Starlings in flight

understanding patterns of animal group movements
from the complex system perspective

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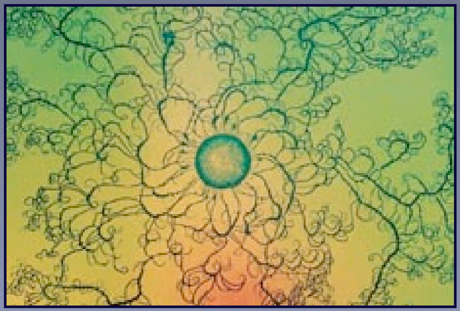
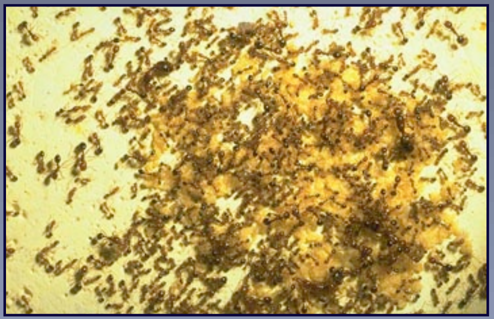
STARLING FLOCKS

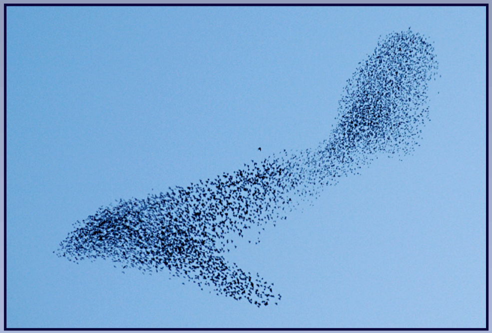
Termini railway station, Rome
Evening roosting time, November 2004

<u>Collective phenomena</u> often occur in biological systems

Bacteria colonies , blood cells, insects swarms, fish schools, birds flocks, quadrupets herds



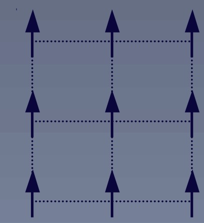




What are the rules governing coordination and collective motion ?

Collective phenomena have been widely studied in physics

- *Cooperative behaviour in phase transitions and ordering*
- *Local interactions can generate long range order*
- *Universality, renormalization* → *the details are not important*
- *Efficient simple models*



The Physics Paradigm

⬇

the microscopic mechanisms determining flocking pattern formation and coordinated collective motion are local and simple and do not depend dramatically on the complex nature of the individuals

Hypothesis !

SIMPLE MODELS

Minimal Models of Flocking

Each individual bird determines its direction of motion on each time step by averaging the direction of its neighbours (allelomimesis) with some noise

Self-Propelled Particles

Reynolds, Comput. Graph., 87

Vicsek et al., PRL 95

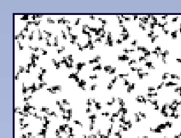
$$\theta_i(t+1) = \arg\left[\sum_{j\sim i} \vec{v}_j(t)\right] + \eta_i(t)$$

direction — *velocity* — *noise*

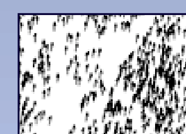
- Nonequilibrium analog of the ferromagnetic XY model (in 2D) *Rotational Symmetry*

- Onset of collective motion for small noise, even in 2D *(Mermin-Wagner does NOT hold)*

$$\phi = \frac{1}{Nv}\left|\sum_i \vec{v}_i(t)\right|$$



$|\eta|=2$
$\phi=0$



$|\eta|=0.1$
$\phi>0$

- Navier-Stokes like equations for the coarse-grained velocity *Toner & Tu, PRL 1995*

