UNIVERSITÉ LIBRE DE BRUXELLES
Interdisciplinary Centre of Nonlinear Phenomena and Complex Systems (CeNoLi-ULB)
&
Department of Physics of Complex Systems and Statistical Mechanics

"Collective Dynamics Control in Physics and Biology:

Macroscopic Level: Aggregation & Self-Organization"

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<u>ODE 1 :</u> Non-standard Aggregation
(the story of the genesis of a new paradigm)

<u>Ode &Monte Carlo 1:</u> Zeolites' Fractals

<u>Ode & Monde Carlo 2:</u> Ants Sharing Food

<u>ODE 2:</u> Seek a Shelter and Try to Settle Down

a history of a new paradigm

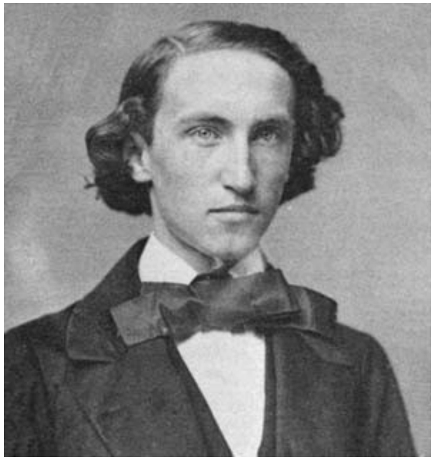
Non-standard Aggregation:

Crystallization,

Nucleation,

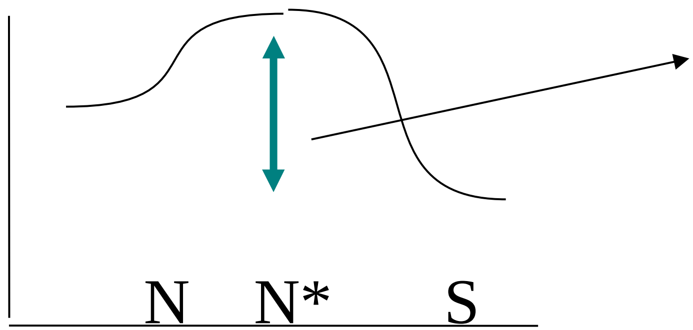
Self-assembly

And the role of intermediate crecursors



Josiah Willard Gibbs
(1839 - 1903)

stealing an idea from Gibbs to understand nucleation:



$\Delta G = n(j)\,\Delta G(j) - T\Delta S(n(j))$

$[\, d\,\Delta G / d\; n(j)\,] = 0$ at $n^*(i)$

Equilibrium Assumption

$N \rightleftarrows N^* \longrightarrow S$

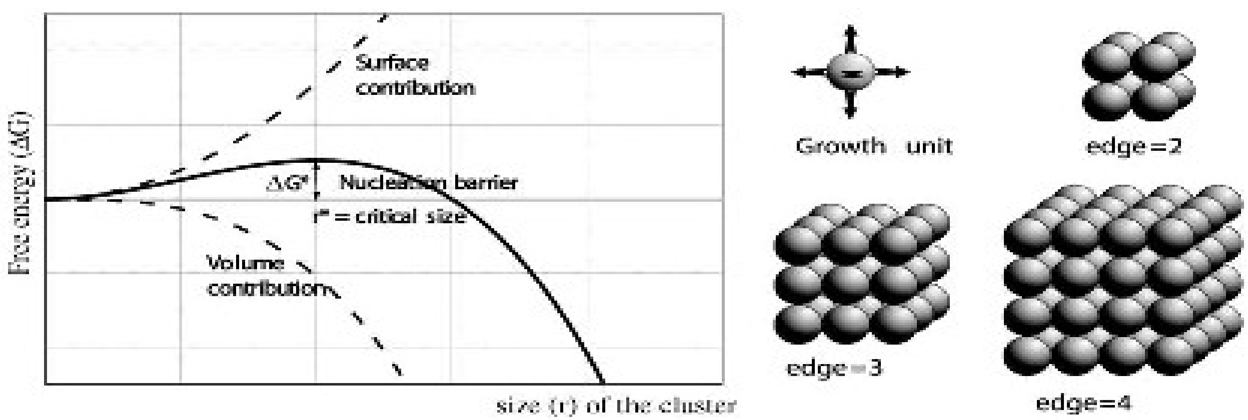
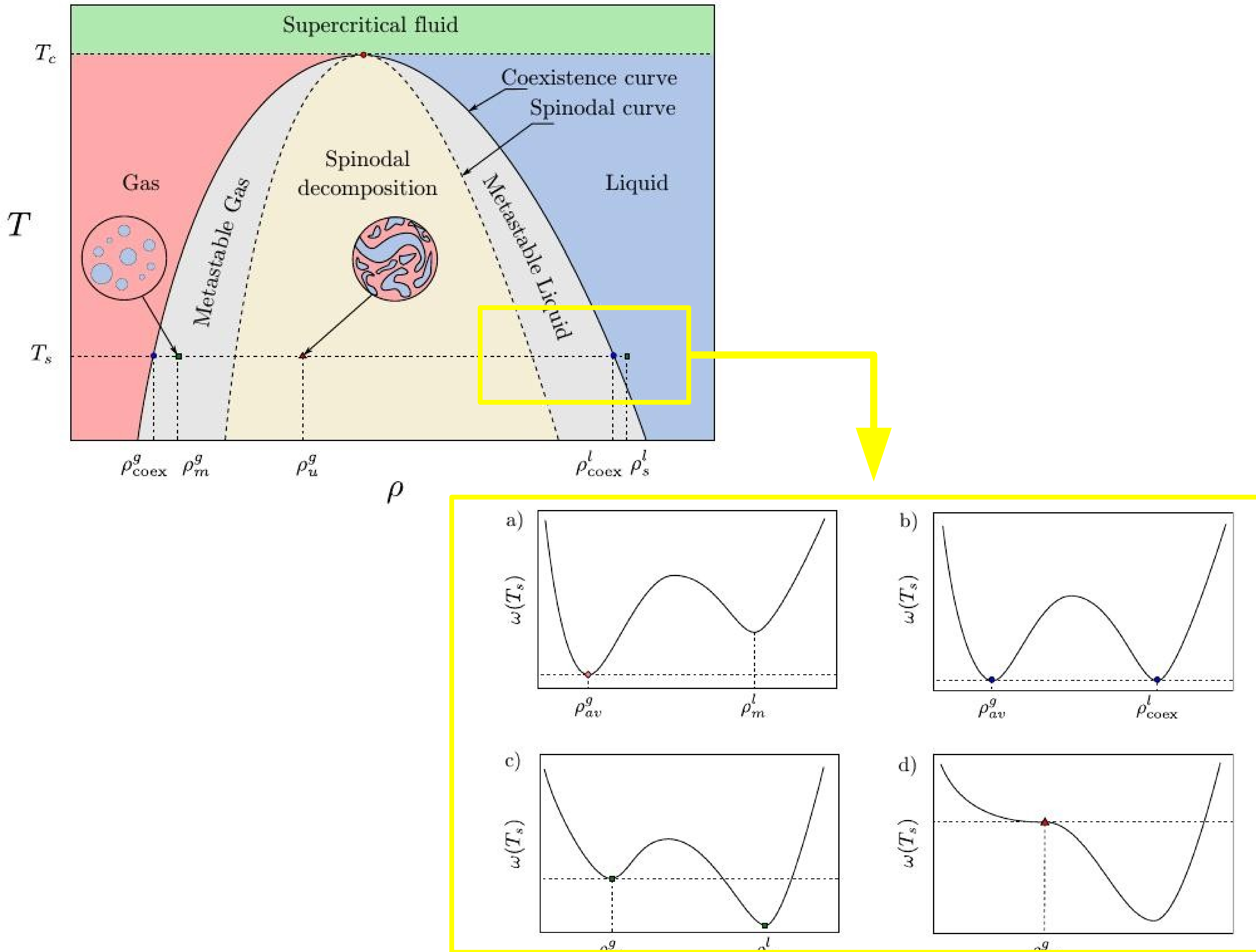
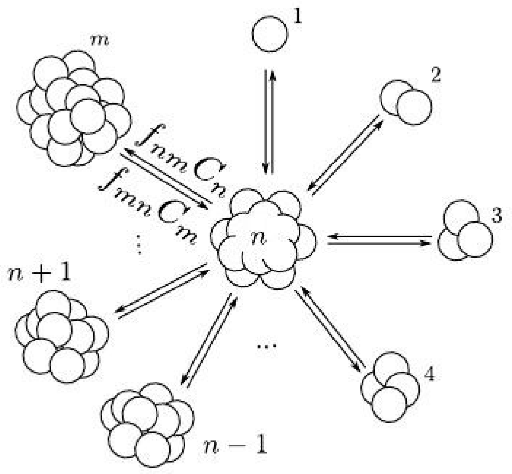
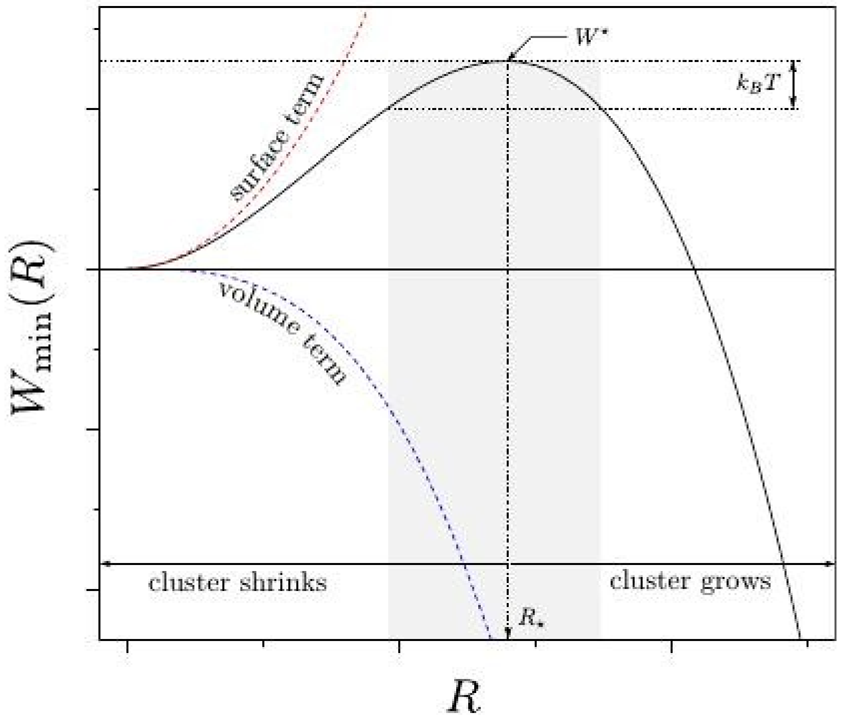


Fig. 1. Energetics of cubic cluster formation as a function of the cluster's size.



Supercritical fluid
T_c
Coexistence curve
Spinodal curve
Spinodal decomposition
Gas
Liquid
Metastable Gas
Metastable Liquid
T
T_s
ρ^g_{coex} ρ^g_m ρ^g_u ρ^l_{coex} ρ^l_s
ρ
a)
$\omega(T_s)$
ρ^g_{av} ρ^l_m
b)
$\omega(T_s)$
ρ^g_{av} ρ^l_{coex}
c)
$\omega(T_s)$
ρ^g_{av} ρ^l_s
d)
$\omega(T_s)$
ρ^g_{av}



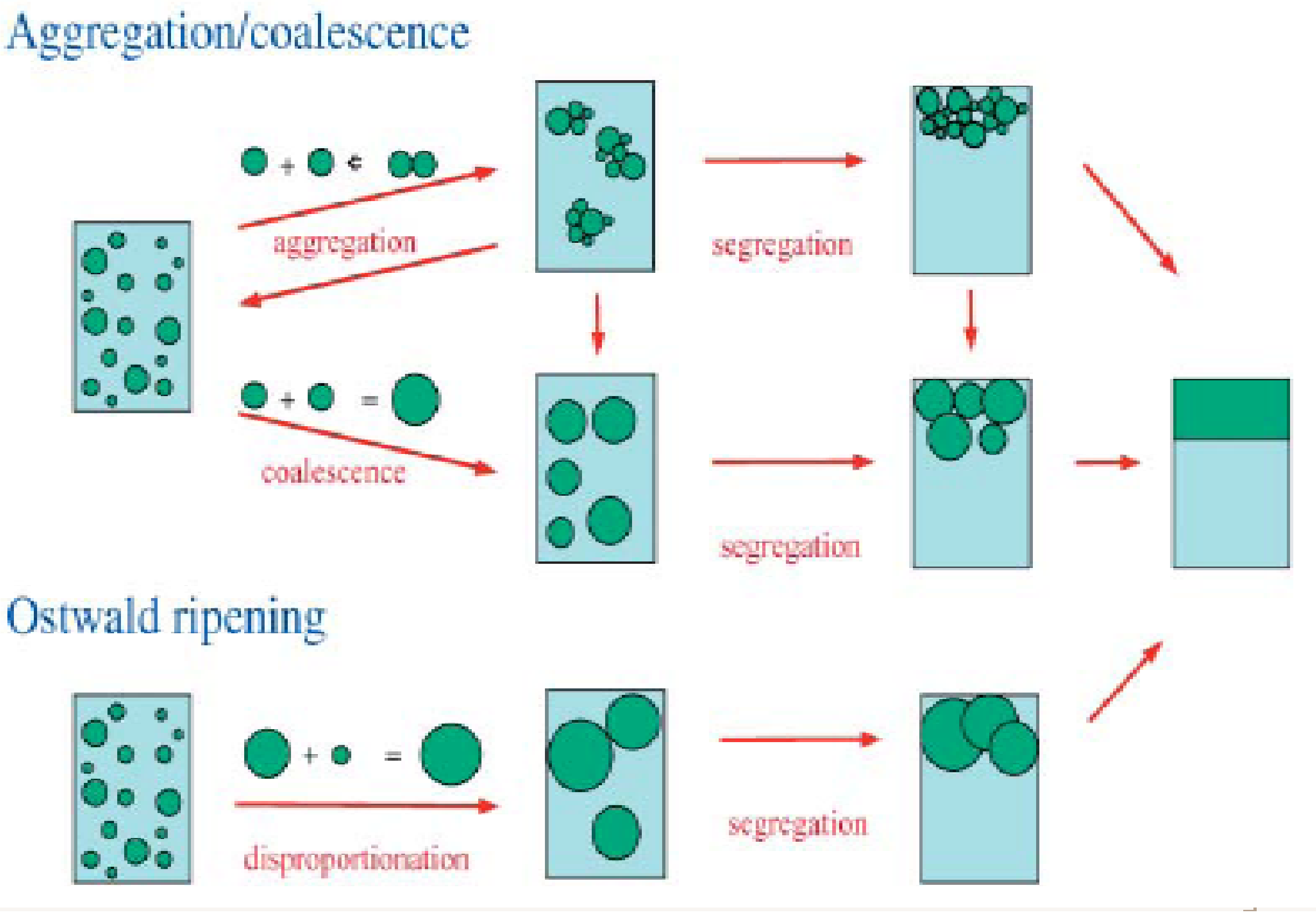


$$W_{\min}(R) = (\omega(\rho_{\text{new}}, T) - \omega(\rho_{av}, T))\,\frac{4\pi}{3}R^3 + \alpha_{R\to\infty}4\pi R^2$$
$$= \frac{4\pi}{3}R^3\Delta\omega + 4\pi R^2\,\alpha_{R\to\infty}.$$

Capilary Approximation

$\rho_{cl} = \rho_{\text{new}}$. That is, the distinctive properties of the small condensed phase are size independent.

The surface tension, so-called surface free energy, is the same as for a planar interface of the new and the mother phase. That is equivalent to assume clusters with a sharp boundary. That is, $\alpha(R) = \alpha_{R\to\infty} + \mathcal{O}(R)$

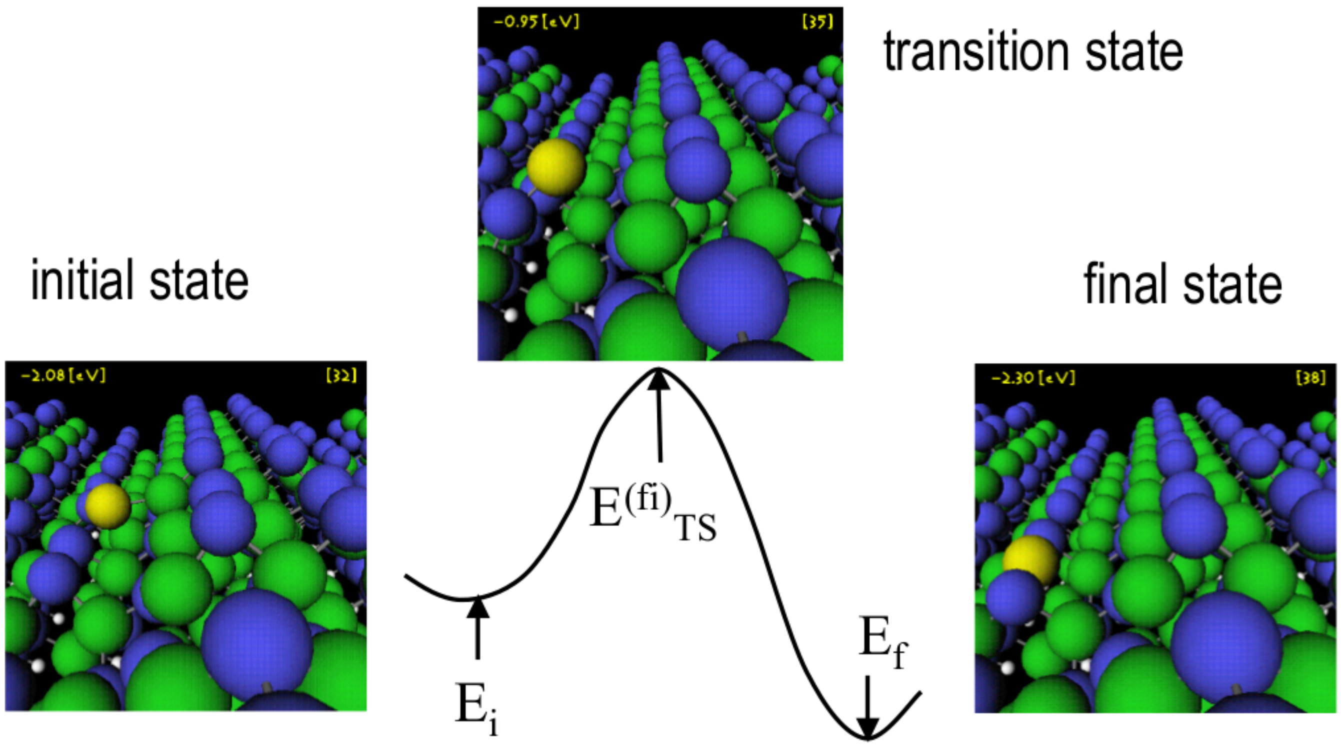


Classical aggregation -- nucleation:

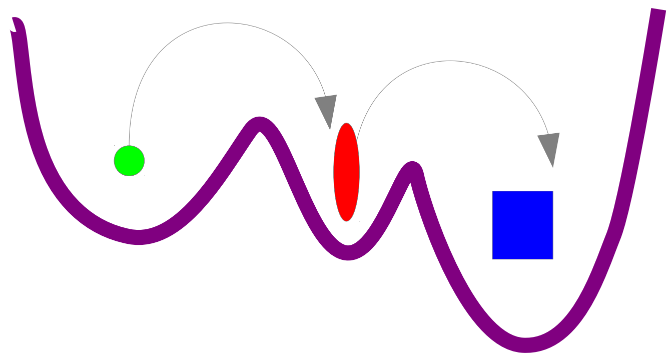
- Equilibrium, kinetics are “averaged out”
- Large critical nucleus, small isotropic molecules
- Single phases one for the liquid and one for the solid
- One reaction coordinate

