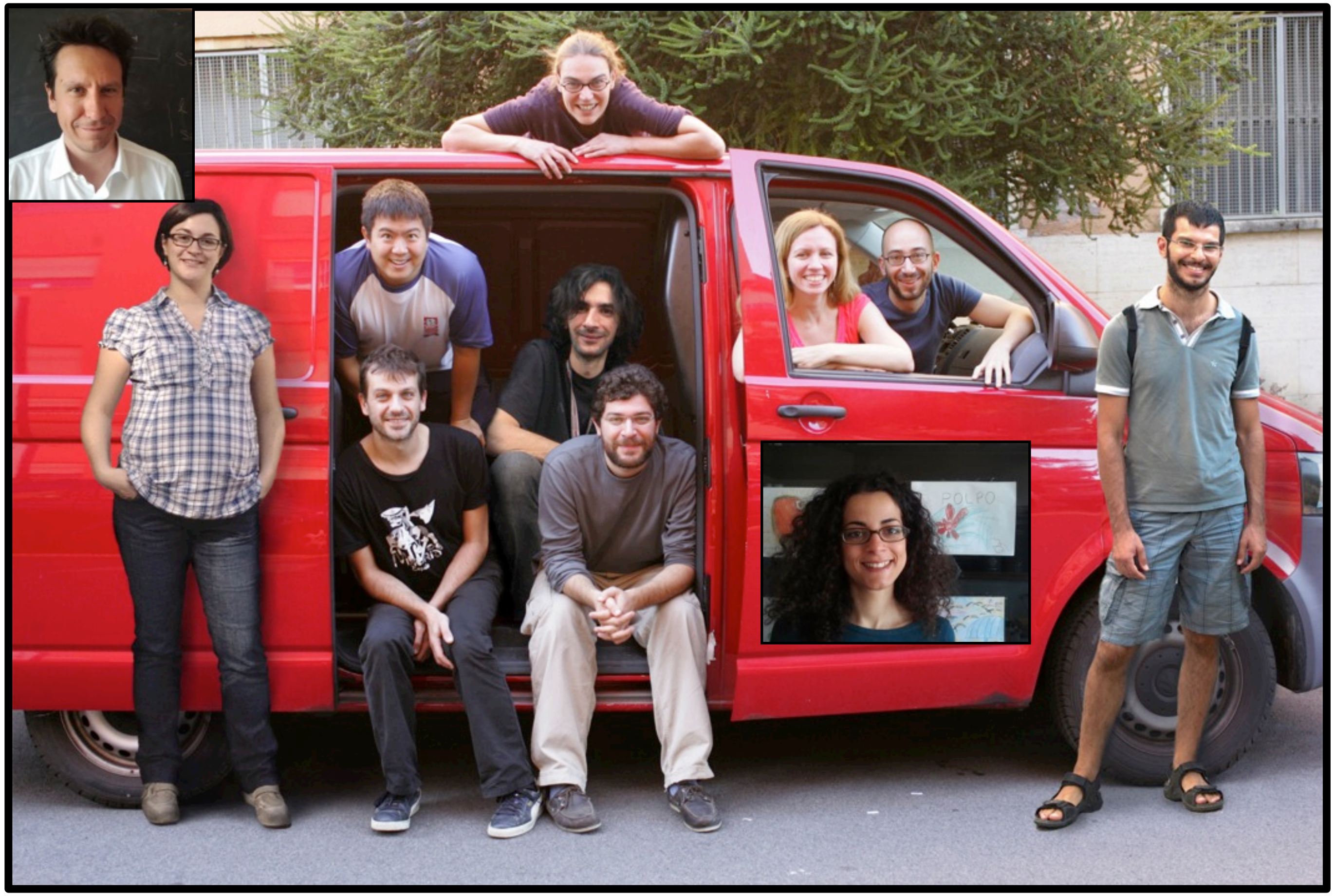
- ✧ Tracking in three dimensions via multi-path branching

  arXiv:1305.1495

- ✧ Flocking and turning: a new model for self-organized collective motion

  arXiv:1403.1202

The team



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Oliver Pohl
Edmondo Silvestri
Ed Shen
Massimiliano Viale
Agnese D'Orazio

and... the Big Red