Convective relevant non-linear terms ⇒

Non trivial RG fixed point

Exact exponents in D=2

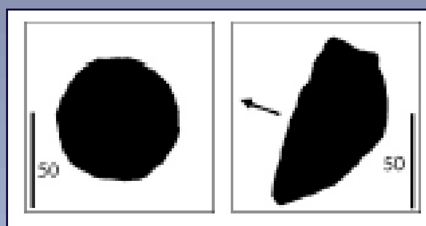
Effective long-range interactions

SPP with cohesion

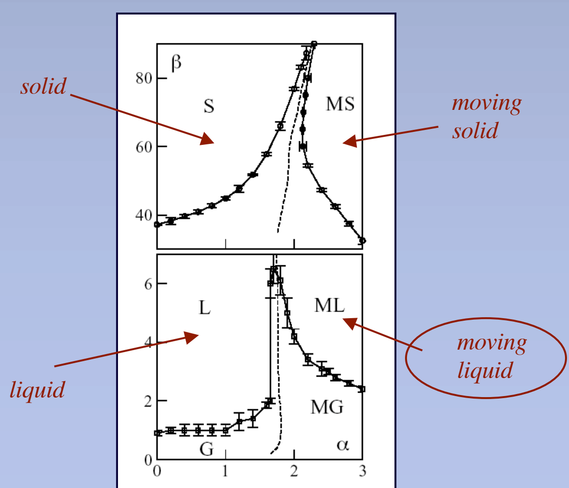
Gregoire, Chate & Tu, PRL 2001
Gregoire & Chate, PRL 2004
Gregoire, Chate & Tu, PRE 2004

$$\theta_i(t+1) = \left[\alpha \sum_{i\sim j} \vec{v}_i(t) + \beta \sum_{i\sim j} f_{ij}\right] + \eta_i(t)$$

Hard-core repulsion +
Short-range attraction (r_0)



• Non trivial infinite space limit
cohesive moving flocks in infinite space



• Complex phase diagram

$$\phi = \frac{1}{Nv}\left\|\sum_i \vec{v}_i(t)\right\|$$

Moving/Non moving

$$n_{clust} \qquad \Delta_{i\sim j}^{diff}$$

Cohesive/Sparse
Gas - Liquid - Solid

• Discontinuous first order transitions

Experiments

Stereoscopic 3D reconstruction of
- Flock shape and movement
- Individual birds positions
- Individual birds trajectories