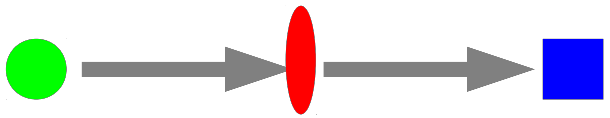
transition states for reactive processes

$$\Gamma^{(k)} = W(f,i) = \Gamma^{(fi)}_0 \exp(- (E^{(fi)}_{TS} - E_i)/kT)$$

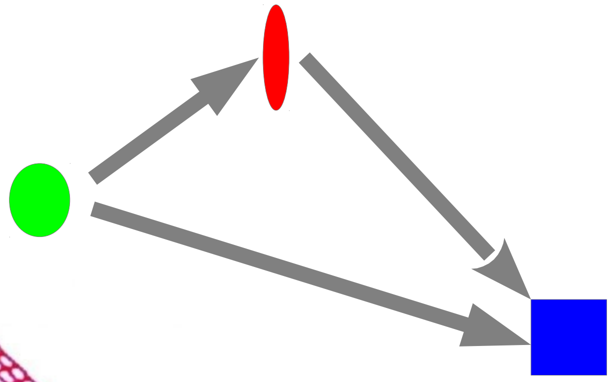


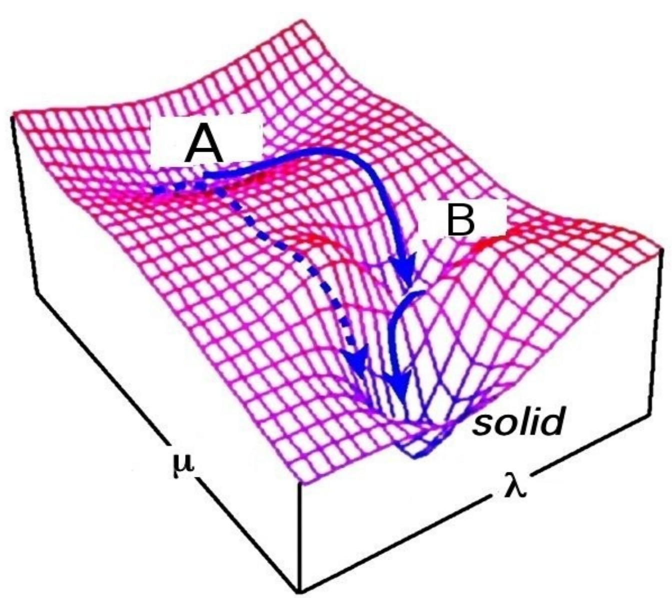
2-steps & ONE order-parameter

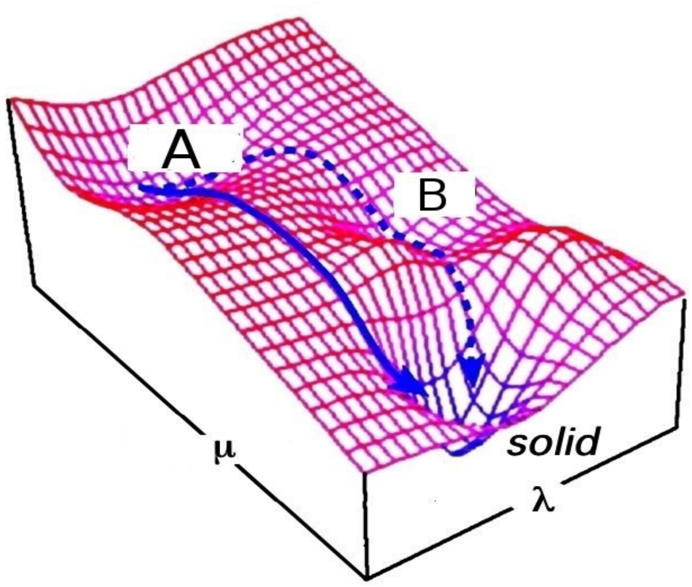




2-steps & TWO order-parameters



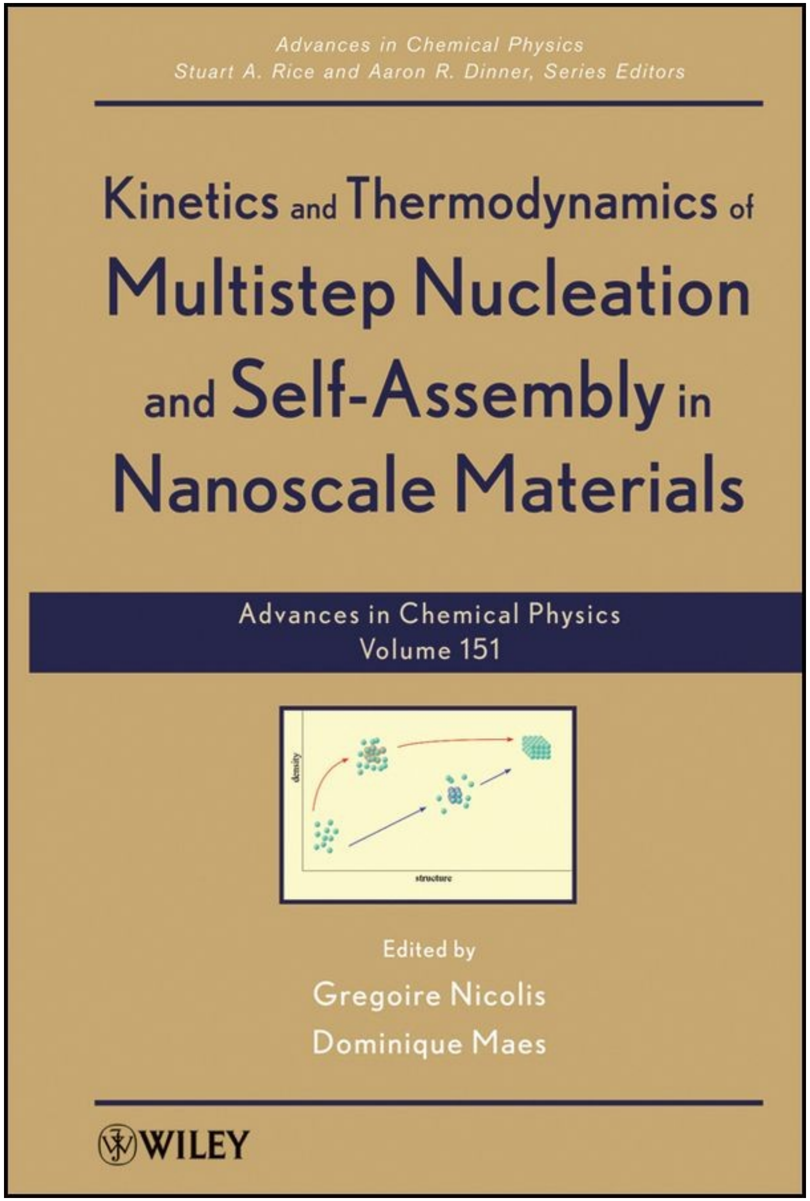




ODE model I:

Bifurcations in multistep aggregation

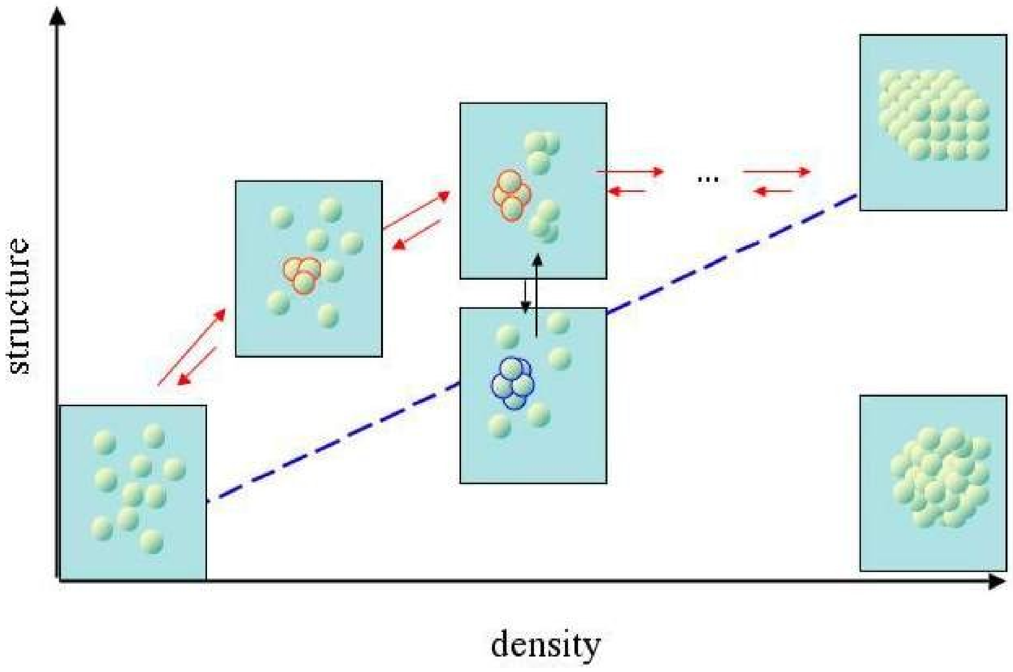
“A new paradigm”



Non standard nucleation mechanisms with combined structural and density fluctuations

- Importance of kinetic effects arising from the co-existence of competing mechanisms

- Enhancement of nucleation rate under certain conditions via favourable pathways in the two order-parameter phase diagram



"Nonlinear Dynamics and Self-organization in the Presence of Metastable Phases"
G. Nicolis & C. Nicolis

Kinetics of barrier crossing : formulation

$\rho, \; m$ order parameters

$\lambda, \; \mu, \cdots$ control parameters

F Landau type free energy

L matrix of Onsager coefficients

Transitions between states governed by

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\rho \\ m\end{pmatrix} = -\text{Ł} \cdot \nabla F(\rho, \; m) + \begin{pmatrix} R_\rho(t) \\ R_m(t)\end{pmatrix}$$

where $R_\rho, \; R_m$ are Gaussian white noises whose covariance matrix must satisfy fluctuation-dissipation type relationships

Kinetic potential and its bifurcation set

Requirements :
Switch as the control parameters are varied, from

$$F_1 \rightarrow S\,(2\ -\text{well}\ U)$$

to

$$F_1 \underset{\longrightarrow}{\overset{\longleftarrow}{}} F_2 \rightarrow S\ \ (3\ -\text{well}\ U)$$

"Parabolic umbilic" catastrophe scenario. Full unfolding by four control parameters

Simple Model Equations:

$$\frac{dx}{dt} = -\frac{\partial U}{\partial x} = -\lambda x - \mu x^2 + \gamma y^2 - x^3,$$
$$\frac{dy}{dt} = -\frac{\partial U}{\partial y} = -\lambda y + 2\gamma xy - y^3 ,$$

Steady states:

$$-\lambda x_S - \mu x_S^2 + \gamma y_S^2 - x_S^3 = 0 ,$$
$$-\lambda y_S + 2\gamma x_S y_S - y_S^3 = 0 ,$$

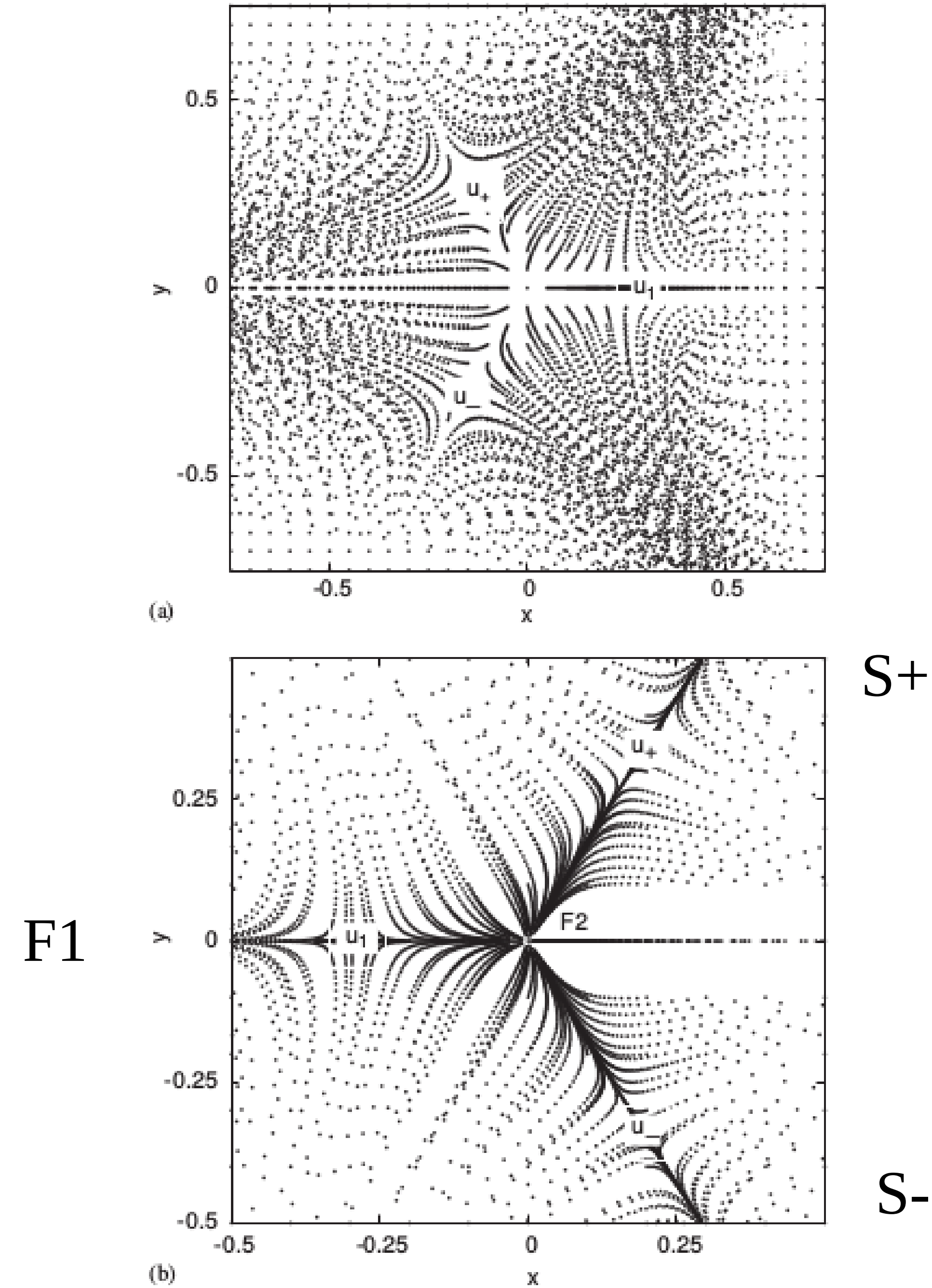
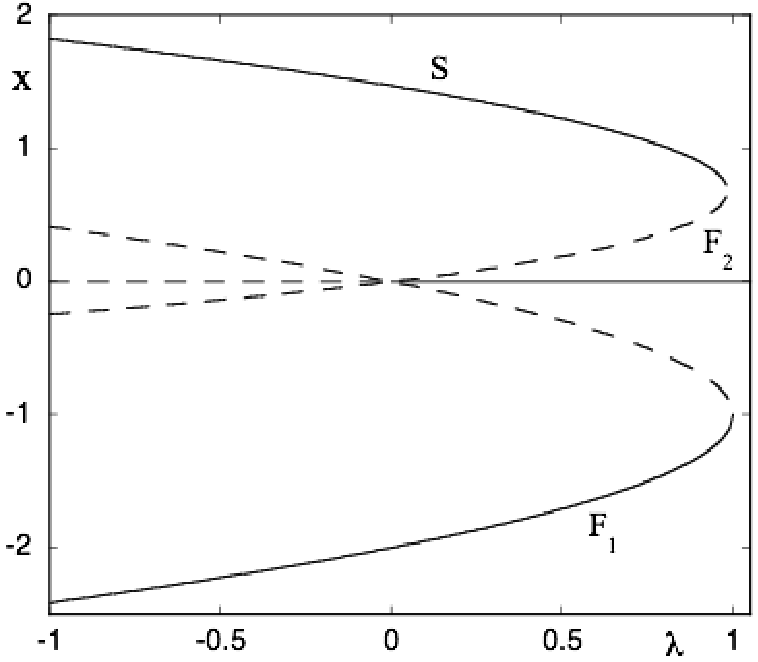


Fig. 4. Phase portraits of system (19) in the region of 3 stable steady states, $\lambda = -0.5$ (a) and in the region of 4 stable steady states, $\lambda = 0.5$ (b) with $\mu = 2$. The u's stand for the unstable states involved in the transitions. State $F1$ is in the far left of the diagrams and states S_+, S_- in the far up right and down right parts.

In absence of external fields and other sources of asymmetry

$$U(x,y) = \frac{\lambda}{2}\left(x^2 + y^2\right) + \frac{\mu}{3}x^3 - \gamma x y^2 + \frac{1}{4}\left(x^4 + y^4\right)$$



Transition dynamics

$\lambda < 0,\ \mu$ fixed :

direct transition $F_1 \to S$

$$\frac{\mathrm{d}p_1}{\mathrm{d}t} = -k_1 p_1$$

transition via F_2

$$\begin{aligned}\frac{\mathrm{d}p_1}{\mathrm{d}t} &= -k_1 p_1 + k_1' p_2 \\ \frac{\mathrm{d}p_2}{\mathrm{d}t} &= k_1 p_1 - (k_1' + k_2)\, p_2\end{aligned}$$

where the $k's$ are related to mean first passage times statistics associated to the Fokker-Planck equation for $\lambda < 0$

$$k \approx \frac{1}{2\pi}\left(\frac{\sigma_u^+}{|\sigma_u^-|}\right)^{1/2}\left(\sigma_{s_1}\sigma_{s_2}\right)^{1/2} \exp\left(\frac{U\left(unst\right)-U\left(st\right)}{\epsilon}\right)$$

for $\lambda > 0$

$$\frac{1}{2}\,| -\left(k_1+k_2+k_1'\right)+\sqrt{\left(k_1-k_2\right)^2+k_1'^2+2k_1'\left(k_1+k_2\right)}\,|$$

$(k_1 \rightarrow k_2 \text{ for } k_1' << k_1)$

$\tau^{-1}\ (F_1 \longrightarrow S)$: *lowest eigenvalue*

Optimization near the F_1 - F_2 coexistence

Non -trivial cross-over at $\lambda = 0$

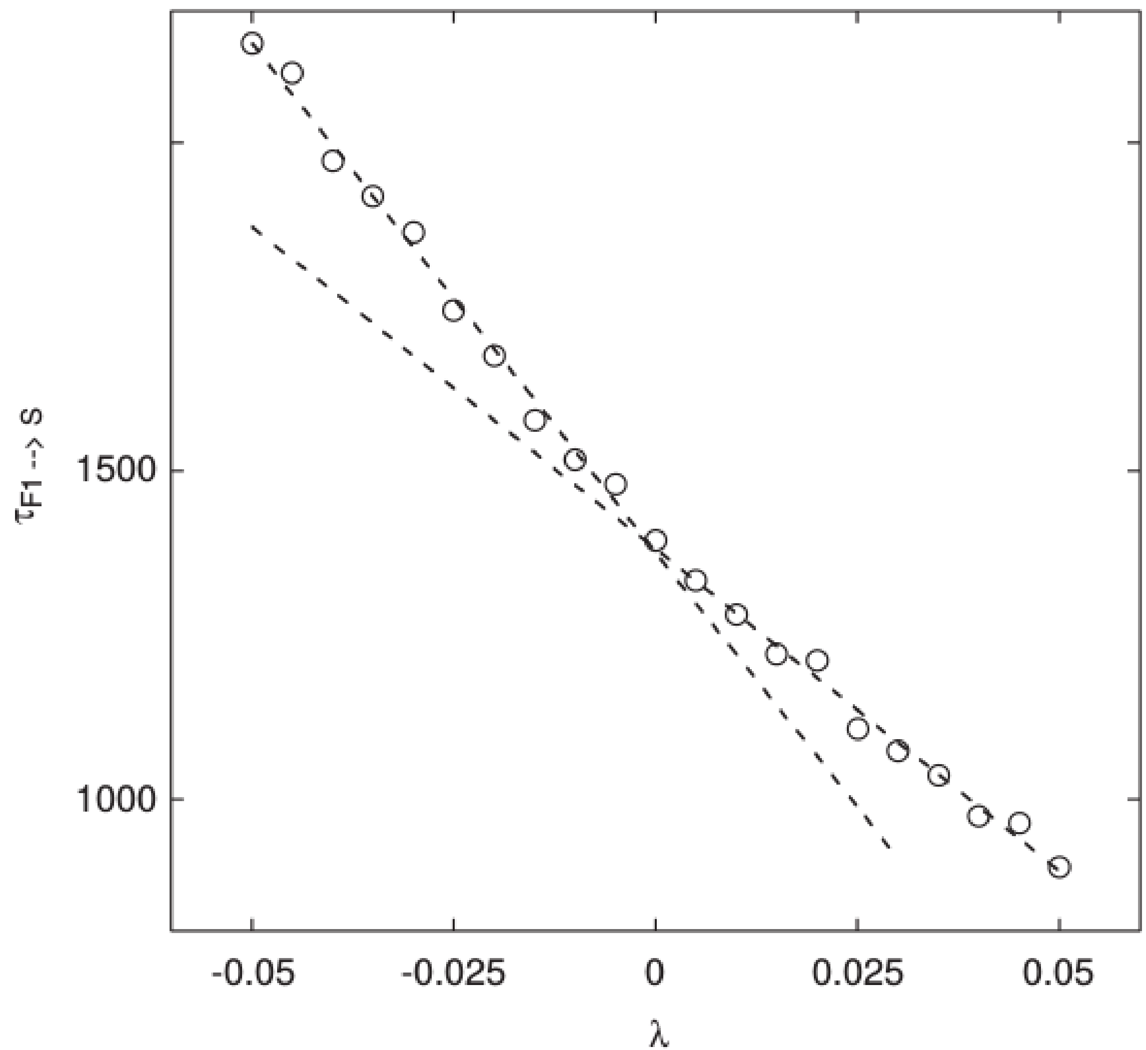
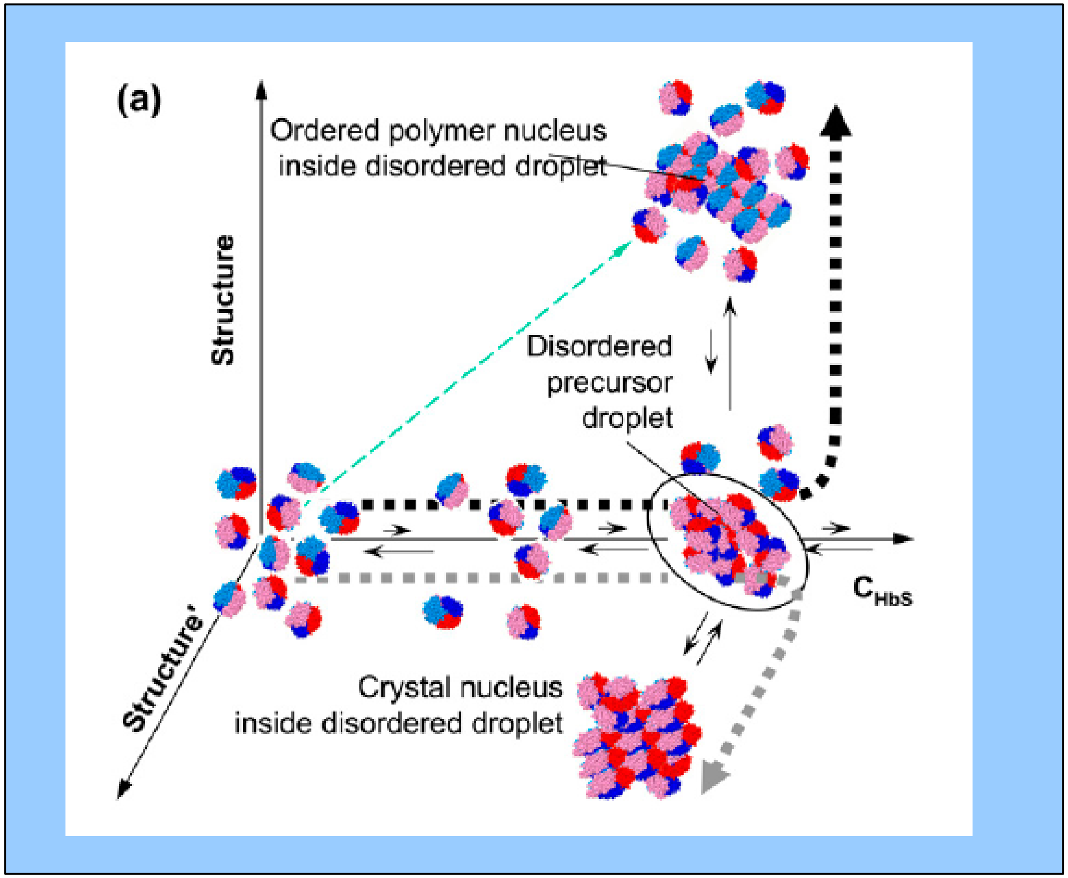


Fig. 6. Mean transition times between states $F1$ and S versus λ in the vicinity of $\lambda = 0$, obtained numerically from the Langevin equations (24) after an averaging over 5000 realizations. Dashed lines stand for linear fits in the regions $\lambda < 0$ and $\lambda > 0$. Parameter values $\mu = 2$, $\gamma = 1.6$ and $q^2 = 0.6$.