Stereoscopic Photography

2 D images

↓

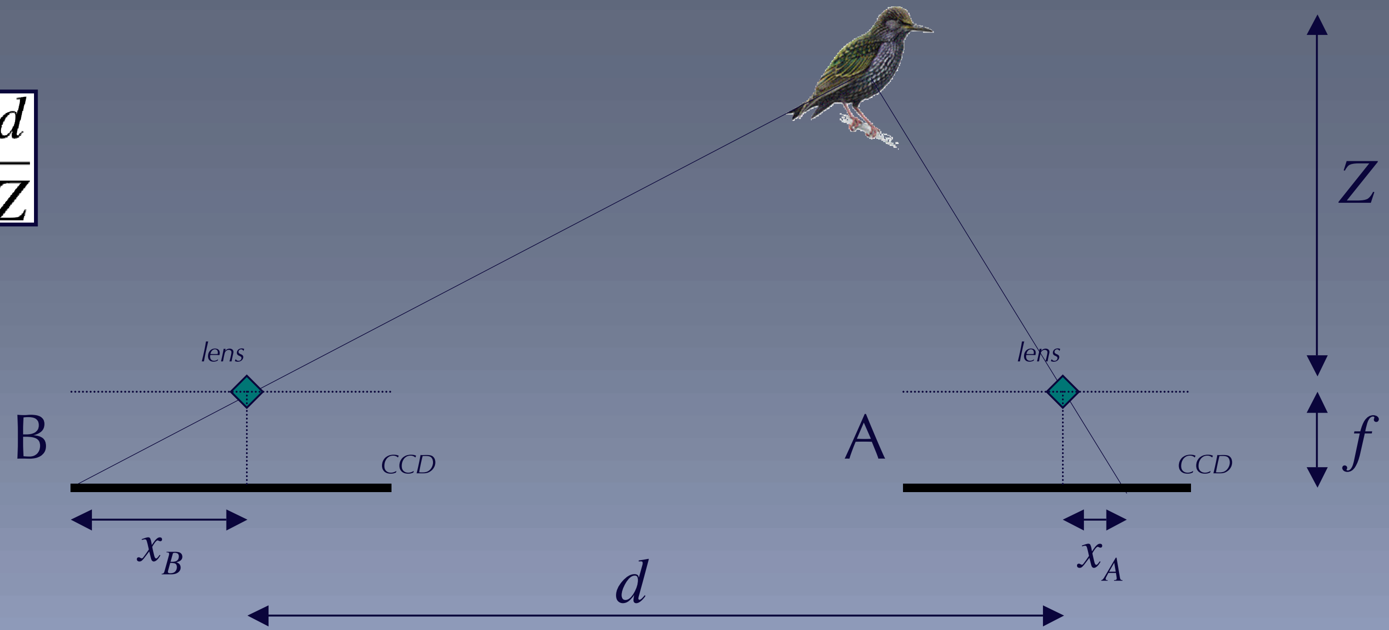
3D coordinates

Stereometry

- image elaboration
- birds recognition
- stereoscopic matching
- epipolar post-calibration

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

Stereoscopic shift



- the larger the distance, the better the resolution

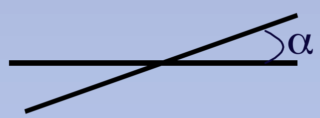
neighbouring birds

$$\delta s = f\,\frac{d}{Z^2}\,\delta Z$$

f = 4000
Z = 200 m
δZ = 0.5 m
δs = 1

⇒ d = 20 m

- misalignements strongly affect absolute distances

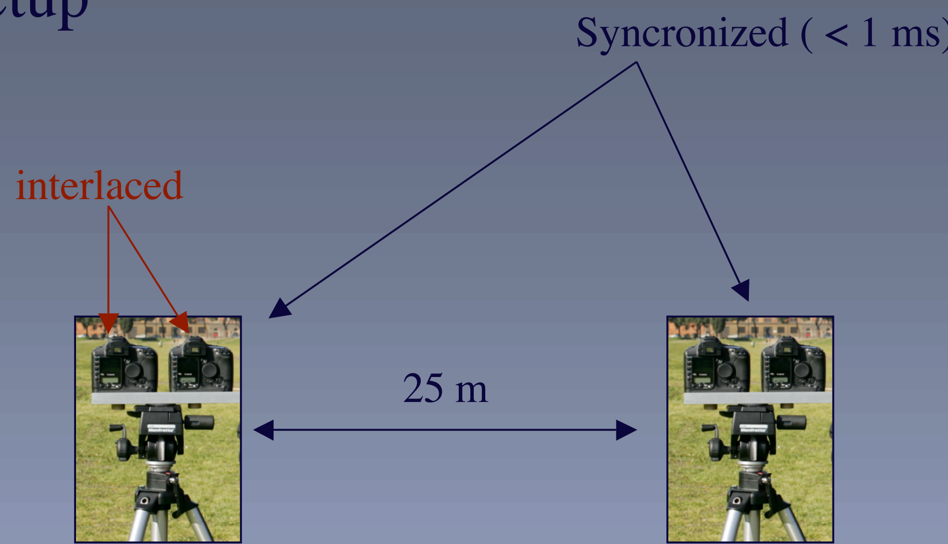


$$\frac{\delta Z}{Z} = \alpha\,\frac{Z}{d}$$

α = 0.001 rad $\delta Z/Z$ = 2.0 / 200
α = 0.0003 rad $\delta Z/Z$ = 0.5 / 200

The setup

Palazzo Massimo, Rome



- <u>Alignement</u>

  There are 5 external angles to be fixed → *4 with precision ~ 0.001 rad* / → *1 with precision ~ 0.0005 rad*

- <u>Calibration</u>

  There are the internal parameters to be calibrated (or postcalibrated)

- <u>Temporization</u>

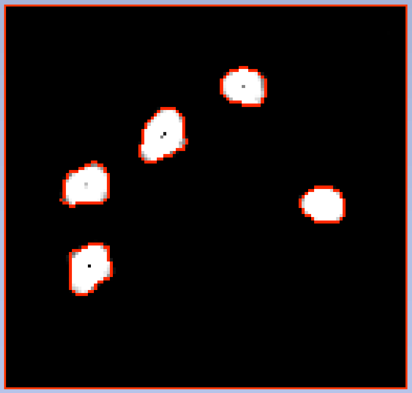
  5fps @ 16m/s : *birds travel 3.2 m between two consecutive shots*

  2 interlaced cameras ⇒ 10 fps *1.6 m*

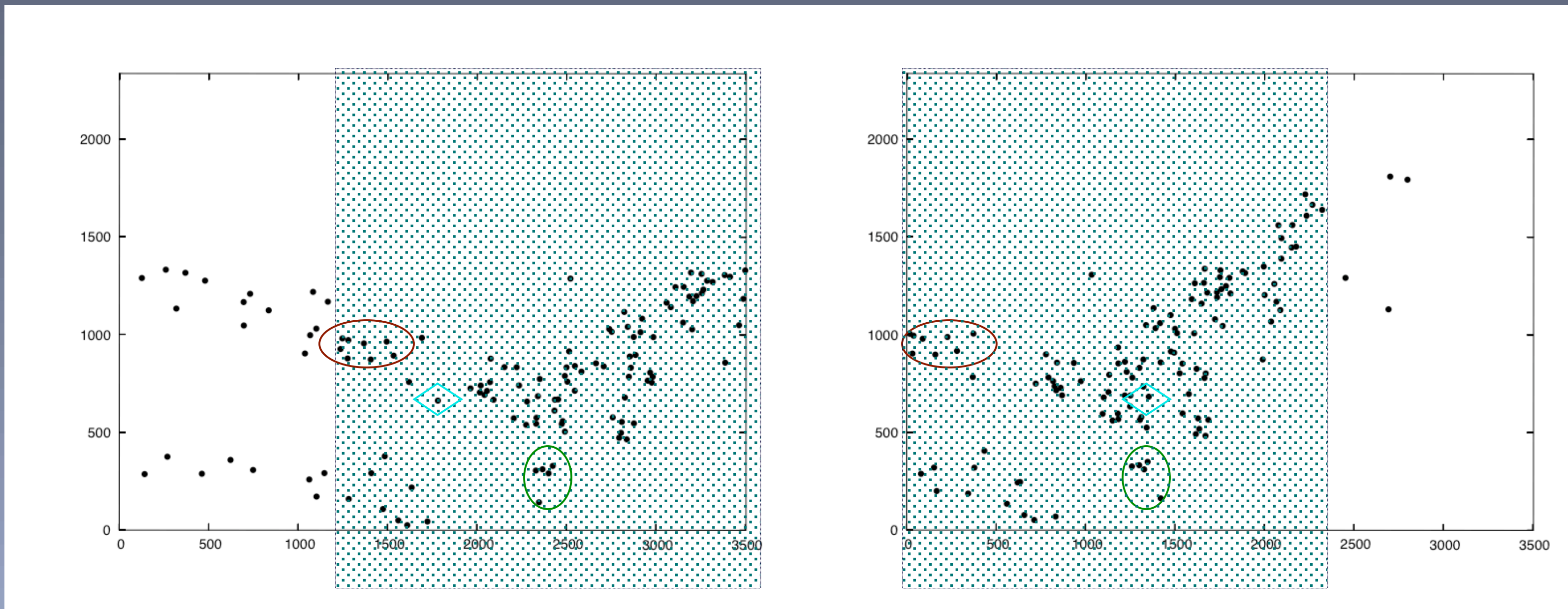
Matching and 3D reconstruction