Biophysical Journal Volume 93 July 2007 1–12

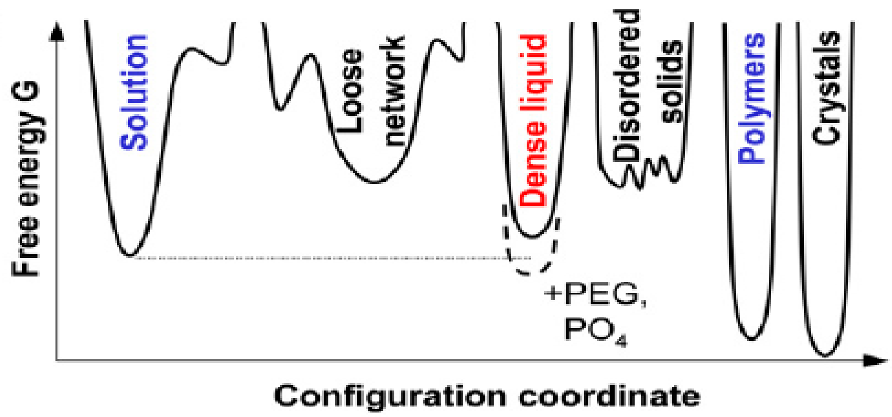
Two-Step Mechanism of Homogeneous Nucleation of Sickle Cell Hemoglobin Polymers

Oleg Galkin,* Weichun Pan,* Luis Filobelo,* Rhoda Elison Hirsch,‡§ Ronald L. Nagel,‡ and Peter G. Vekilov*



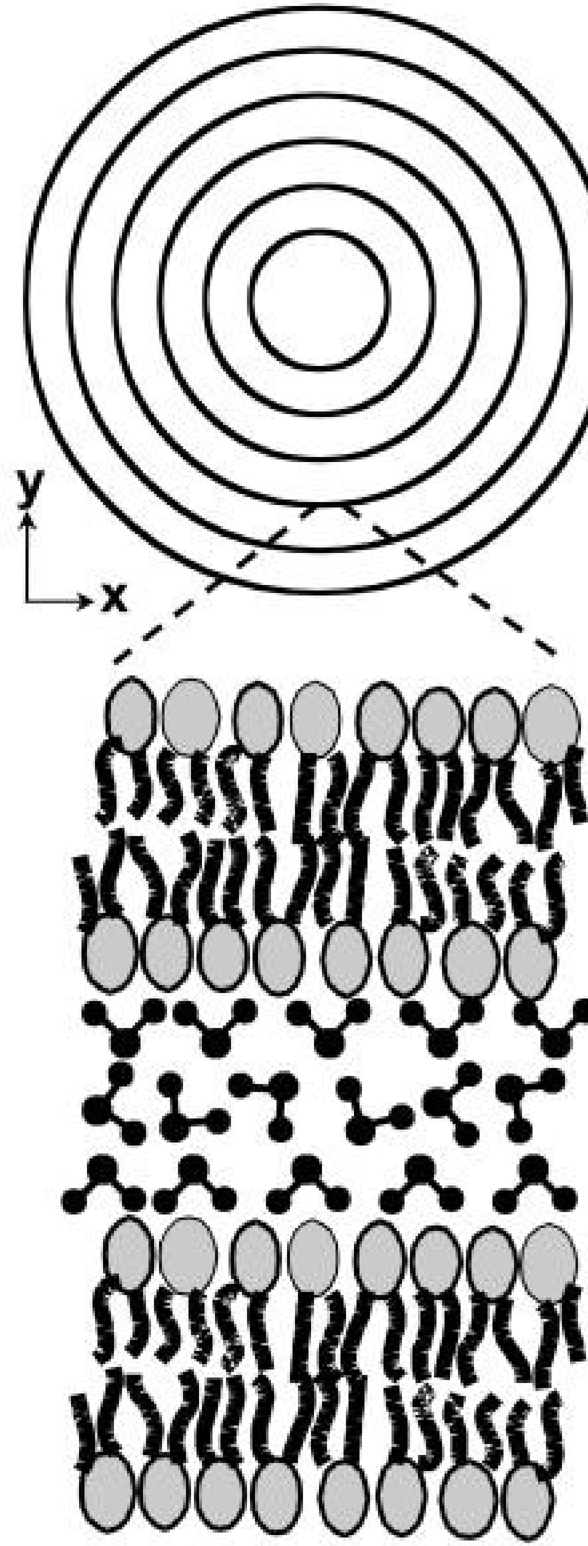
1) Barriers Around~ 100kT

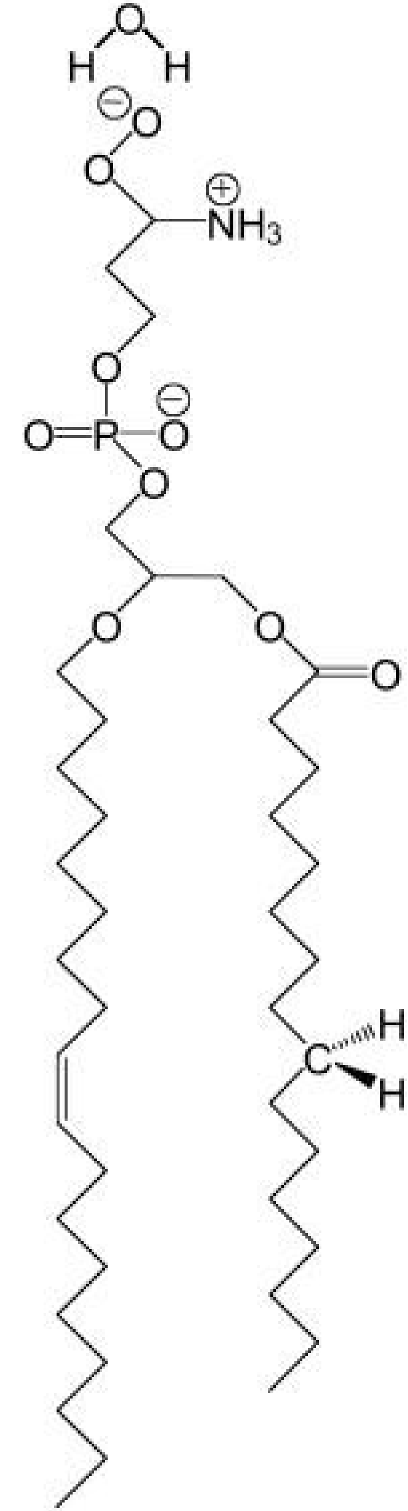
2) Weak & Short ranged interactions compared to simple fluids.



Proc Natl Acad Sci U S A. *Aug 19; 100(17): 9826–9830. 2003*

“Ordering of water molecules between phospholipid bilayers visualized by coherent anti-Stokes Raman scattering microscopy”





Monte Carlo
Lattice Simulation I:
Zeolite Aggregation
(spatiotemporal model)

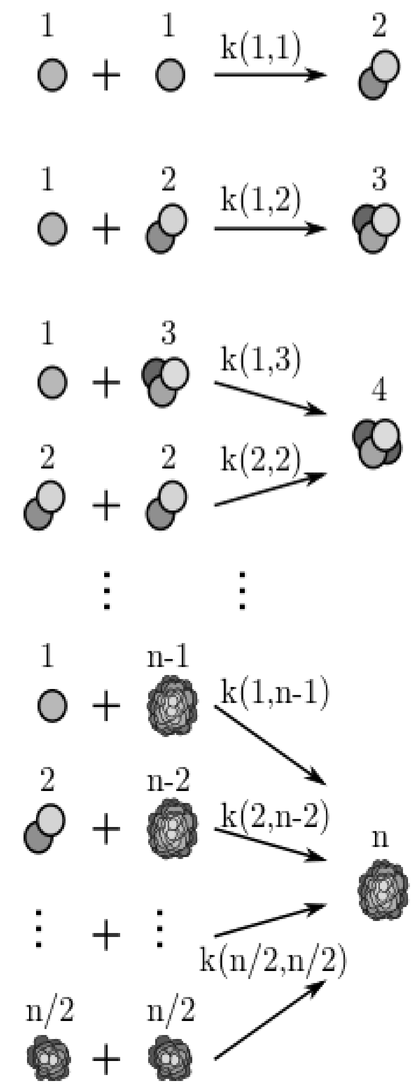
Including intermediate steps:

$$\frac{\partial n(x_i,t)}{\partial t} = \frac{1}{2}\sum_{j=1}^{i-1} K(x_i - x_j, x_j) n(x_i - x_j, t) n(x_j, t) - \sum_{j=1}^{\infty} K(x_i, x_j) n(x_i, t) n(x_j, t).$$

coagulation kernel and describes the rate at which particles different sizes coagulate

n = cluster size distribution evolution (of size x(i) at time(t))

Marian Smoluchowski coagulation equation (Stat. Mech. 1916)



Hierarchical aggregation of Zeolites: 2nd order parameter = Q4 number of Si bonds

164701-2 Lutsko *et al.* J. Chem. Phys. **132**, 164701 (2010)

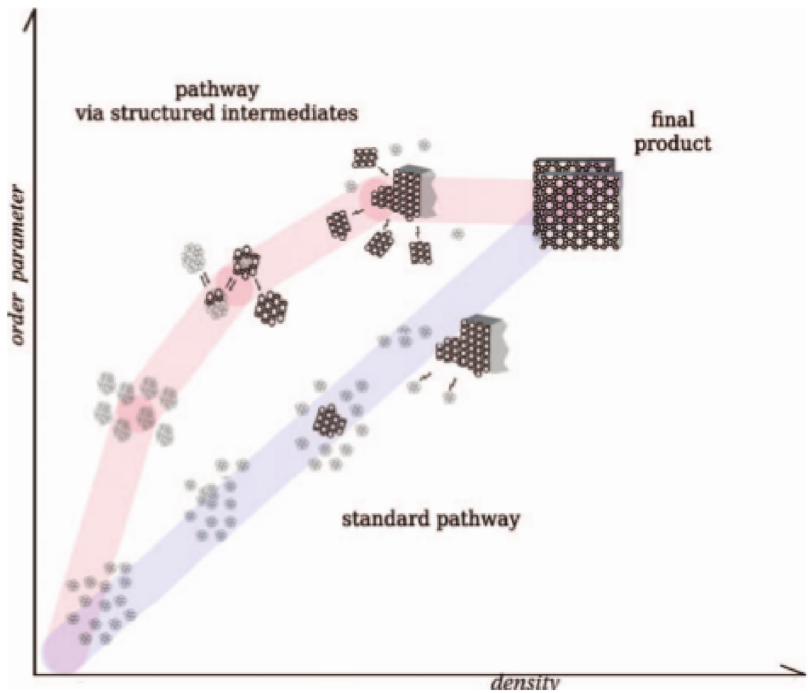


FIG. 1. A schematic demonstration of multistep versus standard synthetic pathways in a two-order parameter space accounting for the presence of partially structured intermediates.

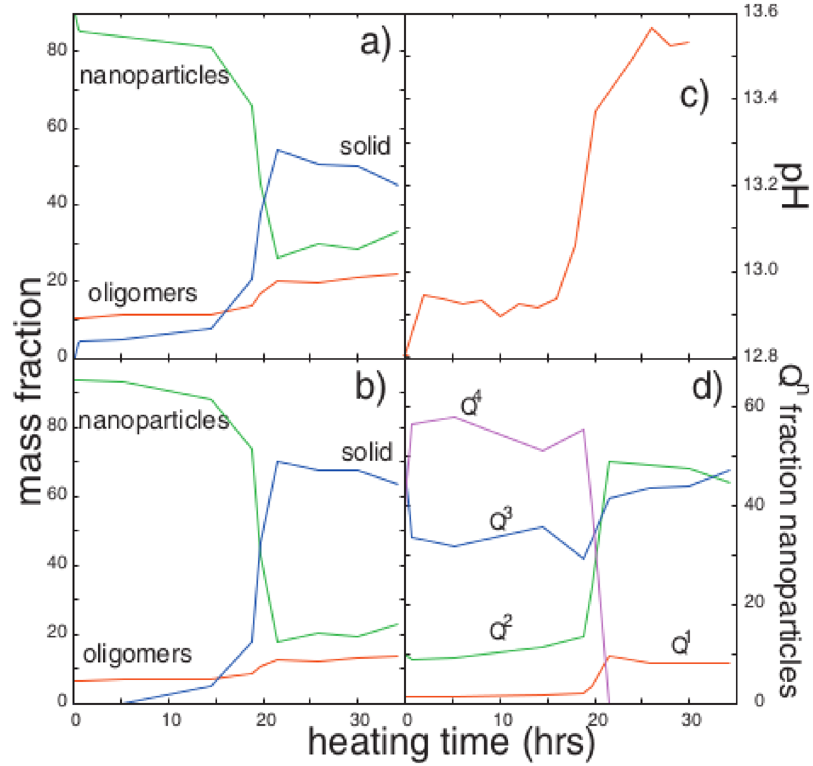
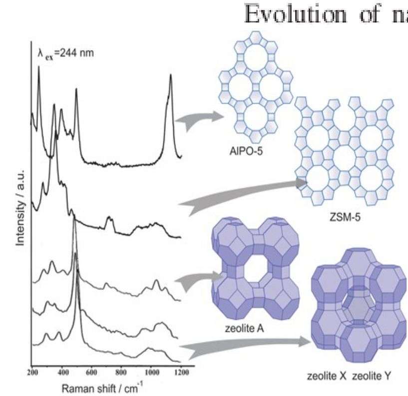


FIG. 2. Liquid state ^{29}Si NMR and pH results from Ref. 36. (a) and (b) Evolution of nanoparticles (N and similarly sized X particles), oligomers,



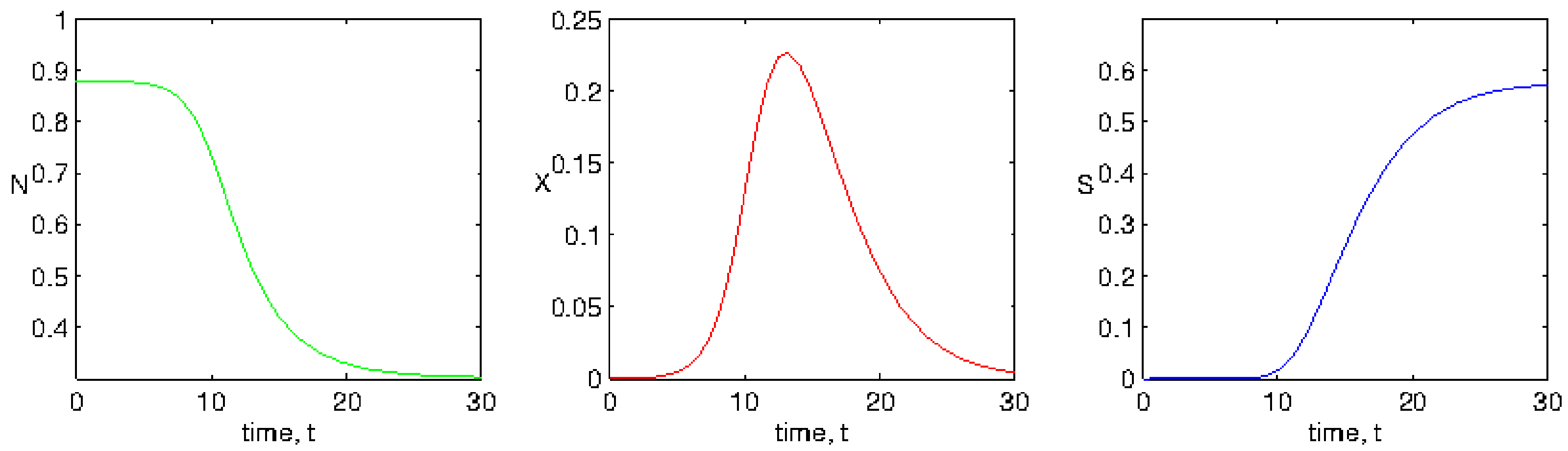
Mean Field model (Lutsko, Basios et al 2010)

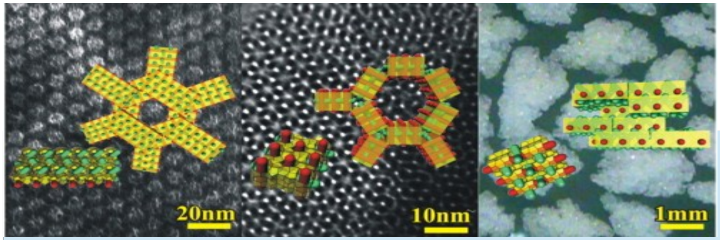
$$\frac{dN(t)}{dt} = -\,2k_{N-N(X)}N^2(t)X(t)$$

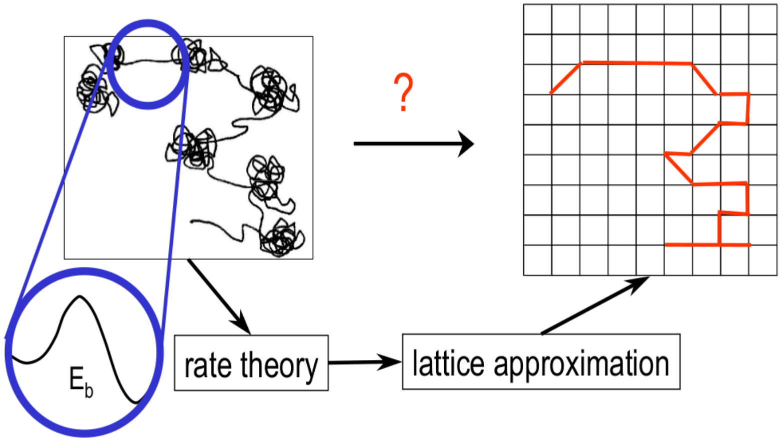
$$\frac{dX(t)}{dt} = k_{N-N(X)}N^2(t)X(t) - k_{X-S}X(t)S(t)$$

$$\frac{dS(t)}{dt} = k_{X-X}X^2(t) + k_{X-S}X(t)S(t)$$

$$k_{X-S} = K_{xs}S^{\alpha}$$







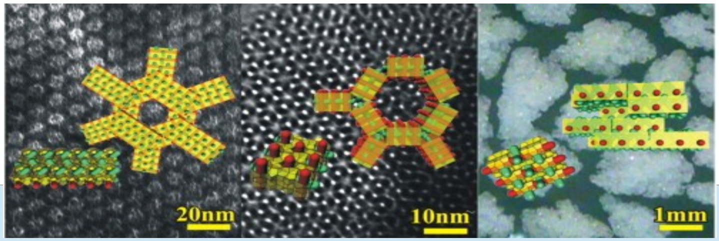
Reaction Steps

N "monomers", X "intermediates", S "crystallite"

$$N_i + N_j + X_{kl} \overset{p_{N-N(X)}}{\rightarrow} X_{ij} + X_{kl} \quad (1a)$$

$$X_{ij} + X_{kl} \overset{p_{X-X}}{\rightarrow} S_{ijkl} \quad (1b)$$

$$X_{ij} + S_{m_1 m_2, \cdots m_l} \overset{p_{X-S}}{\rightarrow} S_{ij m_1 m_2, \cdots m_l} \quad (1c)$$