- <u>Bird recognition</u>

Contrast filters, segmentation algorithms



- <u>Matching</u>



1) Pattern recognition algorithm → Zero-matching (partial) M_0

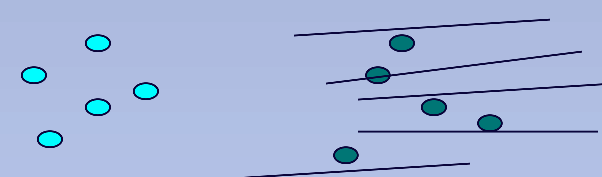
2) Epipolar geometry

$$r_B^T \, F \, r_A = 0$$

F = *fundamental matrix*

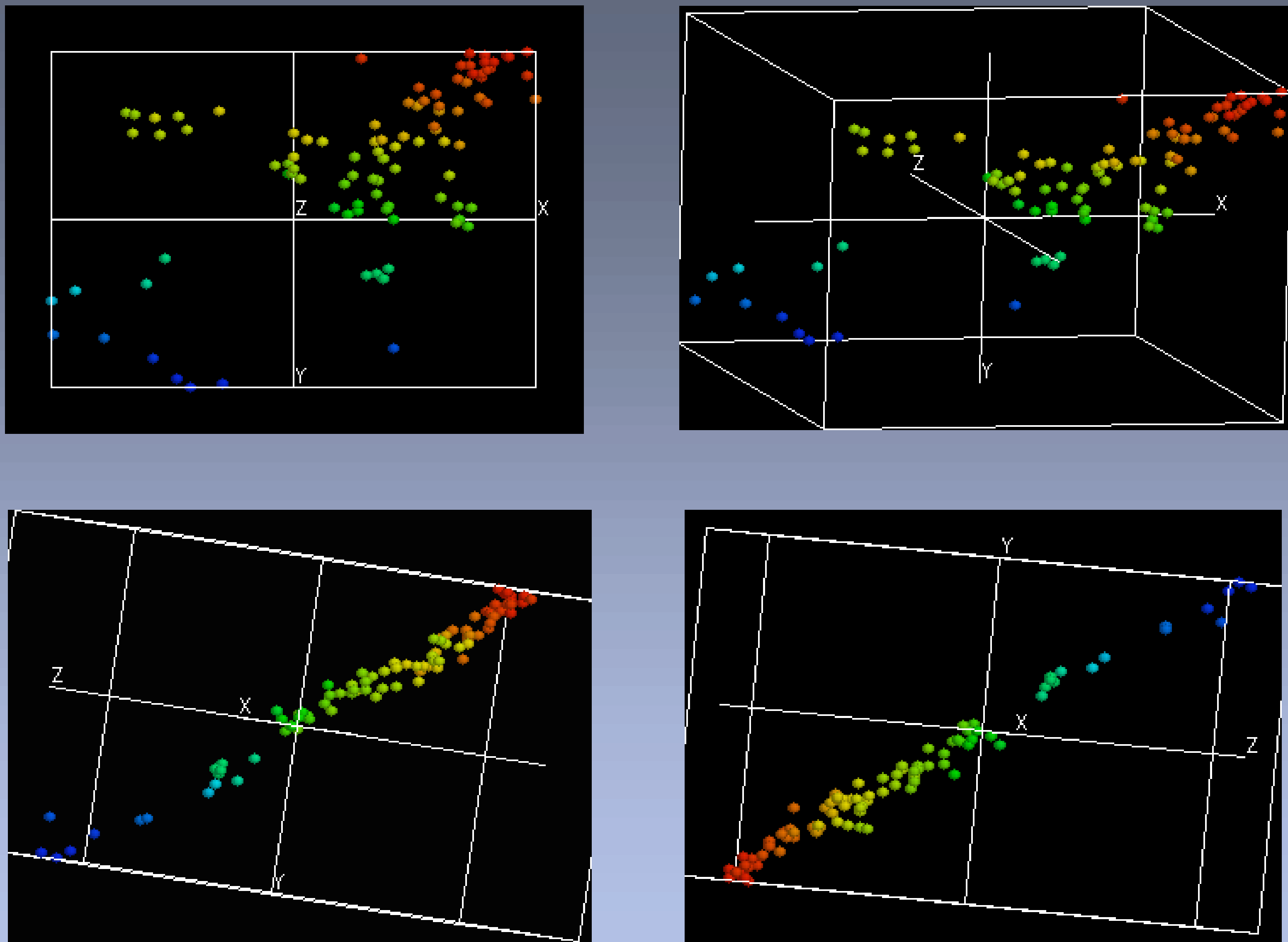
depends on the angles !