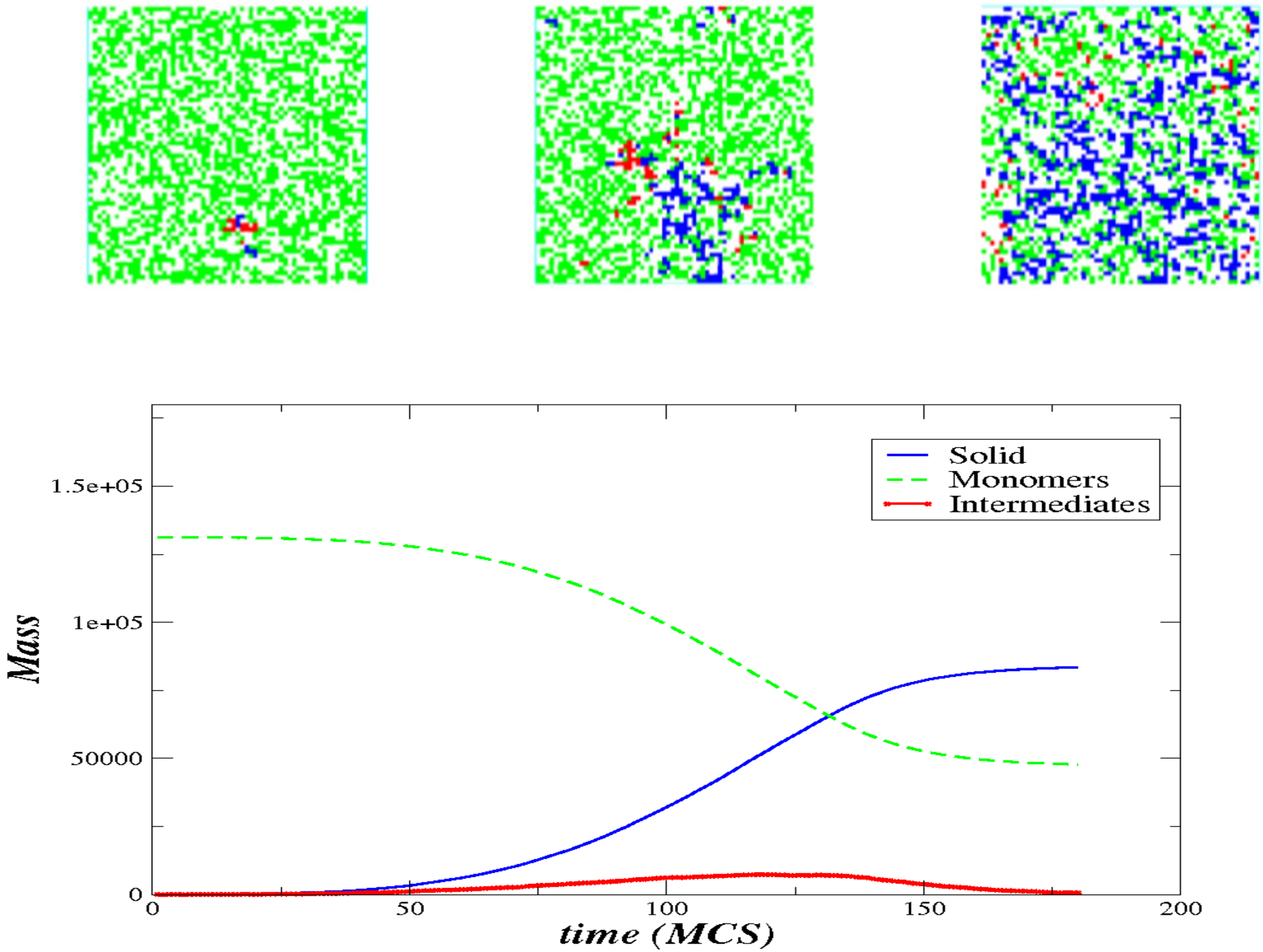
Diffusion Steps

(S does not diffuse,V is the empty site)

$$N_i + V_j \stackrel{p_{diff-N}}{\longrightarrow} V_i + N_j \tag{2}$$

$$V_i + X_{kl} \stackrel{p_{diff-X}}{\longrightarrow} X_{ik} + V_l \tag{3}$$

Cooperativity in forming the solid: $p_{X-S}(S) = c_{X-S} S^{\alpha}$

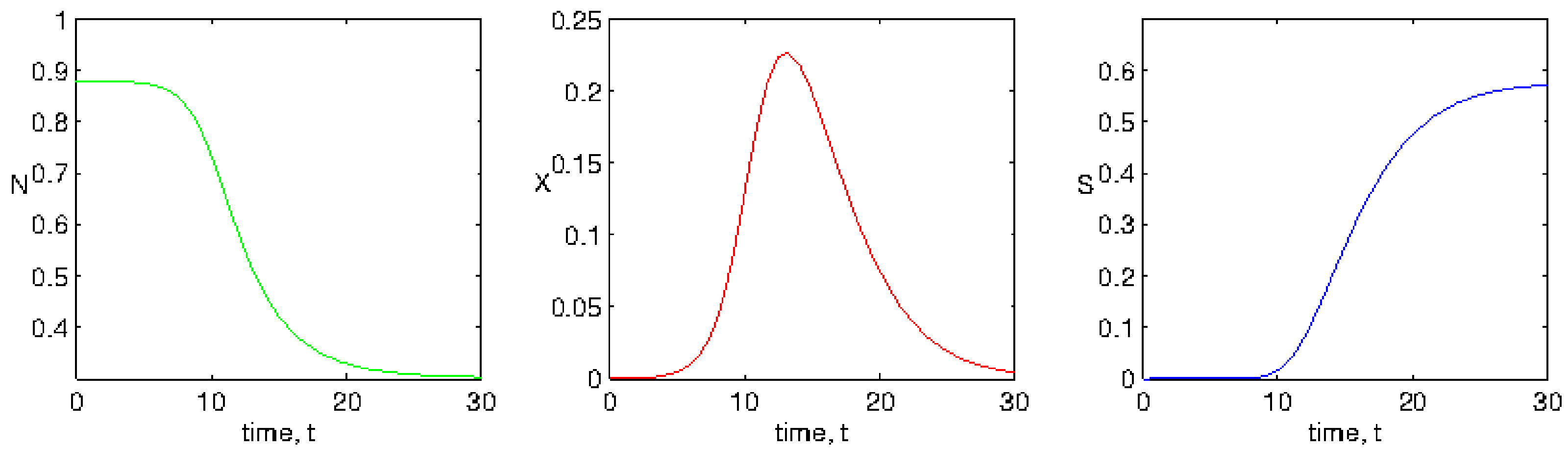


Solid
Monomers
Intermediates
1.5e+05
1e+05
50000
0
Mass
0
50
100
150
200
time (MCS)

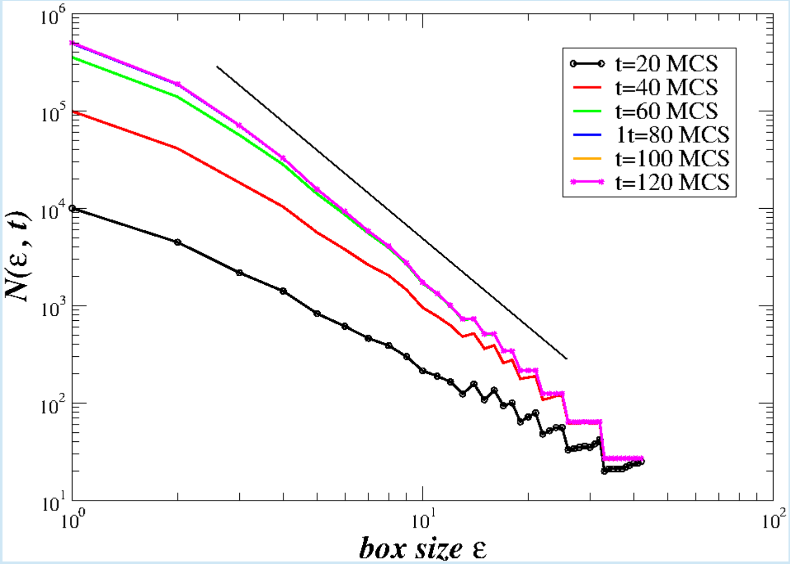
Mean Field model compatible with MC & previous work
(Lutsko, Basios et al 2010)

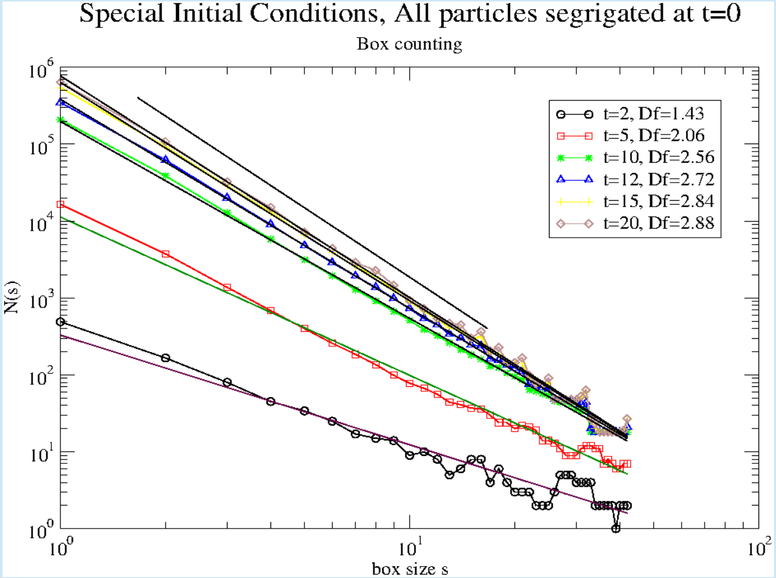
$$\frac{dN(t)}{dt} = -2k_{N-N(X)}N^2(t)X(t)$$
$$\frac{dX(t)}{dt} = k_{N-N(X)}N^2(t)X(t) - k_{X-S}X(t)S(t)$$
$$\frac{dS(t)}{dt} = k_{X-X}X^2(t) + k_{X-S}X(t)S(t)$$

$$k_{X-S} = K_{xs}S^{\alpha}$$



Properties of the aggregates (II)
Different initial conditions (a) homogeneous (b) seeding)





Complex Matter Science initiative at ESA
&
the SOYUZ missions in ISS

Monte Carlo
Lattice Simulation II:

Food Aggregation in Ant Colonies
(spatiotemporal model)

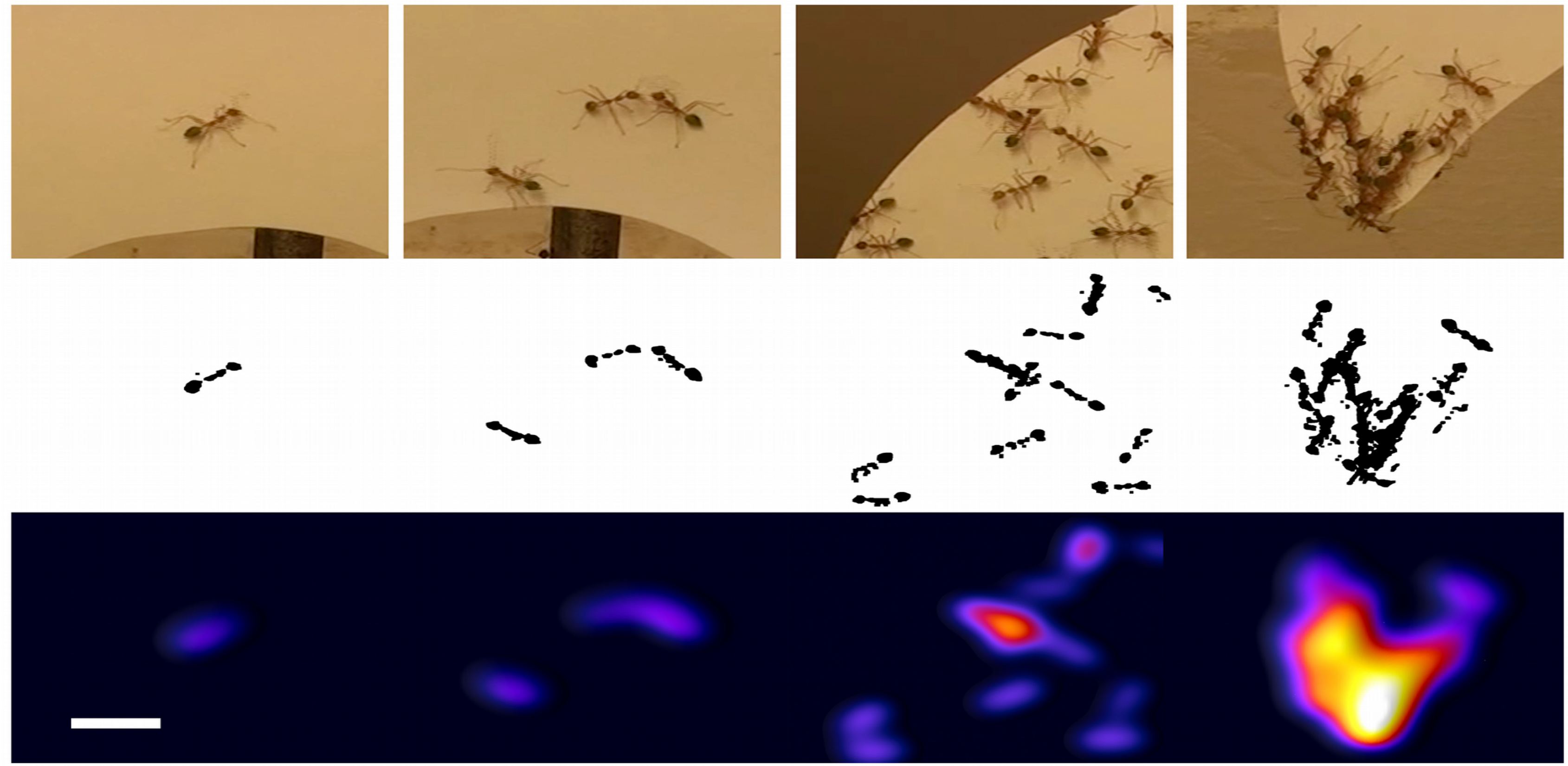
Same Pathways in Selforganization in biology!

Trophallaxis

(food exchange):

Work partition and specialization by individuals, some gather food (Foreagers 15%-20%) some keep it saving for “rainy days”(Domestics). Ant Colony's Social Stomach fills up

Hierachical Systems in Social Biological Systems



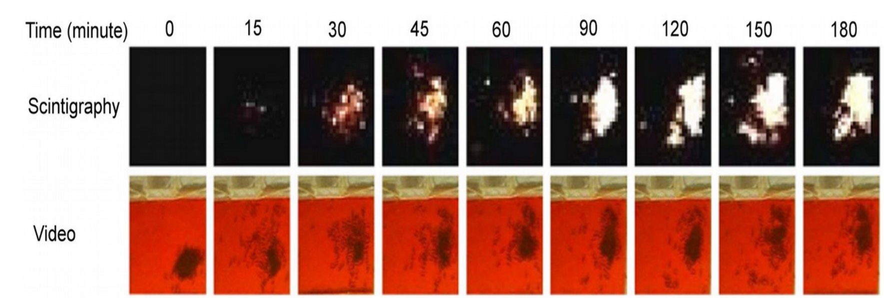
credits:

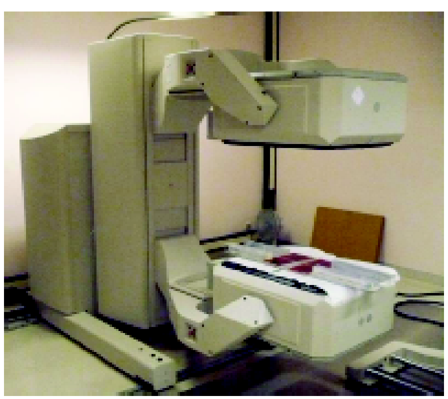
Physical and Biological Determinants of Collective Behavioural Dynamics in Complex Systems
Bochynek T, Robson SKA (2014)
PLoS ONE 9(4): e95112. doi:10.1371/journal.pone.0095112

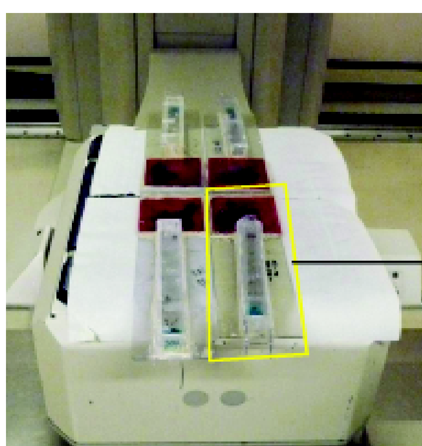
Experimental Set Up

Methods

Experimental nests (10 cmx10 cm x 0.2 cm) contained 200 workers of *F. fusca* no brood, no queen) (Fig. 1). The colonies were deprived of food for 1, 4 and 7 days prior to each experiment. Four nests were tested at a time. At the beginning of the experiment, we placed 1ml of radiolabeled sucrose 0.5M. For 3 hours, we monitored the spreading of the food inside the nest with a scintigraph.

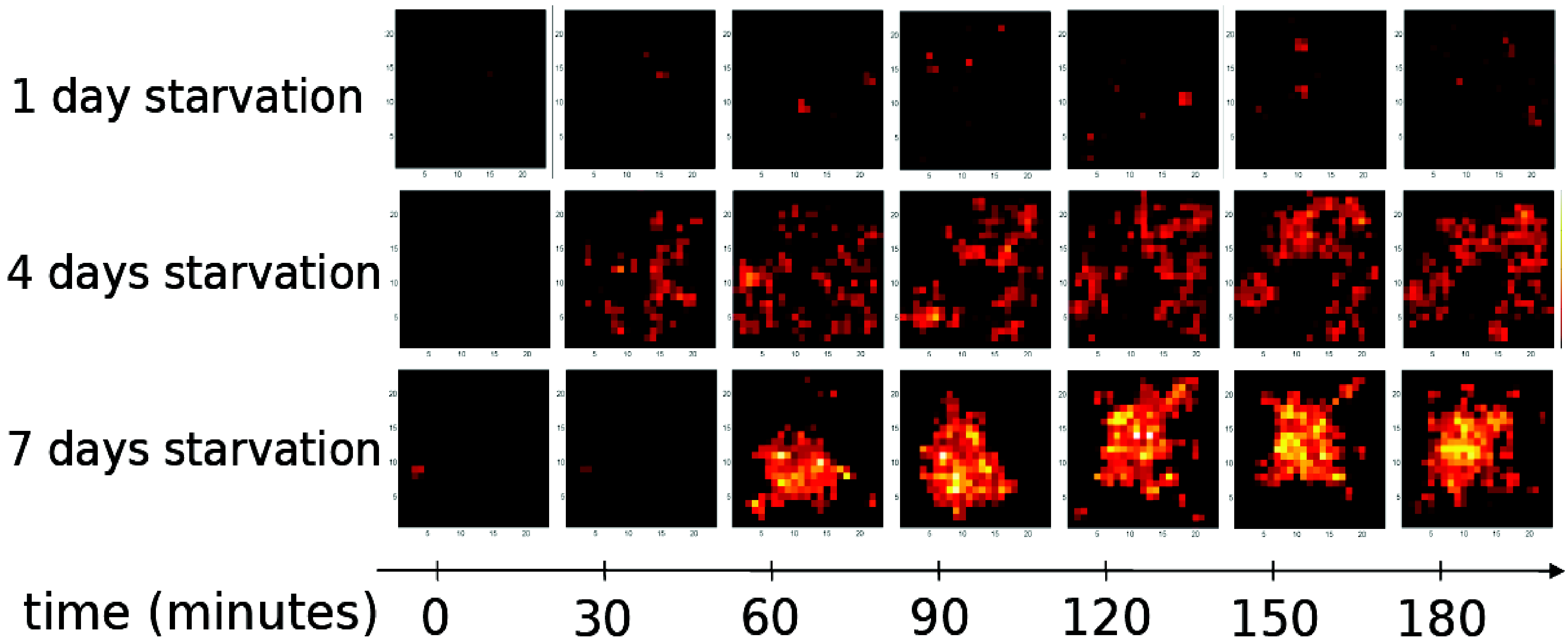






nest

Experimental setup


1 day starvation
4 days starvation
7 days starvation
time (minutes)
0
30
60
90
120
150
180

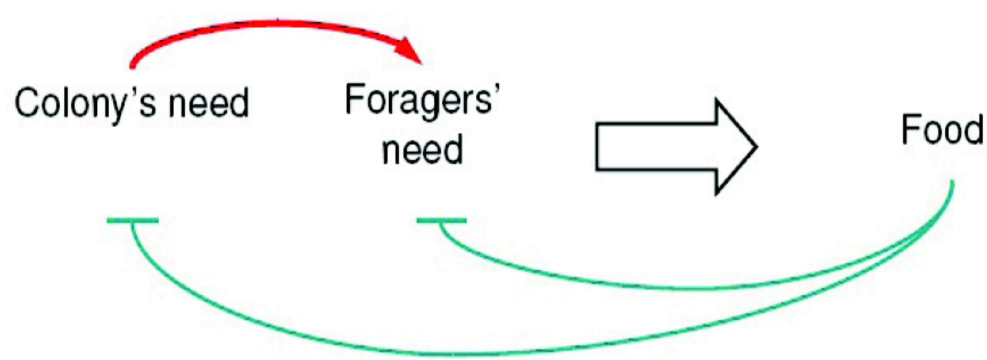
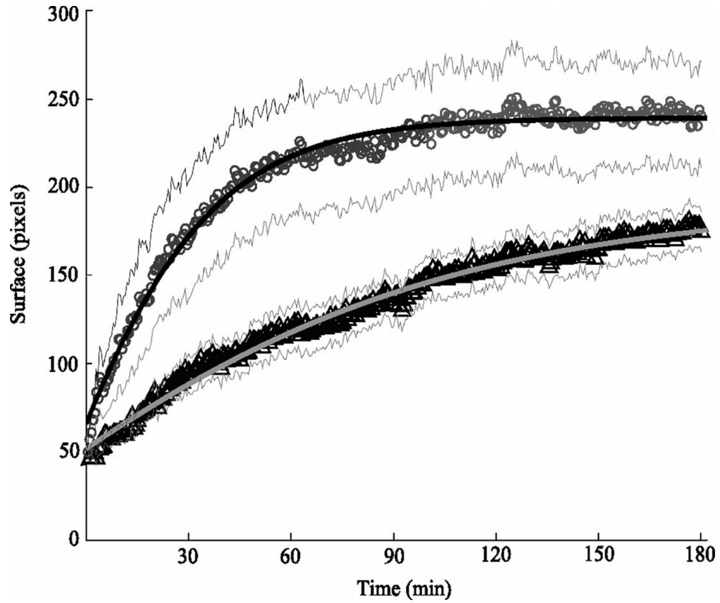
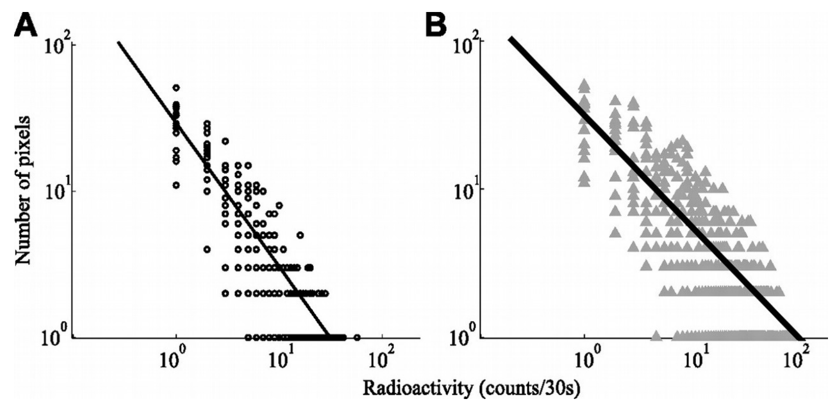

Colony's need
Foragers' need
Food

Figure 2. Radioactive surface growth.

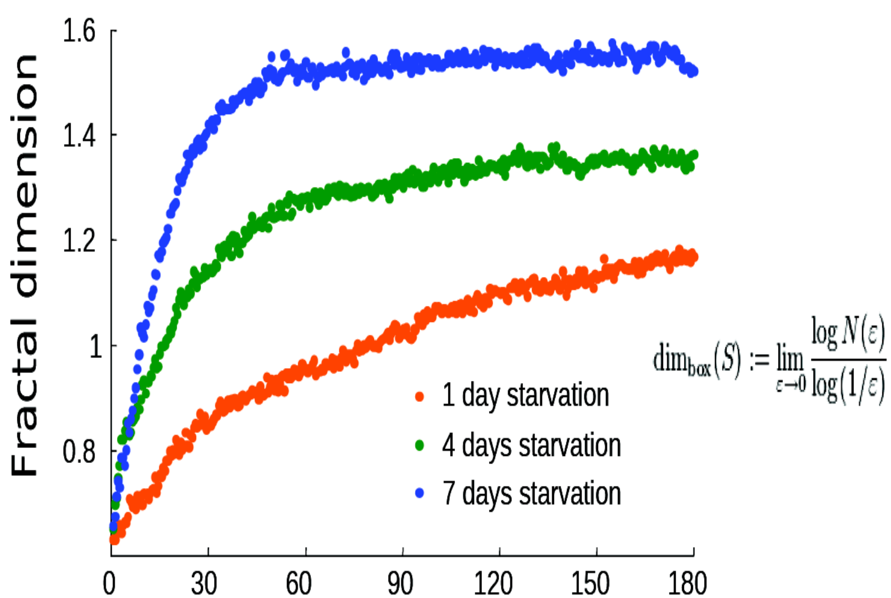


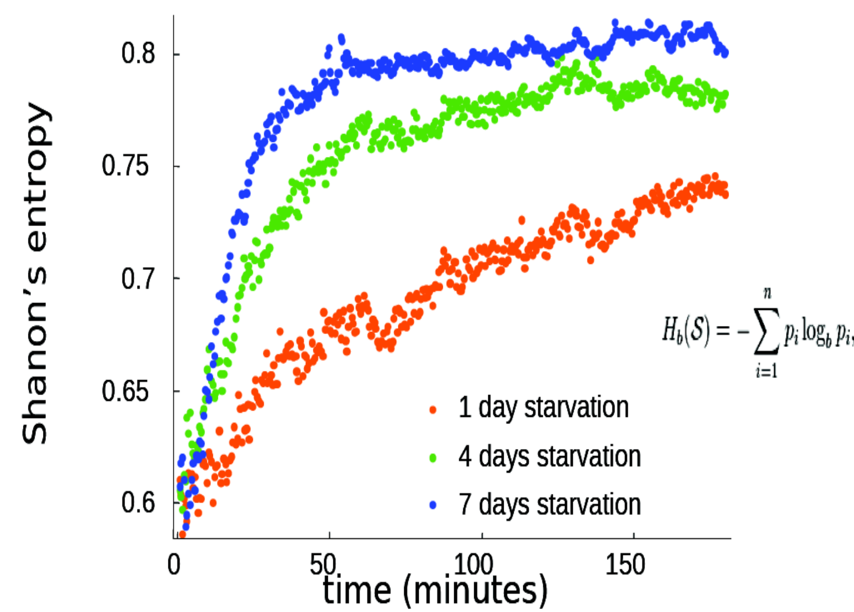
Buffin A et al. FASEB J 2012;26:2725-2733

Figure 4. Distribution of the radioactive pixels at the end of the 3 h of experiment.



Buffin A et al. FASEB J 2012;26:2725-2733





Trophallaxis

(food exchange):

Ant Colony's Social Stomach
fills up by the combined action of:
Foreagers (A) and Domestics (B)

THEORETICAL MODELLING

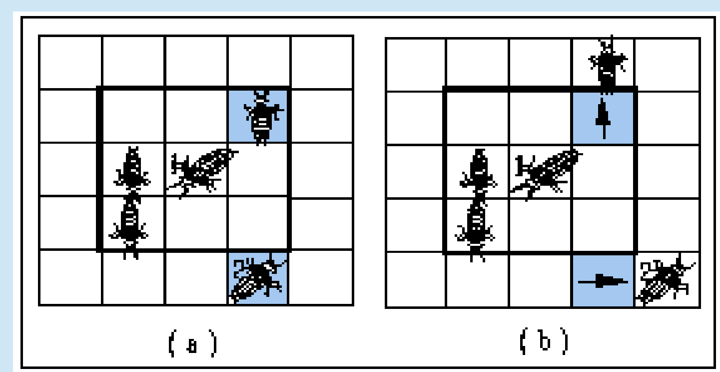
Two levels:

(i) food exchange kinetics:

$$S+A \rightarrow A^*$$

$$A^*+B \rightarrow A+B^*$$

(ii) ants diffussion



4.1.2 The reaction steps

In particular we start with the minimum number of food exchange steps, labeling the forward and backward steps as k_* and k^r_* respectively. (BOOKEEPING ISSUE ... ANY IDEA FOR A MORE "SHARP, SLIM AND CLEAN" LABELING CONCERNING THE REACTION STEPS AND CONSTANS IS MUCH MUCH WELCOMED!)

1. *Filling up of the foragers:* When they meet sugar sources, we assume that all foragers fill up at once. The sugar source is inexhaustible so it remains constant throughout the reaction.

$$\boxed{S + A_n \xrightarrow{k_n} A_N + S}$$

for $n = 0, 1, 2, 3 \ldots N - 1$.

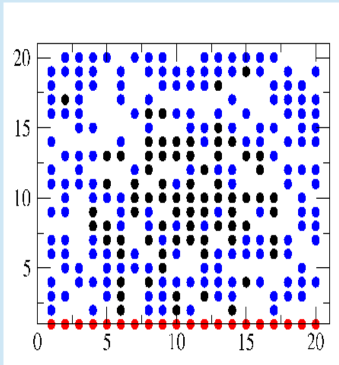
2. *Feeding the domestics:* Encounters of foragers with domestics result in trophallaxis. The foragers give out part of their load in discrete quantal changing their "species" from$n$ to$n - 1$ and the domestics stock it up changing from m to $m + 1$:

$$\boxed{A_n + B_m \underset{k^r_{N-1+n+m}}{\overset{k_{N-1+n+m}}{\rightleftharpoons}} A_{n-1} + B_{m+1}}$$

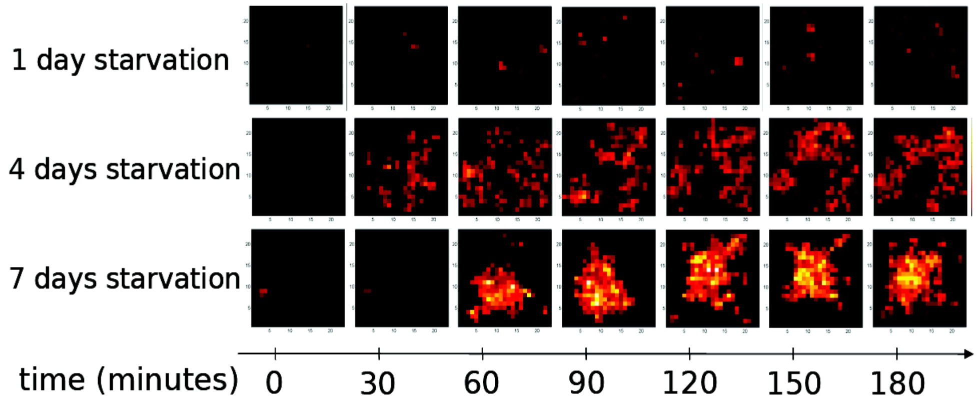
for $n = 0, 1, 2, 3 \ldots N$ and $m = 0, 1, 2, 3 \ldots M - 1$.

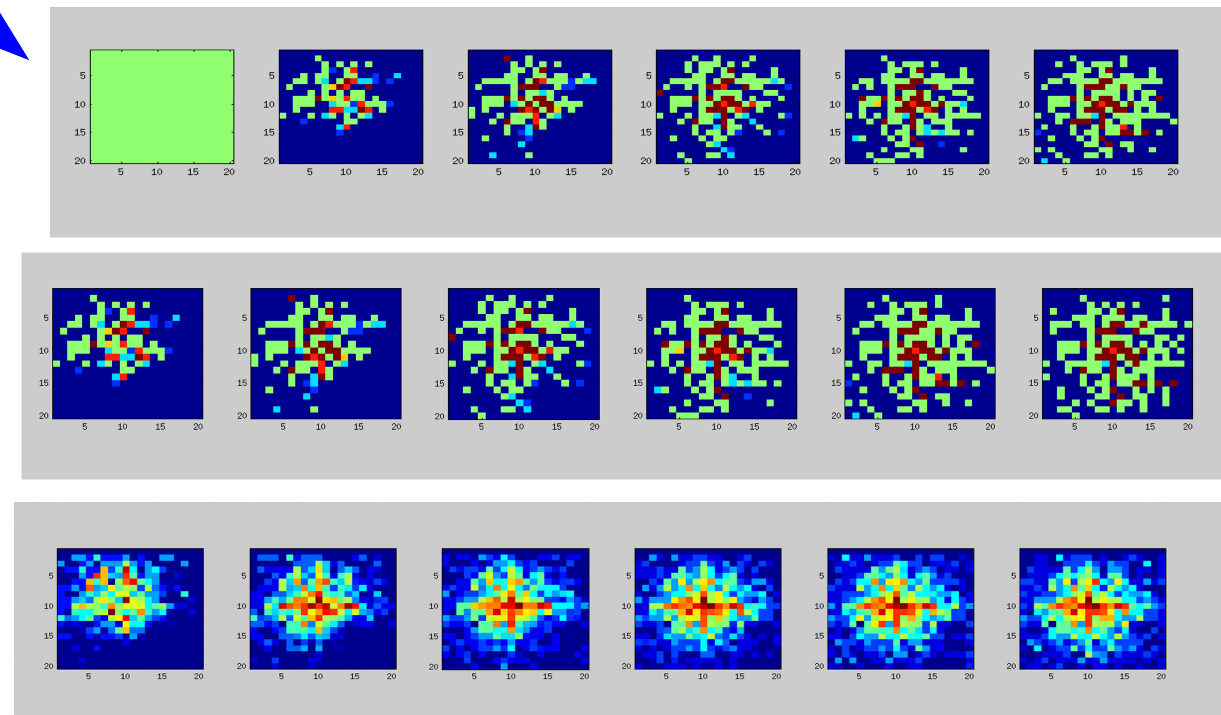
3. *Stocking up in the "collective stomach":* Domestics engage in trophallaxis within the nest. The discrete quantal change of their "species" from m to $m \pm 1$ is simply:

$$\boxed{B_{m'} + B_m \underset{k^r_{N-1+n+m+m'}}{\overset{k_{N-1+n+m+m'}}{\rightleftharpoons}} B_{m'\pm1} + B_{m\mp1}}$$

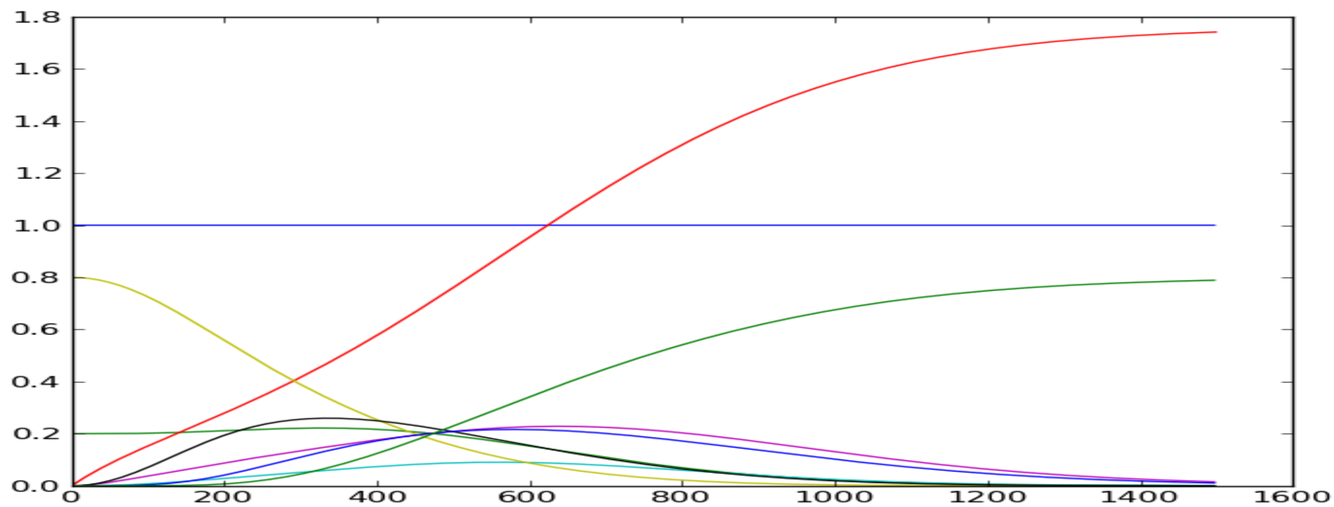


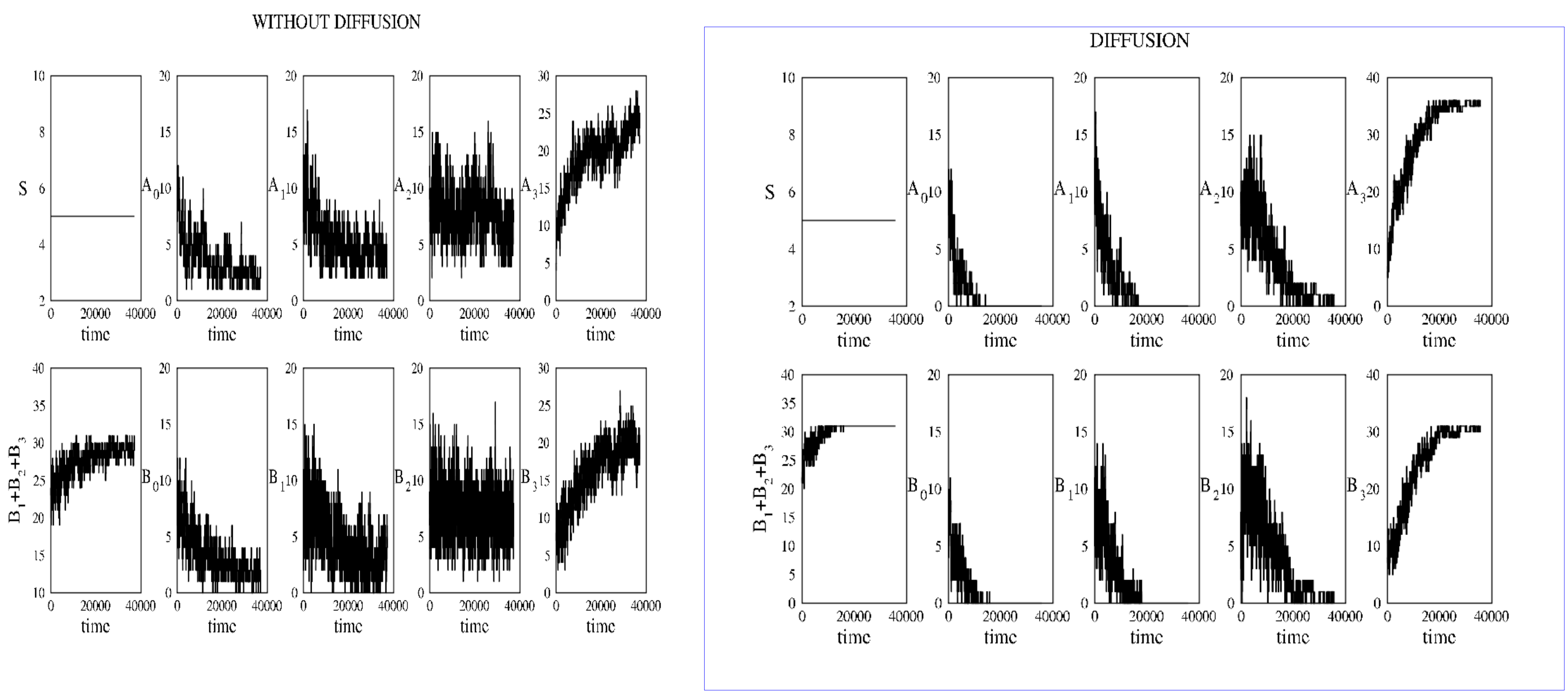
Level I:
Ants,
Domestic &
Scouts

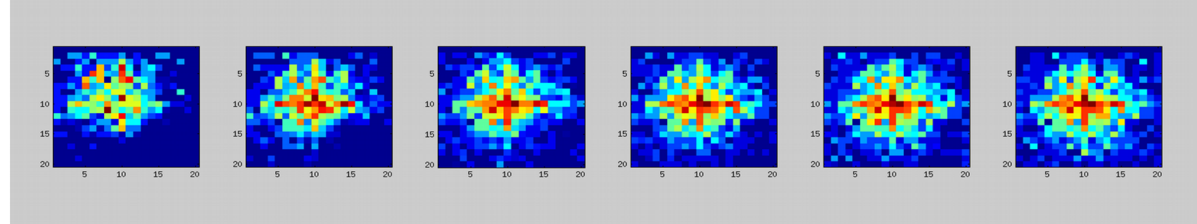




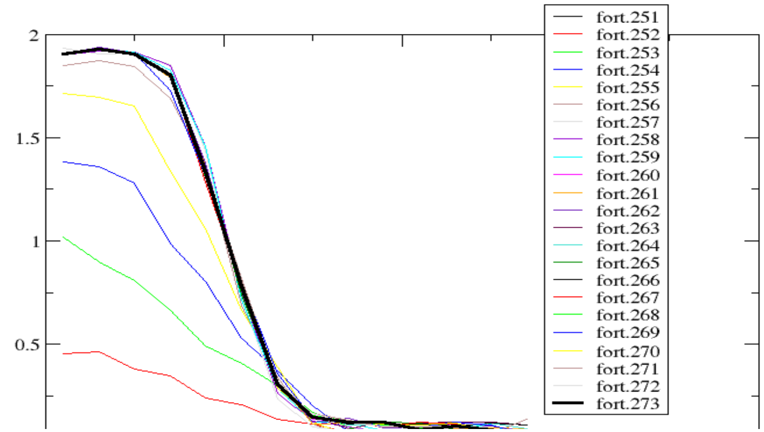
Level II: Social Stomach, density of food



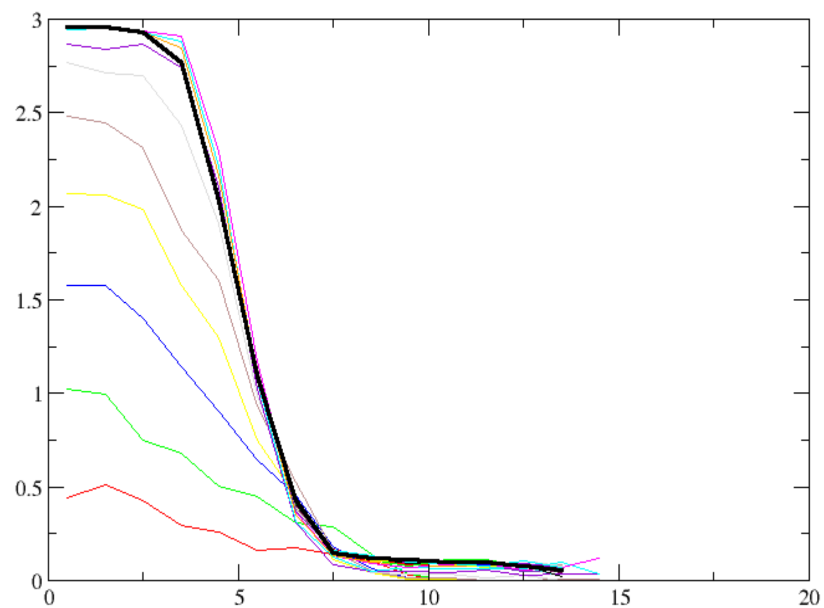

WITHOUT DIFFUSION
DIFFUSION
S
A_0
A_1
A_2
A_3
$B_1+B_2+B_3$
B_0
B_1
B_2
B_3
time



Max Capacity: N =2

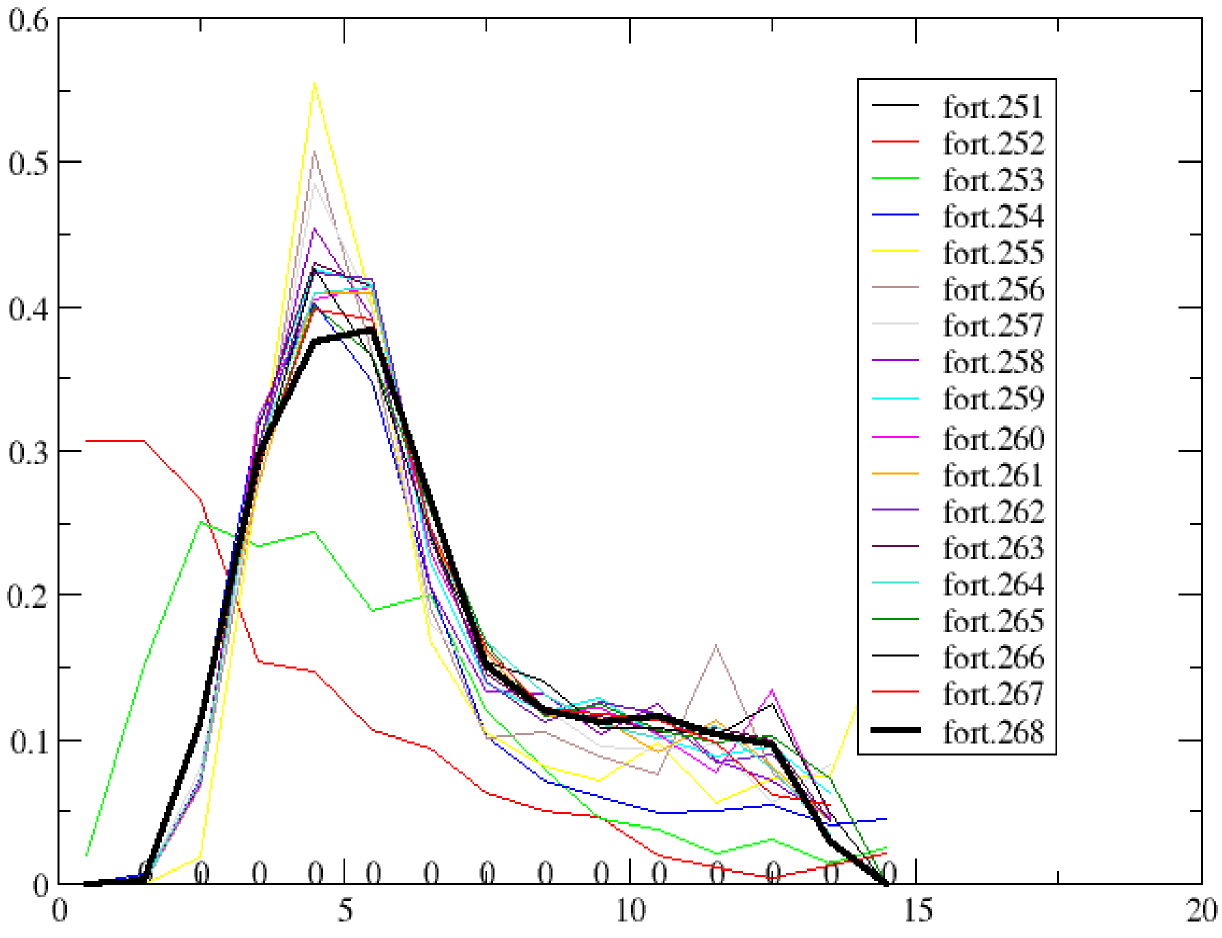


Max Capacity: N =3



Max Capacity =1

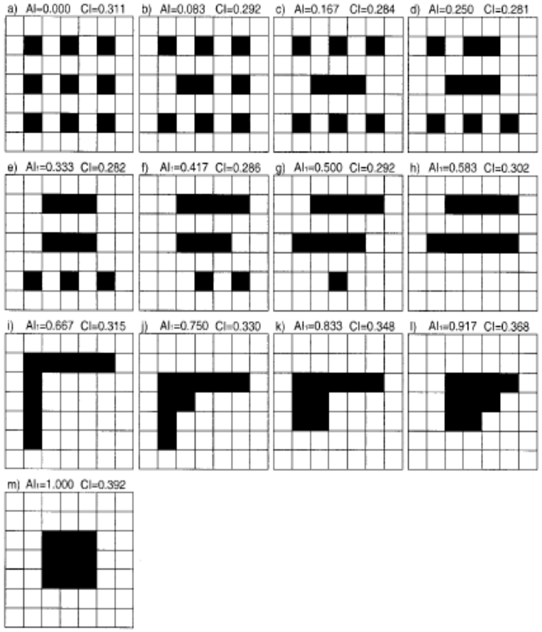
Individual Variability ensures Fuller stomach!!