affected by JPEG Noise



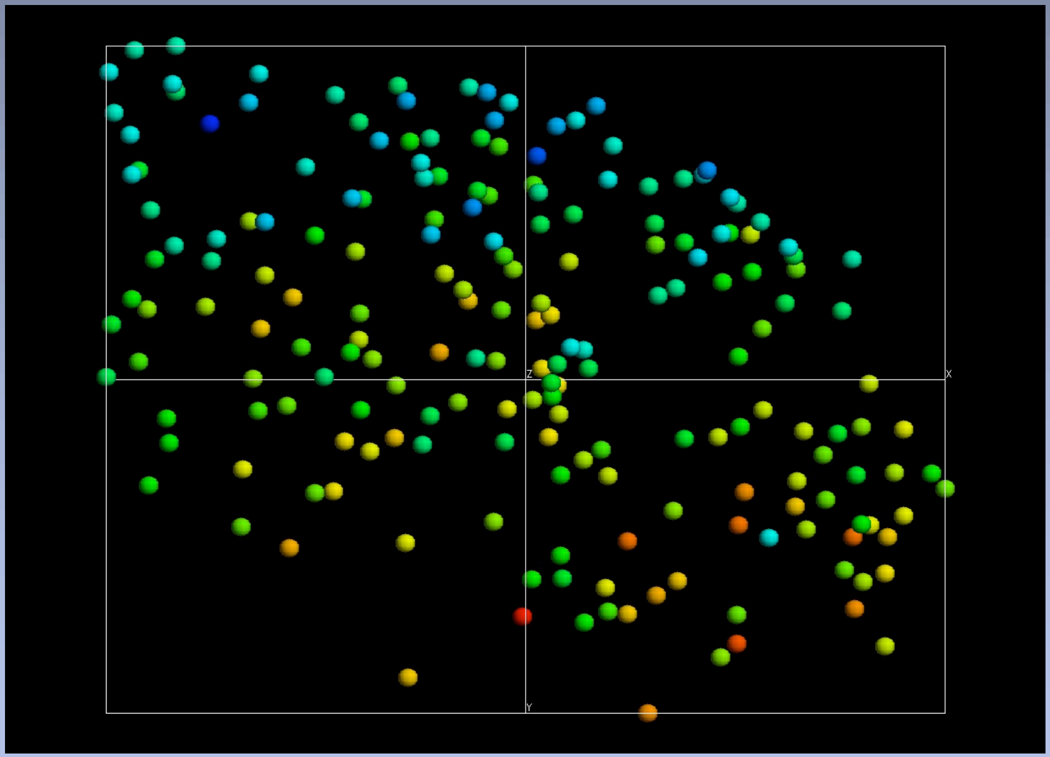
3) K-assignement