Fractal Dimention

&

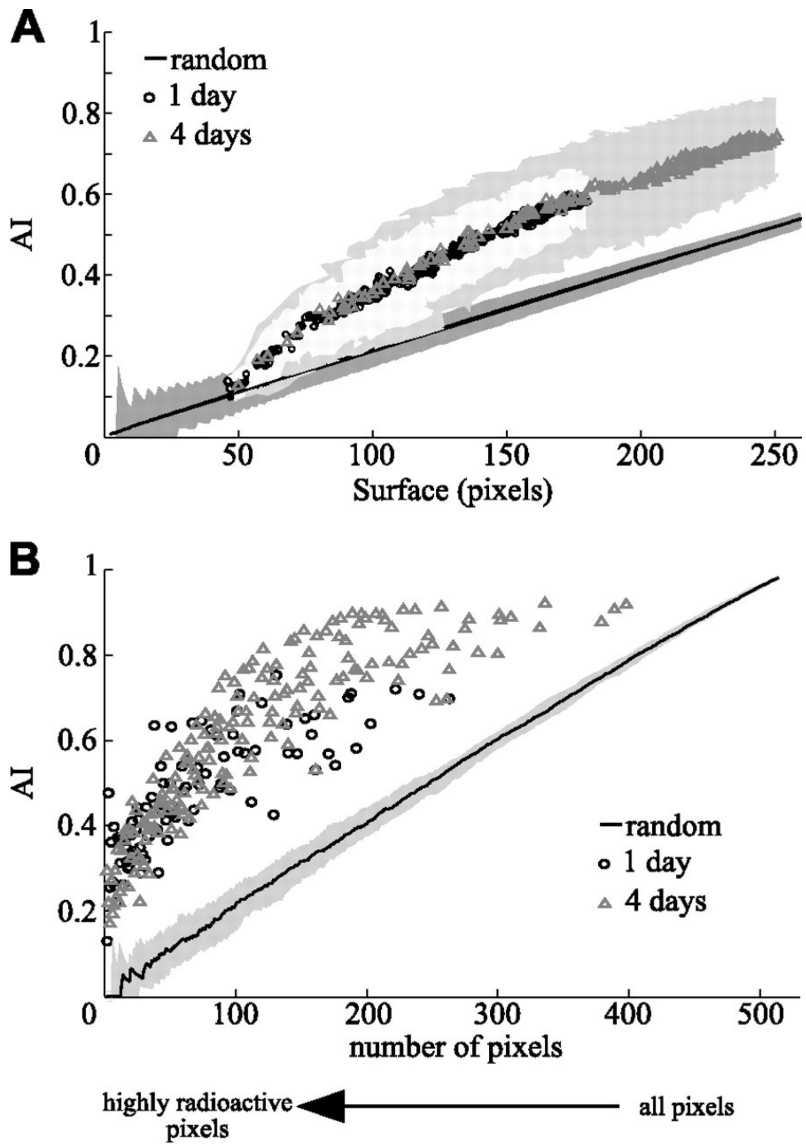
Aggregation Index



$$AI = \left[\frac{g_{ii}}{\max \to g_{ii}} \right] (100)$$

Figure [illegible]. A set of binary maps with 40 background cells in gray and 9 class 1 in black. Class 1 starts from completely disaggregated cells and gradually aggregates to one square patch.

Figure 5. Aggregation index (AI) according to the radioactive surface (in pixels).



Buffin A et al. FASEB J 2012;26:2725-2733

The FASEB Journal

ODE model II:
(back to bifurcations)

Collective decision-making resulting from social behavior

BV. & J.L. Deneubourg
ULB

Emergence of specialized individuals (loaded-unloaded)

Two ants model

Q_1 Q_2 q Q_1+Q_2-q

Kinetics of exchange : only depends on Q1 & Q2 (their loads)
Two symetrical equations with the same parameters values for both ants

Flow between ants : Diffusion Antidiffusion Loading capacity (k)

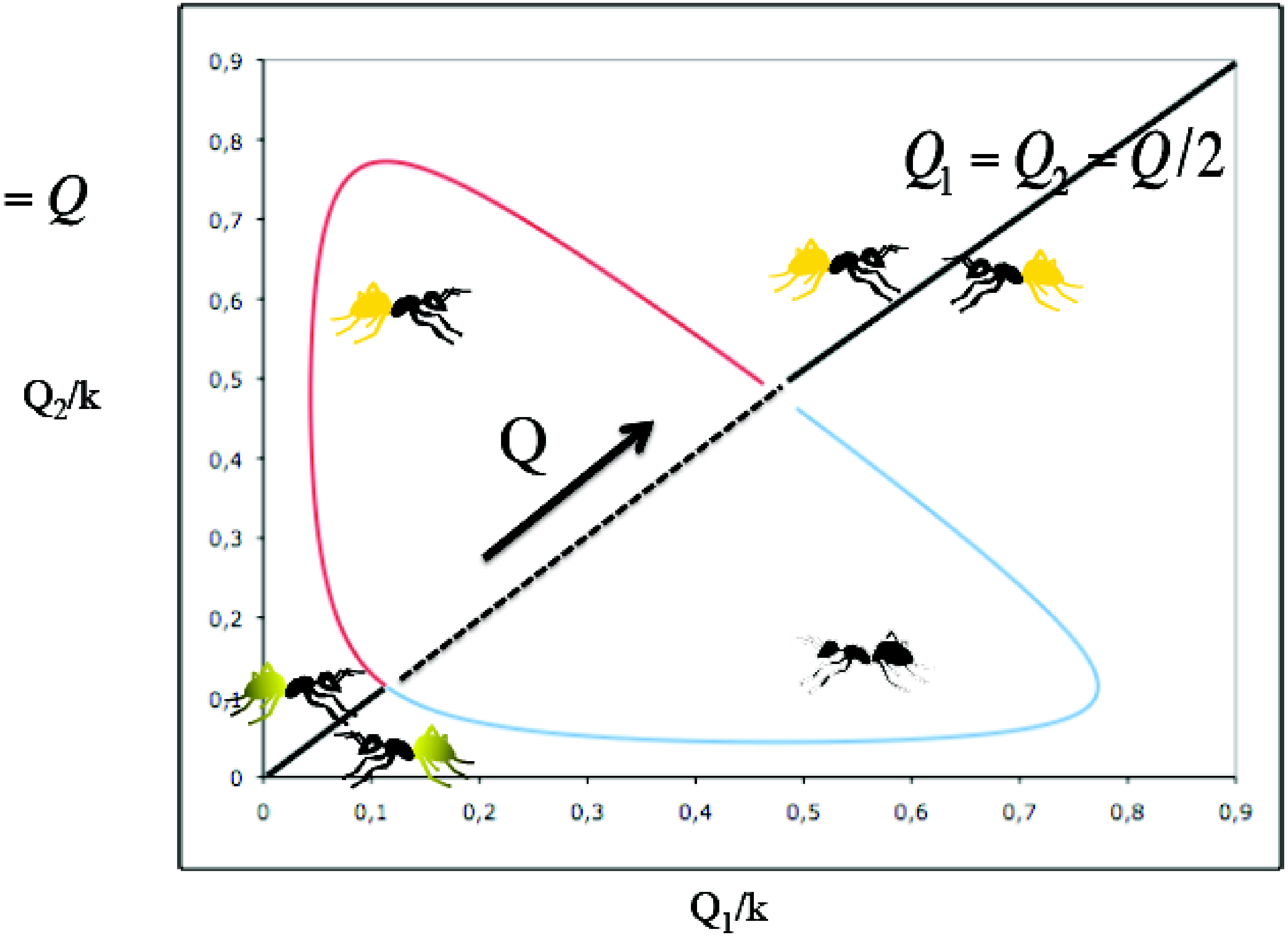
$$\frac{dQ_1}{dt} = (\alpha Q_2 + \beta Q_1^2 Q_2)(1 - \frac{Q_1}{k}) - (\alpha Q_1 + \beta Q_2^2 Q_1)(1 - \frac{Q_2}{k})$$

$$\frac{dQ_2}{dt} = -(\alpha Q_2 + \beta Q_1^2 Q_2)(1 - \frac{Q_1}{k}) + (\alpha Q_1 + \beta Q_2^2 Q_1)(1 - \frac{Q_2}{k})$$

Emergence of specialized individuals (loaded-unloaded)

Two ants model

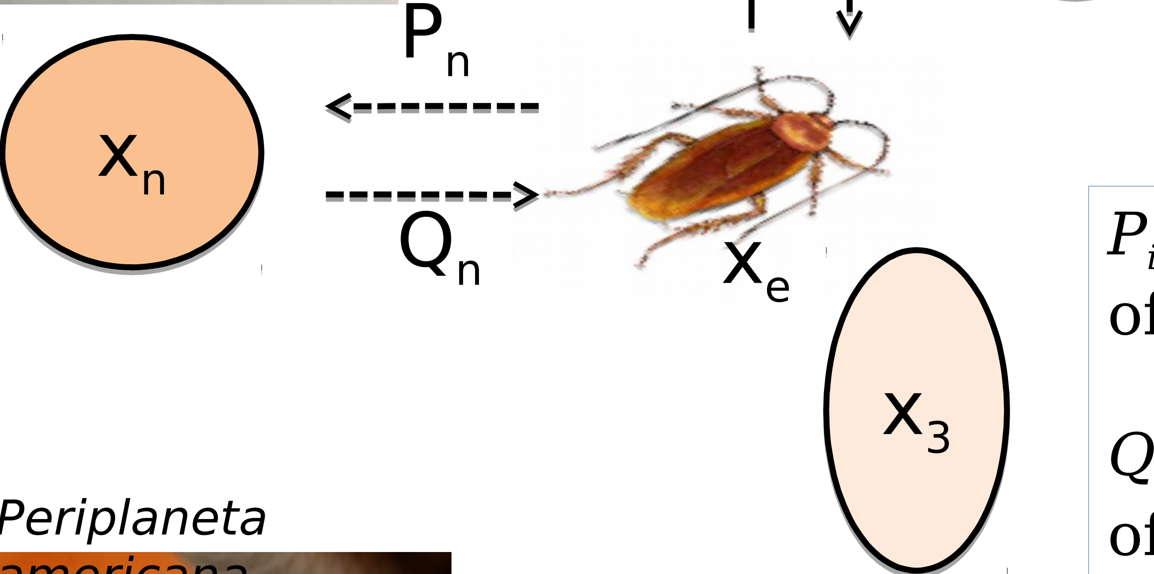
$$Q_1 + Q_2 = Q$$



Aggregation in a patchy environment

- Only aggregation on patches
- Outside patches : individuals are homogeneously distributed

Blattella germanica



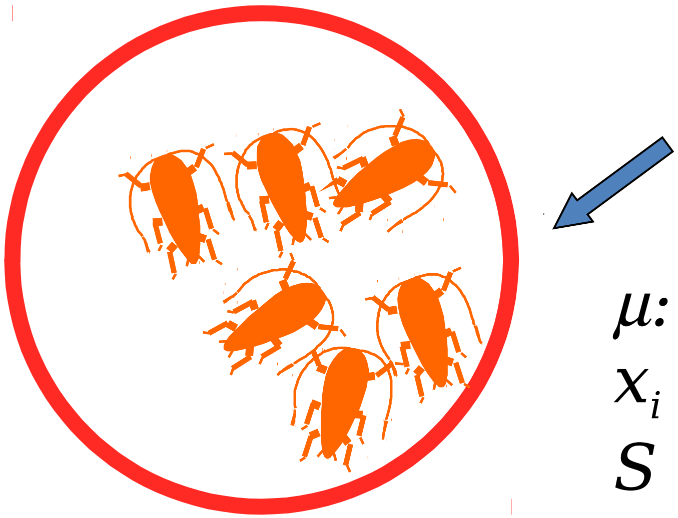
Periplaneta americana

$P_i(x_i)$: individual rate/probability of joining patch i

$Q_i(x_i)$: individual rate/probability of leaving patch i

P , Q depend on the characteristics of the patch and the presence of conspecifics

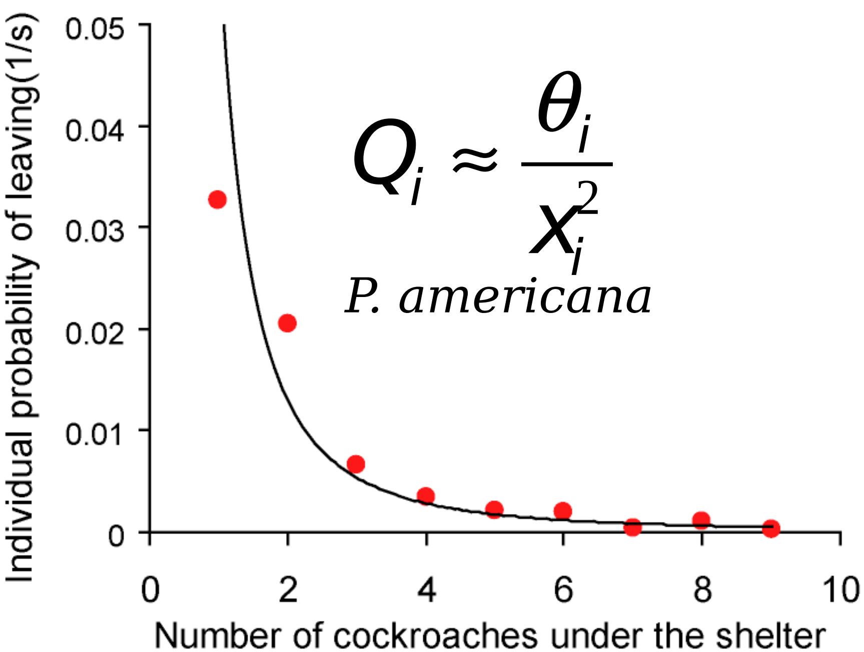
Probability of joining a shelter



$$P_i = \mu\left(1 - \frac{x_i}{S}\right)$$

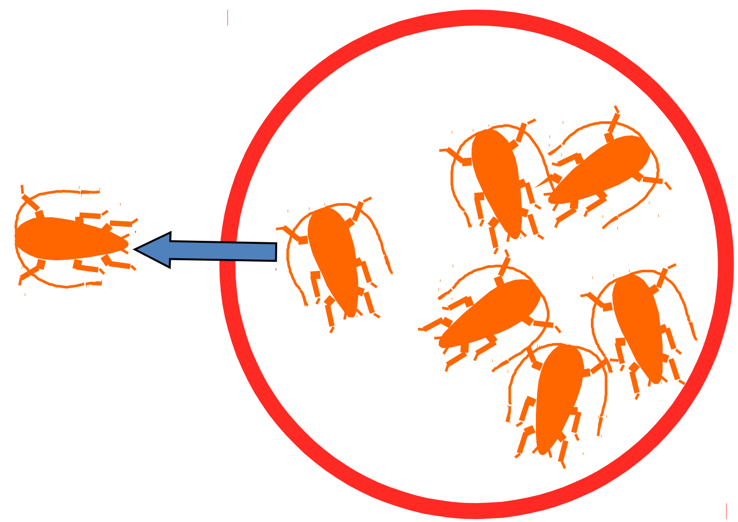
μ: maximal probability of joining
x_i : number of sheltered individuals
S : carrying capacity of shelter i

Probability of leaving (retention) a shelter



$$Q_i \approx \frac{\theta_i}{x_i^2}$$

P. americana



n et al, 2005; Amé et al, 2006; Halloy, et al, 2007; Garnier et al, 2008; Laurent et al, 20

Model

System of differential equations describes the time evolution of the population in each shelter x_i

$$\frac{dx_i}{dt} = P(x_i)x_e - Q(x_i)x_i \qquad i = 1, \dots, p$$

(number of patches)

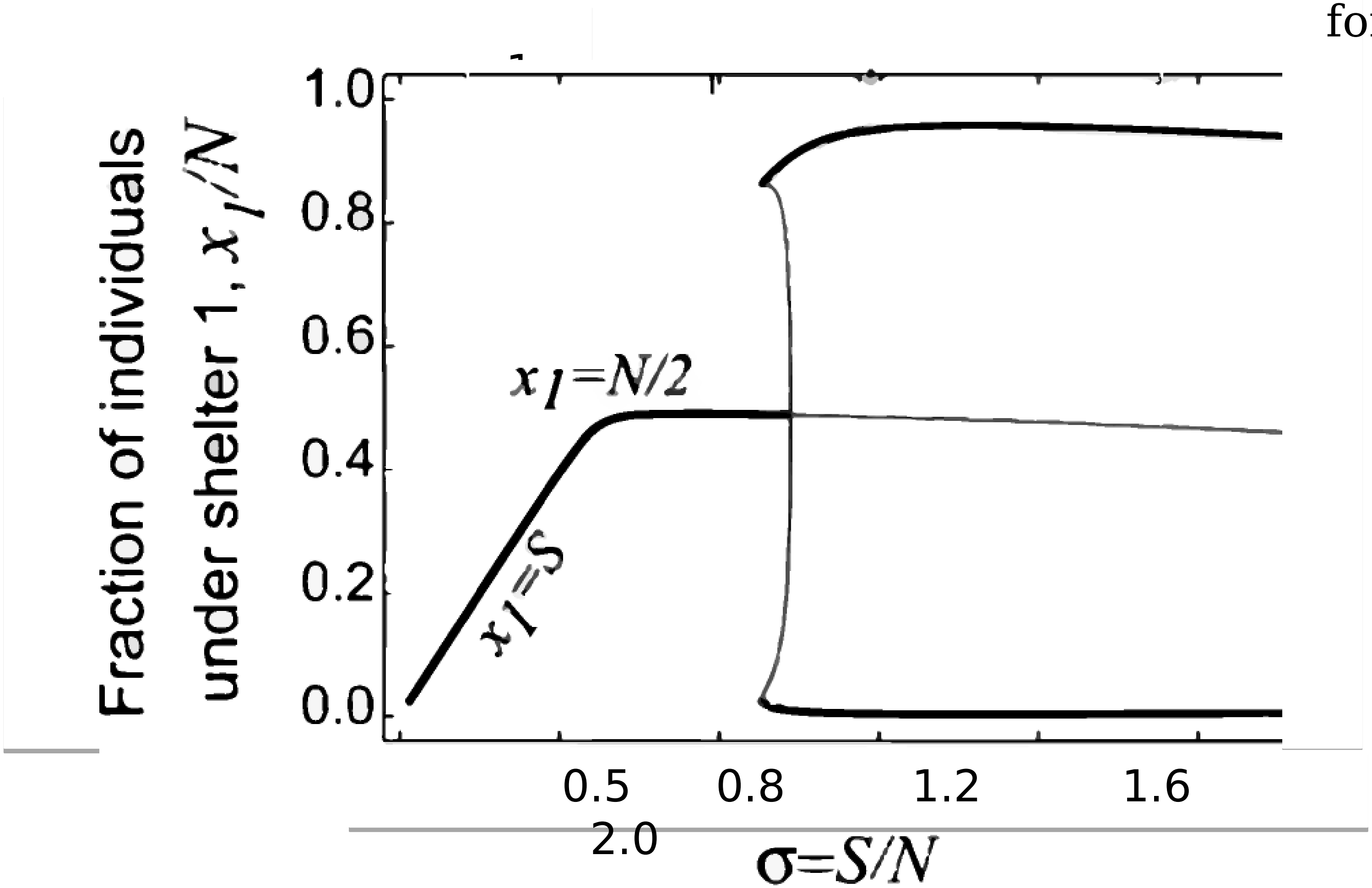
Input Output

Total population: $N = x_e + \sum_{i=1}^{p} x_i$

x_e (outside shelters) is homogeneously distributed outside the patches

Collective choice and crowding
Bifurcation diagram
(2 identical shelters; stationary states)

Parameter values
for *B. germanica*



Consensus

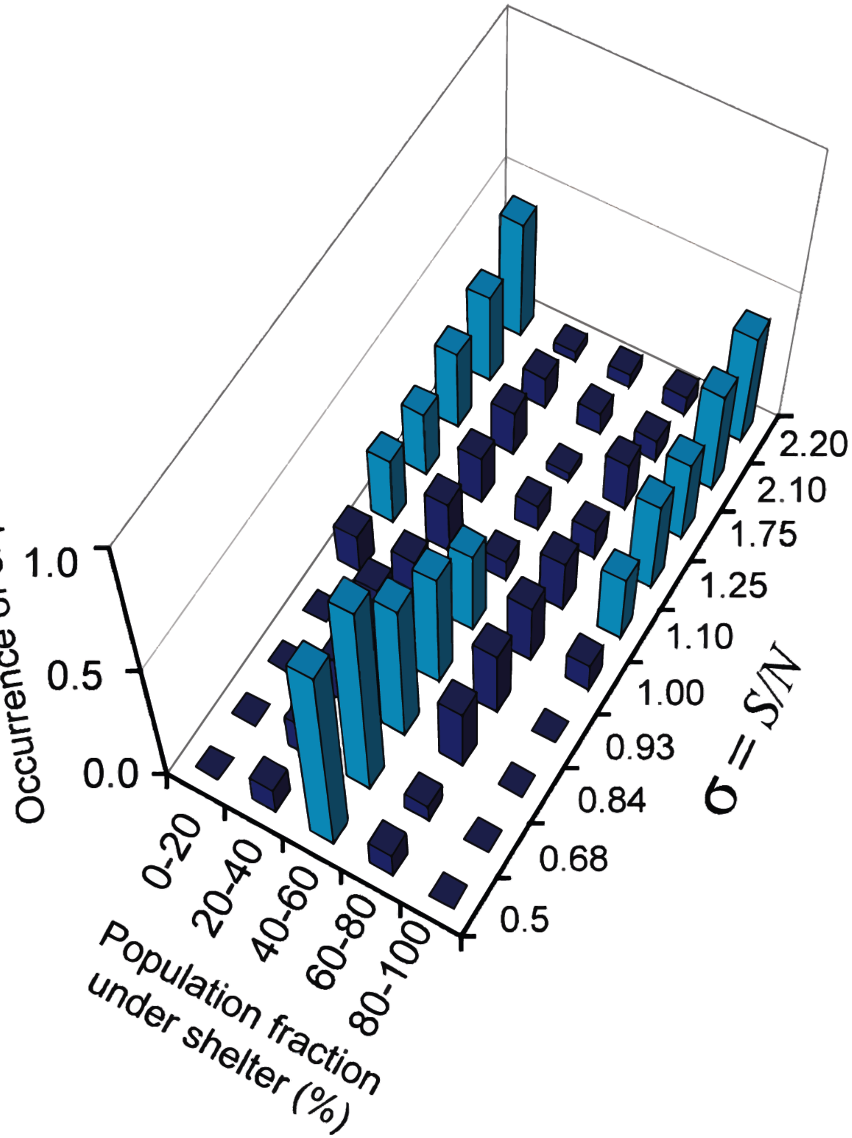
Unstable state

Consensus

Amé et al, PNAS, 2006; Broly et al, 2012

Collective choice and crowding
Experimental bifurcation diagram

B. germanica



Shelter supply influences the collective response

- Identical shelters

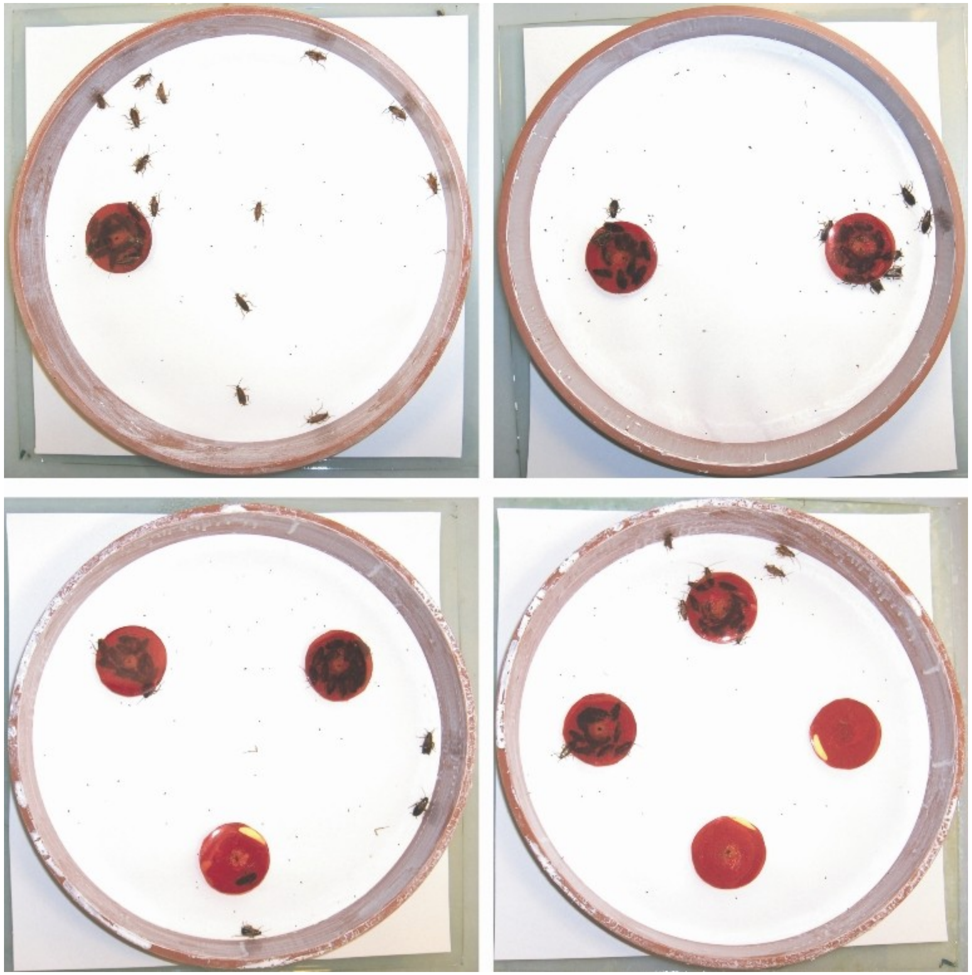
$p<p_c$: Minimization of the number of equally occupied sites

$$\text{Number of occupied sites} = \min(\left\lceil \frac{N}{S} \right\rceil, p)$$

S= 15

N=30

N/S=2



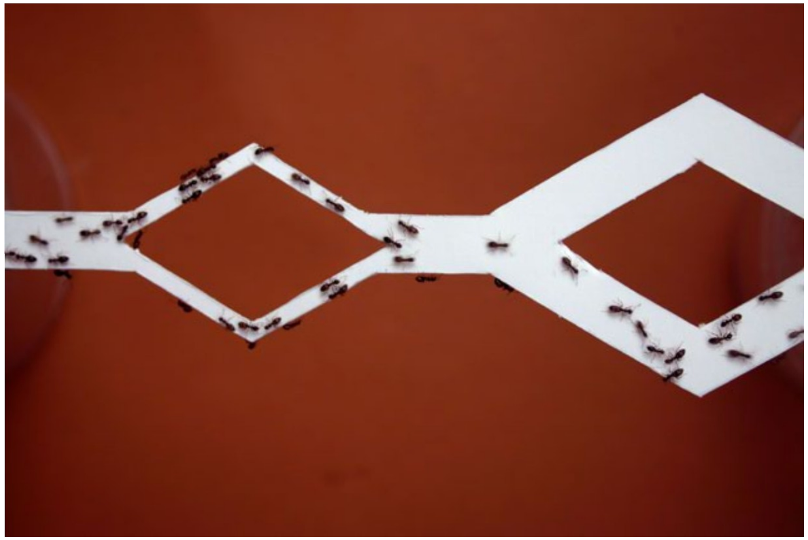
$p \geq p_c$: Dispersion, all shelters are equally occupied $x_1 = \ldots = x_p$

Sempo et al, 2013, PloS One, JAE, 2013

Similar responses in different social situations

Queens of ants *Lasius niger*

Social spider
Anelosimus eximius (Krafft)

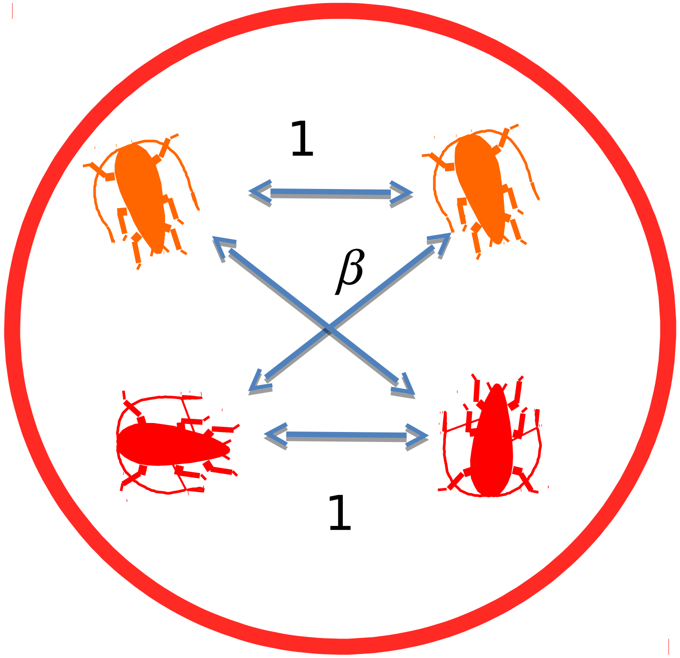


Trail and
traffic regulation
(*Lasius niger*)

Jeanson et al, 2004; Dussutour et al, 2004;Tourneur, 2012;
Devigne et al, 2011; Broly et al, 2014; Aron et al, in prep

Segregation: by–product of the aggregation & crowding

Exp: Individual discriminates between its own strain and a "foreign" strain
Collective level: aggregation- segregation (no agonistic behaviour)



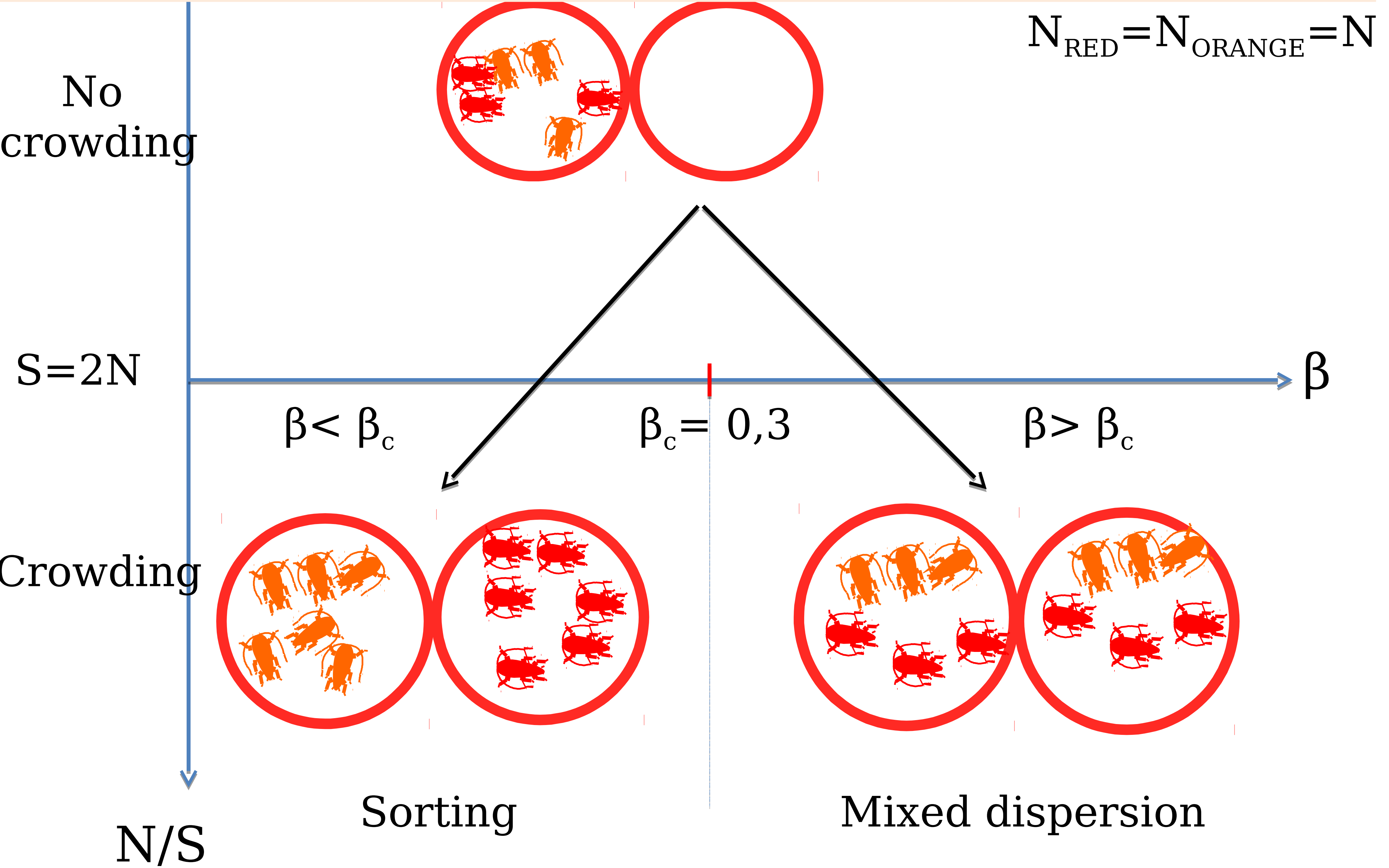
β = (inter strain / intra strain) attraction

β=0 high preference for their strain
β=1 no preference
β>1 preference for the other strain

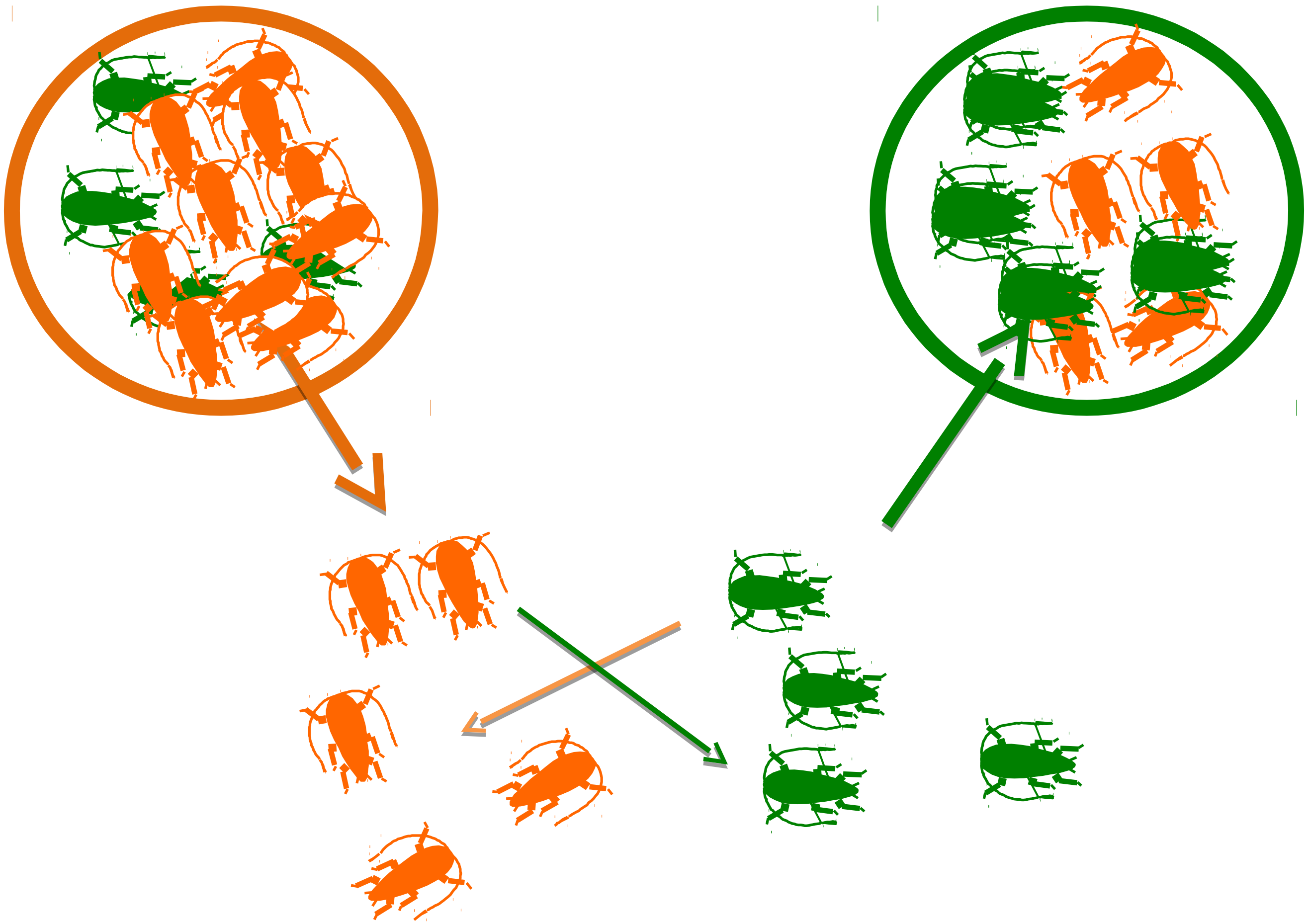
$$Q_O \approx \frac{1}{(O+\beta R)^2} ; Q_R \approx \frac{1}{(R+\beta O)^2}$$

(Rivault & Cloarec, 1999, Amé et al, 2004; Leoncini & Rivault, Ethology, 2005
Mailleux et al 2008; Astudillo et al, in prep)

Segregation: by–product of the aggregation & crowding



Maintaining the cohesion when individuals present opposite preference



Theoretical results : Model Equations

Two equal groups with opposite preferences

$$\frac{dx_i}{dt} = \frac{1}{m-1} \sum_{j=1, j\neq i}^{m} \left[-\frac{\theta_i x_i}{k^n + (x_i + \beta_{xy} y_i)^n} + \frac{\theta_j x_j}{k^n + (x_i + \beta_{xy} y_i)^n} \right]$$

$$\frac{dy_i}{dt} = \frac{1}{m-1} \sum_{j=1, j\neq i}^{m} \left[-\frac{\theta_j y_i}{k^n + (\beta_{yx} x_i + y_i)^n} + \frac{\theta_i y_j}{k^n + (\beta_{yx} x_i + y_i)^n} \right]$$

$$i, j = 1, m, i \neq i$$

$Nx = Ny = 2N$,

$i=2$, $n = 2$,

$\theta 1 > \theta 2$, (X group likes shelter 2 & Y group likes shelter 1)

$\beta xy = \beta yx = 1$

Steady States from a 5th -degree equation

$k \sim 2N$

Theoretical results : Phase diagram

Two equal groups with opposite preferences

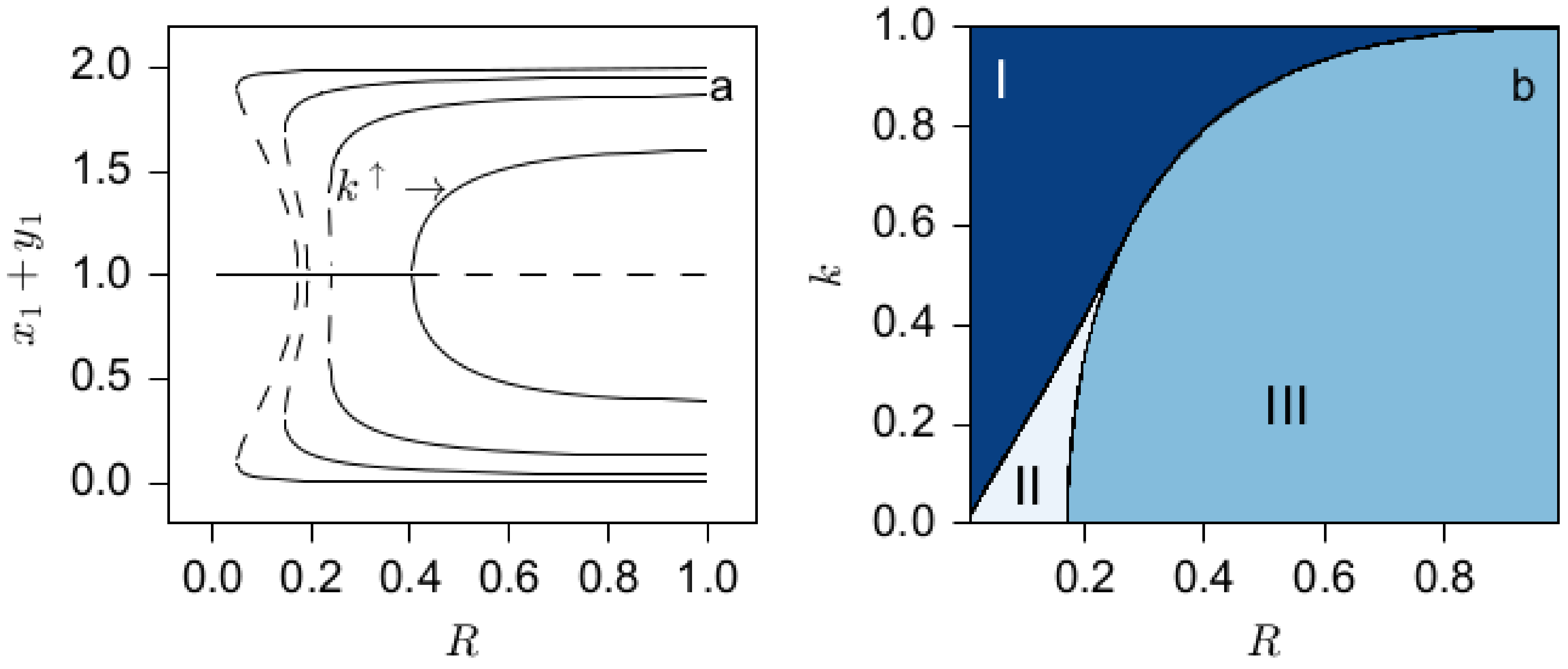


Fig. 2. Bifurcation diagrams of the steady state solutions $x_1 + y_1$ of model 1 as a function of R $(\theta_1/\theta 2)$ for 4 values of k $(k = 0.1, 0.3, 0.5, 0.8)$ (a) and state diagram as a function of R and k (b).