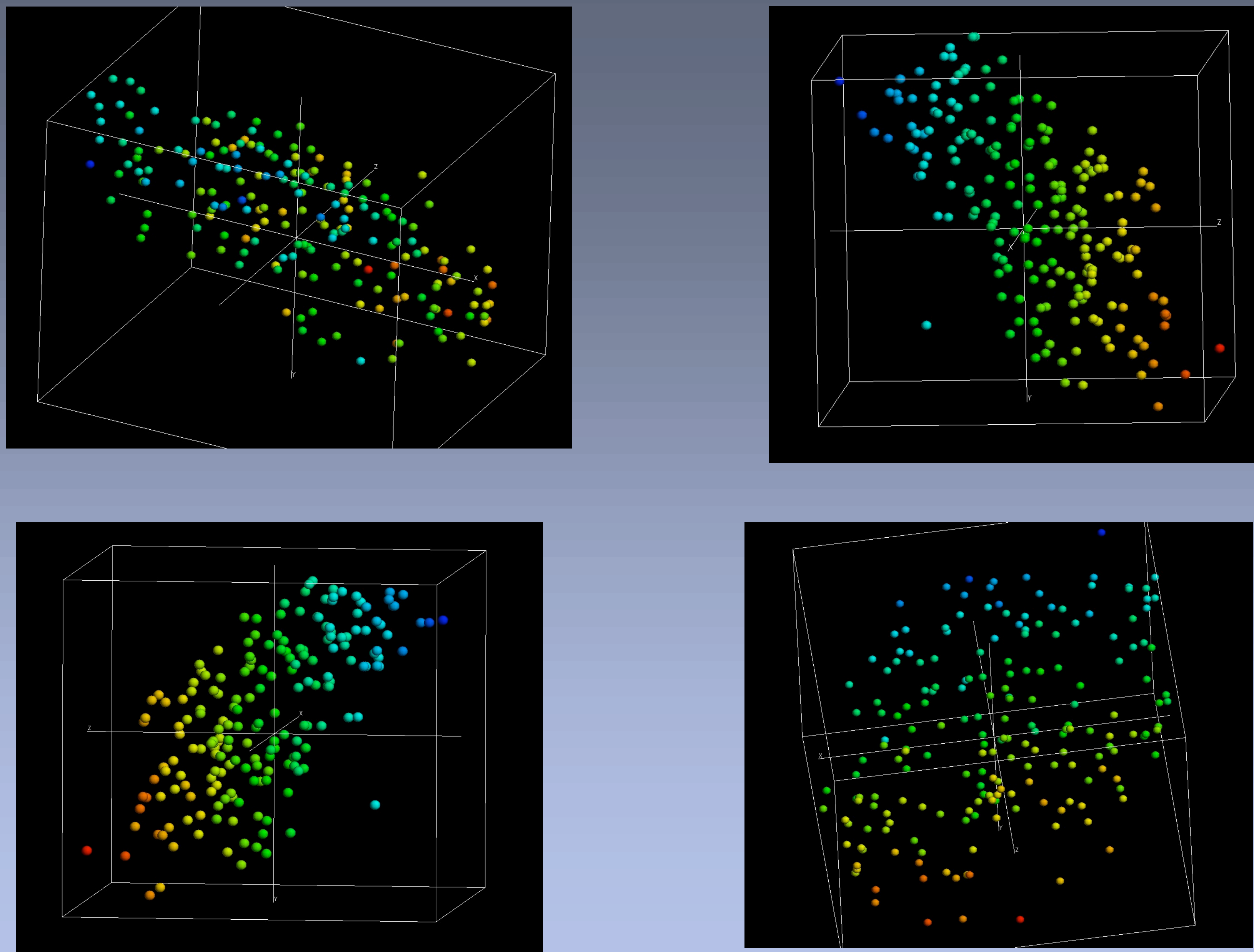
Matching between different set of points with measure F



Planar structure !

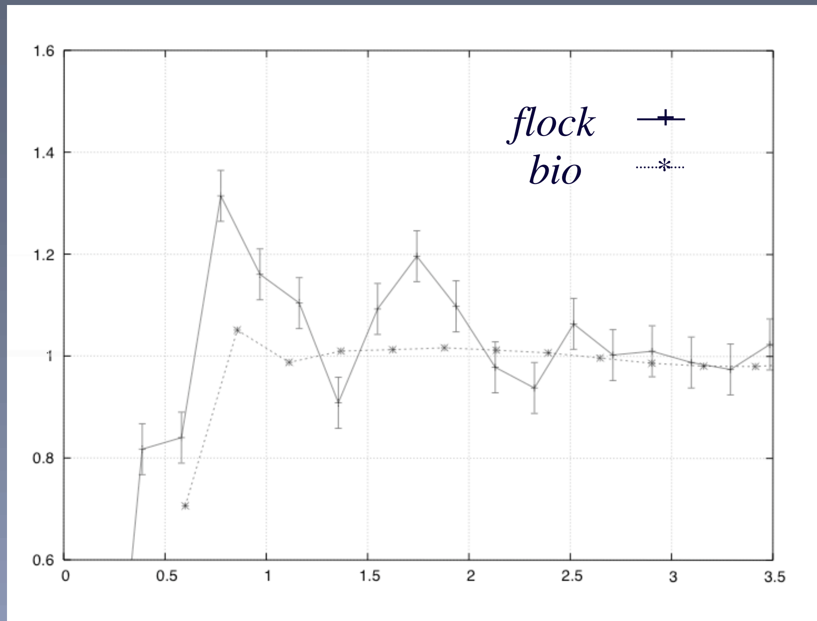
A more complex flock





Discoidal shape

$g(r)$

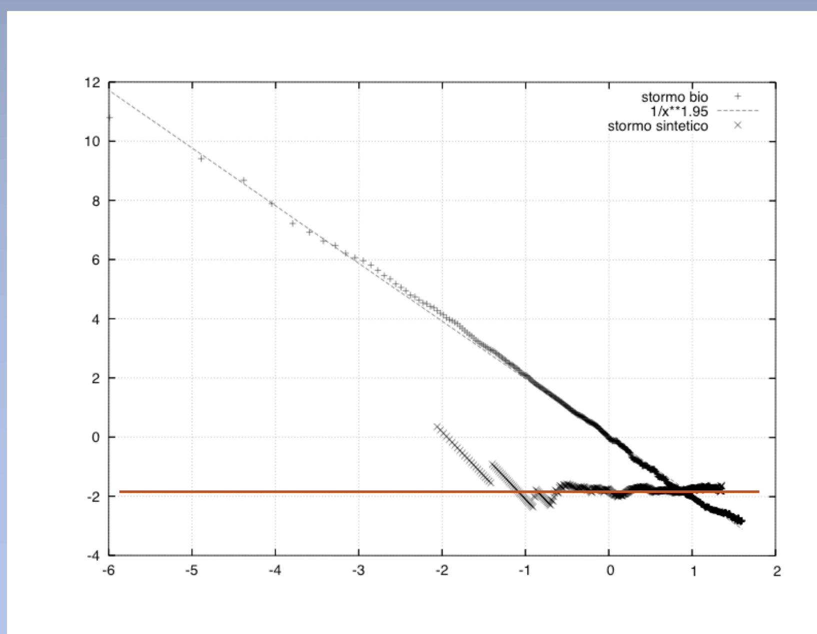


r

Radial distribution function $g(r)$

Liquid like !!!

$\Gamma(r)$



r

Conditional mass $\Gamma(r)$

Scale free (???) *very preliminary*

Finite size effect (L< L*)
Errors in segmentation
Errors in matching ?

Density = N/V

Synthetic flock with same V, N and overall shape as the bio one, but with a uniform distribution of points

Summary and Perspectives

- 3D reconstruction of starling flocks is demanding but possible

- Experimental efficiency related to

  Camera specifications (Canon Eos D Mark II, 8.2 Mp, 8.5 fps)
  alignement capabilities

- Static reconstruction of individual flocks

- Statistics → correlation functions, shape, heterogeneity

- Dynamics → trajectory reconstruction, diffusion, convection

Comparison with models

The team

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