Stam. Nicolis et al
Scientific Reports | 6:32703 | DOI: 10.1038/srep32703

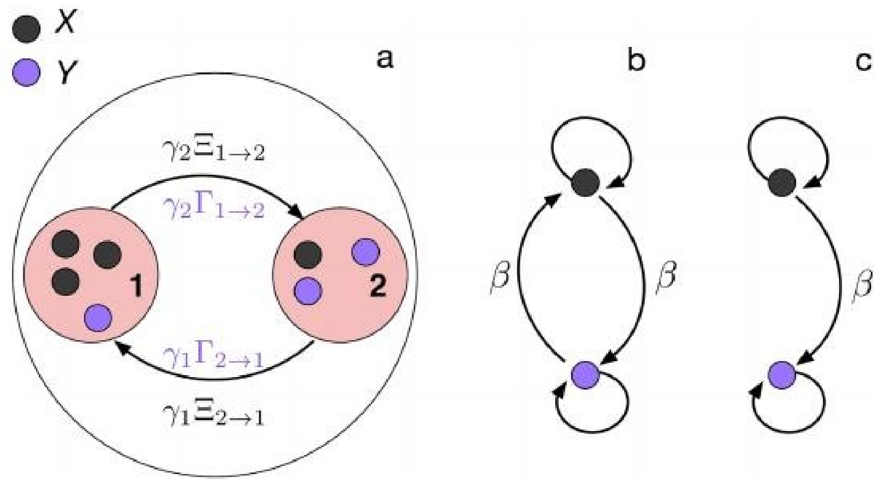


Figure 1. Experimental setup for the study of aggregation/segregation dynamics in an environment containing two equal patches and its relationship with the model defined by eq. (4) (**a**). Positive feedback networks of conspecific and heterospecific interactions : symmetrical (**b**) and asymmetrical (**c**) case.

$$\begin{aligned}
\frac{dx_1}{dt} &= -\frac{x_1\left(1-\frac{1}{s}(x_2+y_2)\right)}{k^2+(\beta_x y_1+x_1)^2}+\frac{x_2\left(1-\frac{1}{s}(x_1+y_1)\right)}{k^2+(\beta_x y_2+x_2)^2}\\
\frac{dx_2}{dt} &= \frac{x_1\left(1-\frac{1}{s}(x_2+y_2)\right)}{k^2+(\beta_x y_1+x_1)^2}-\frac{x_2\left(1-\frac{1}{s}(x_1+y_1)\right)}{k^2+(\beta_x y_2+x_2)^2}\\
\frac{dy_1}{dt} &= -\frac{y_1\left(1-\frac{1}{s}(x_2+y_2)\right)}{k^2+(\beta_y x_1+y_1)^2}+\frac{y_2\left(1-\frac{1}{s}(x_1+y_1)\right)}{k^2+(\beta_y x_2+y_2)^2}\\
\frac{dy_2}{dt} &= \frac{y_1\left(1-\frac{1}{s}(x_2+y_2)\right)}{k^2+(\beta_y x_1+y_1)^2}-\frac{y_2\left(1-\frac{1}{s}(x_1+y_1)\right)}{k^2+(\beta_y x_2+y_2)^2}
\end{aligned} \tag{4}$$

where $x_i = X_i/N$, $y_i = Y_i/N$, $s = S/N$, $k = K/N$ and $t = \theta T/N^2$. We notice that $dx_1/dt + dx_2/dt = 0$ and $dy_1/dt + dy_2/dt = 0$ reflecting that throughout the process the numbers of individuals are conserved ($x_1 + x_2 = 1$, $y_1 + y_2 = 1$). Notice that when $\ell \leq 1$, although the rates still decrease with the populations already on the patches, the only solution is the homogeneous one, $x_i = y_i = 0.5$ ($i = 1, 2$), where the two populations are well-mixed among the two patches (see Supplemental Material A).

Figure 1a shows a typical experimental setup corresponding to our theoretical formulation : two patches of a

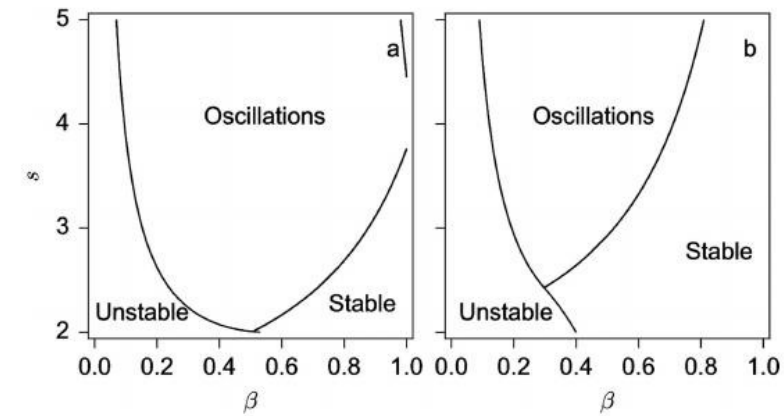


Figure 6. Stability of the homogeneous state of model (4) in the case of asymmetrical case $\beta_x = \beta$ and $\beta_y = 0$ as a function of β and s for $k = 0.1$ (**a**) and $k = 0.3$ (**b**).

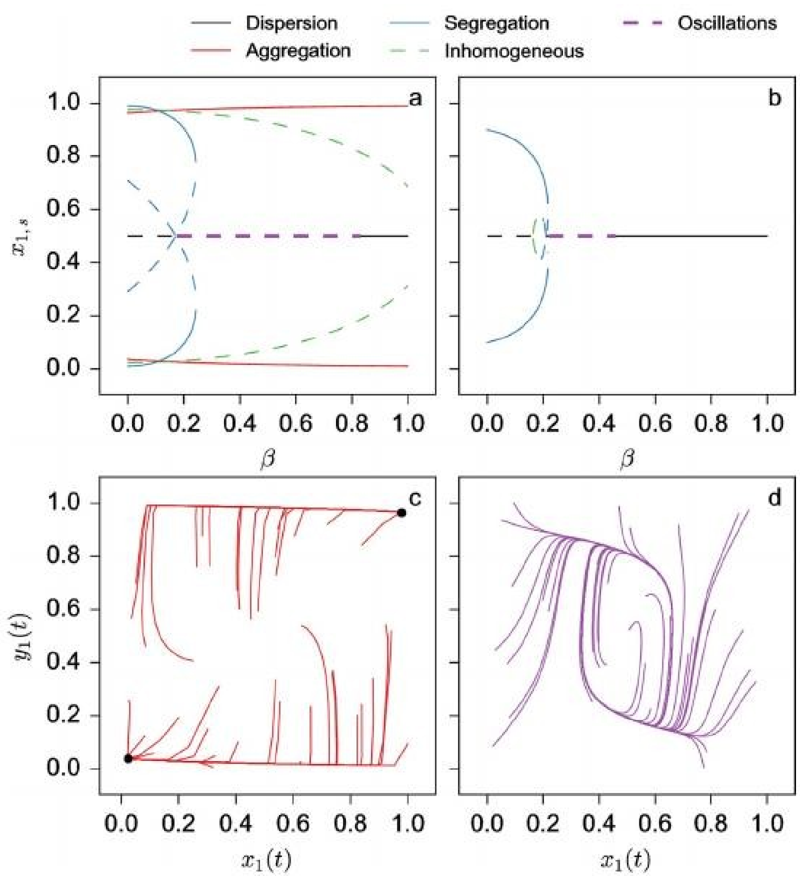
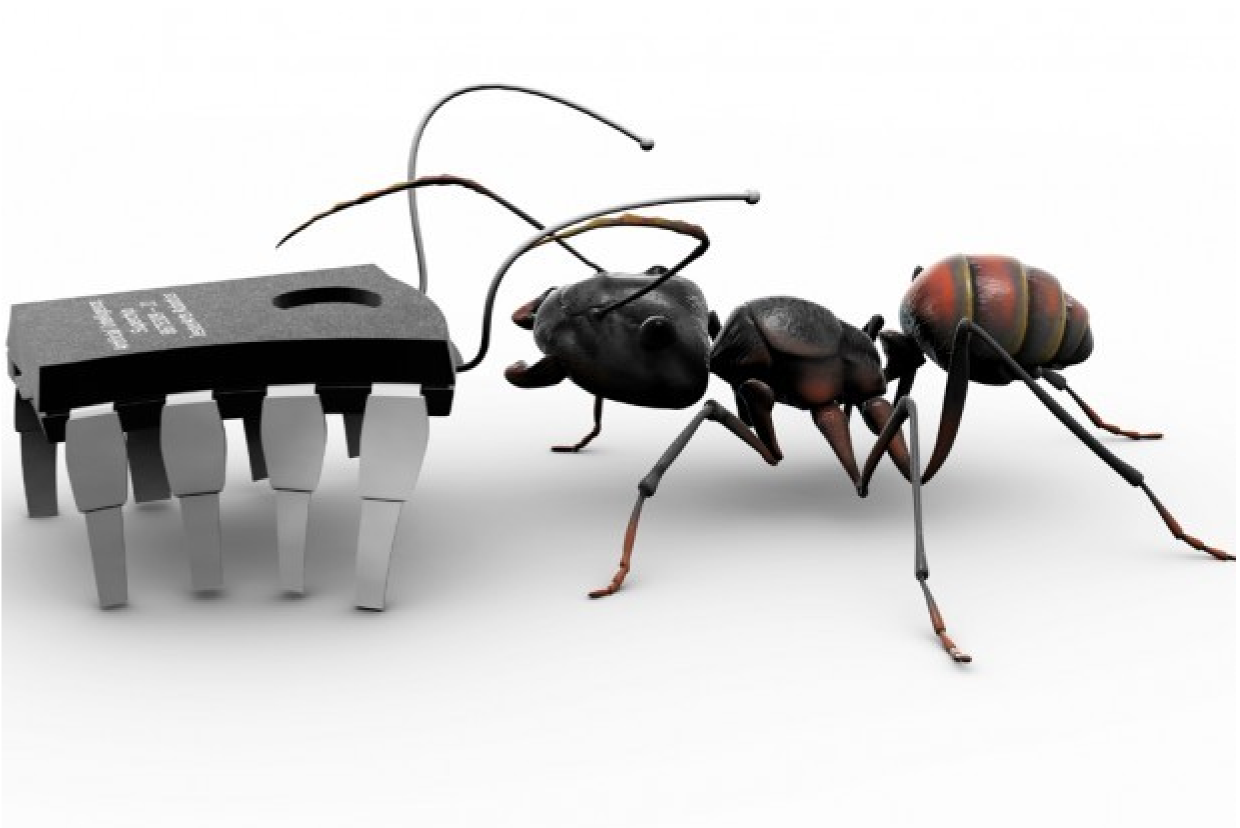


Figure 7. Bifurcation diagrams of the steady states of $x_{1,s}$ of the model (4) as a function of parameter β for $s = 2.8$, $k = 0.1$ (**a**) and $k = 0.3$ (**b**); Numerical integration of the equations of the model (4) for $s = 2.8$, $\beta = 0.35$ and $k = 0.1$ (**c**) and $k = 0.3$ (**d**).

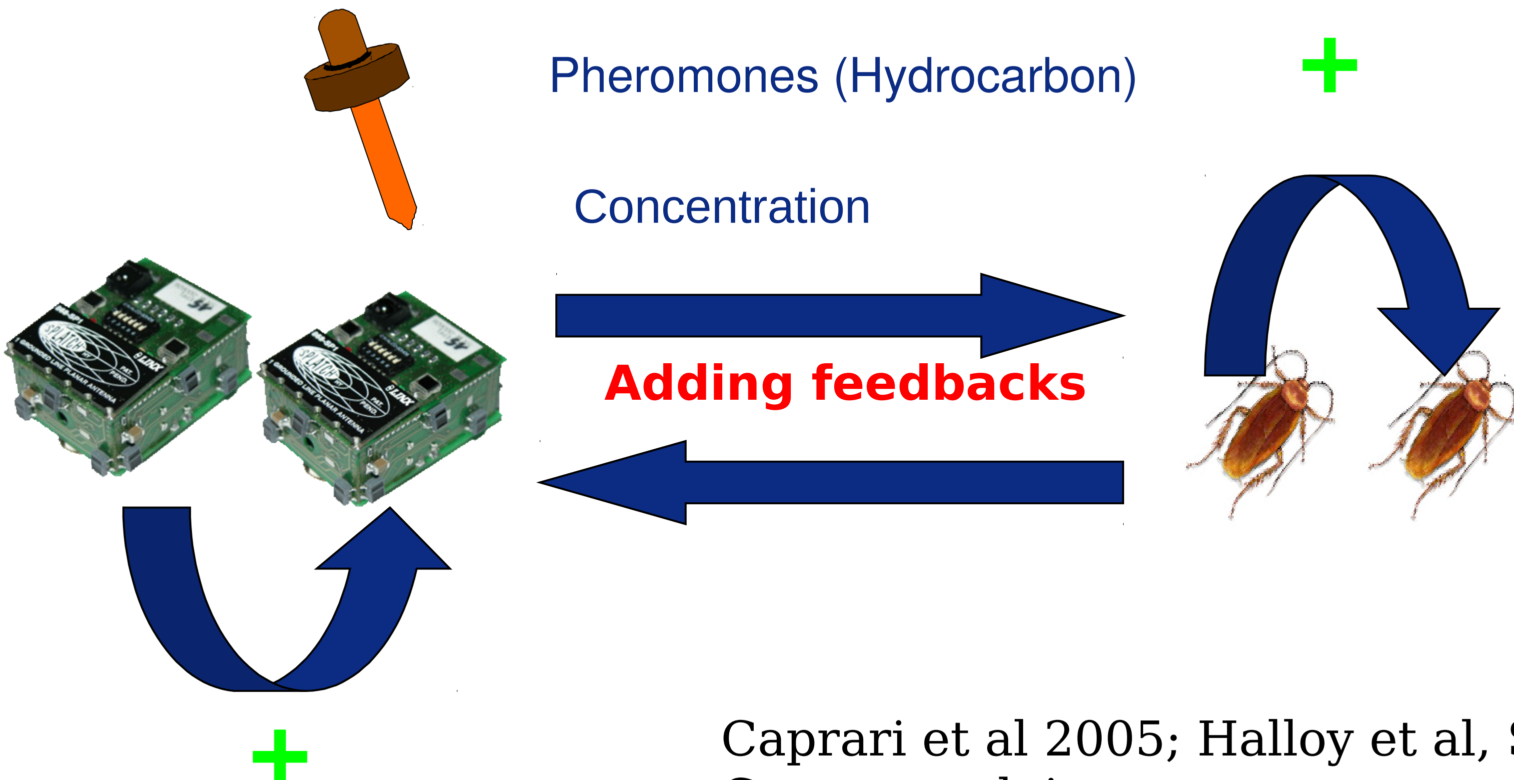


Hybrid Animal – Robot Societies: Control via “info-allaxis”

Mixed groups of cockroaches and socially integrated robots

The robot is designed
- to mimic insect behavior patterns (sensors for wall detection, robots, cockroaches)

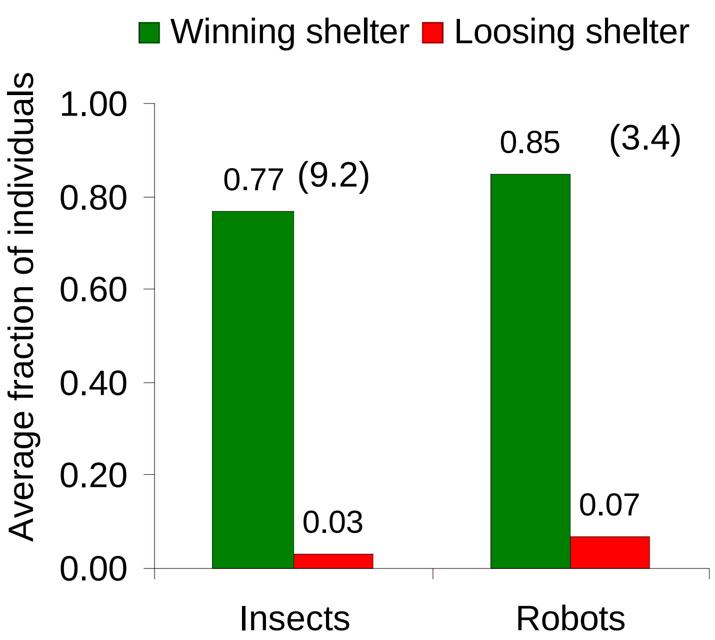
- Artificial agents and organisms interact ("robot is a conspecific") its influence on insects
- is the same as the influence of insects on insects

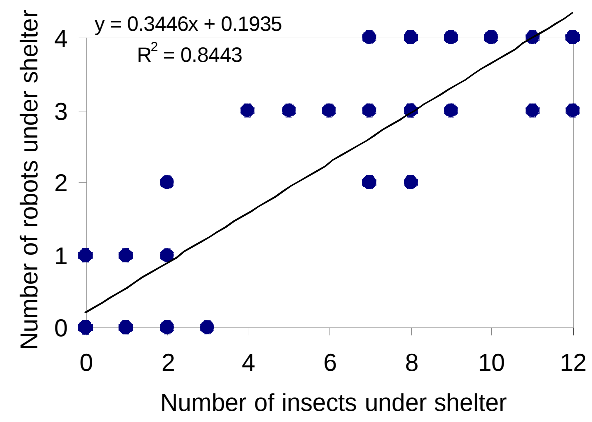


Caprari et al 2005; Halloy et al, Science, 2007; Campo et al, in progress

Collective decision making in mixed groups
Robots mimick the behaviour of the animals

12 cockroaches & 4 robots, 2 identical shelters





Clear choice in 25 out 30 tests

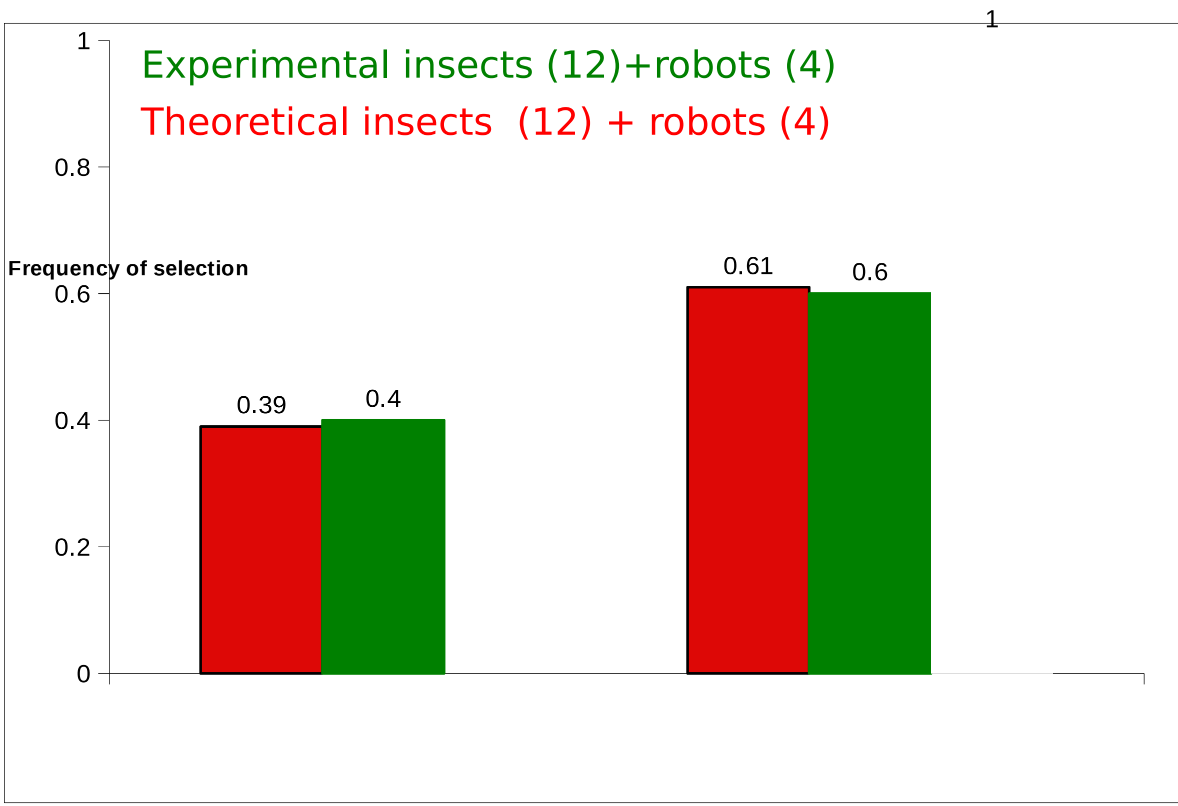
Robots are with insects both like dark nests

(G. Sempo *et al*, 2006; J. Halloy et al, Science, 2007).

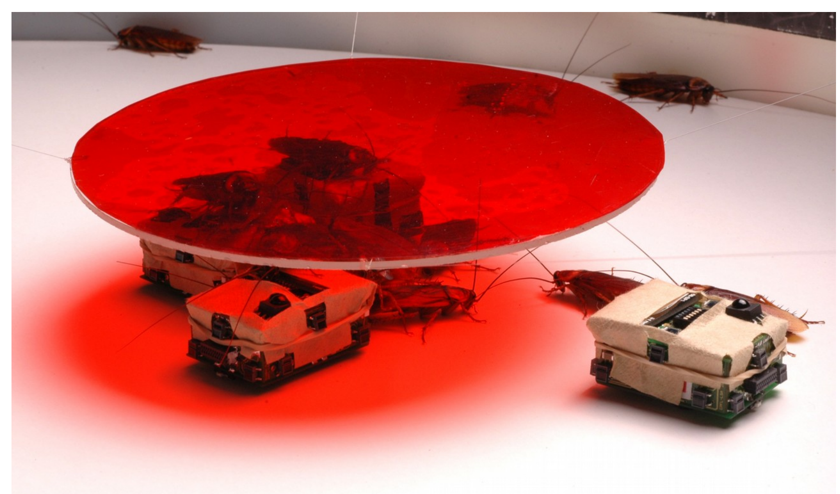
Collective decision making in mixed groups of robots and cockroaches (two different shelters) (II)

Insects prefer dark & Robots prefer light

Robots and insects can present opposite preference for shelters $\theta_{rlight} < \theta_{rdark}$ and $\theta_{light} > \theta_{dark}$

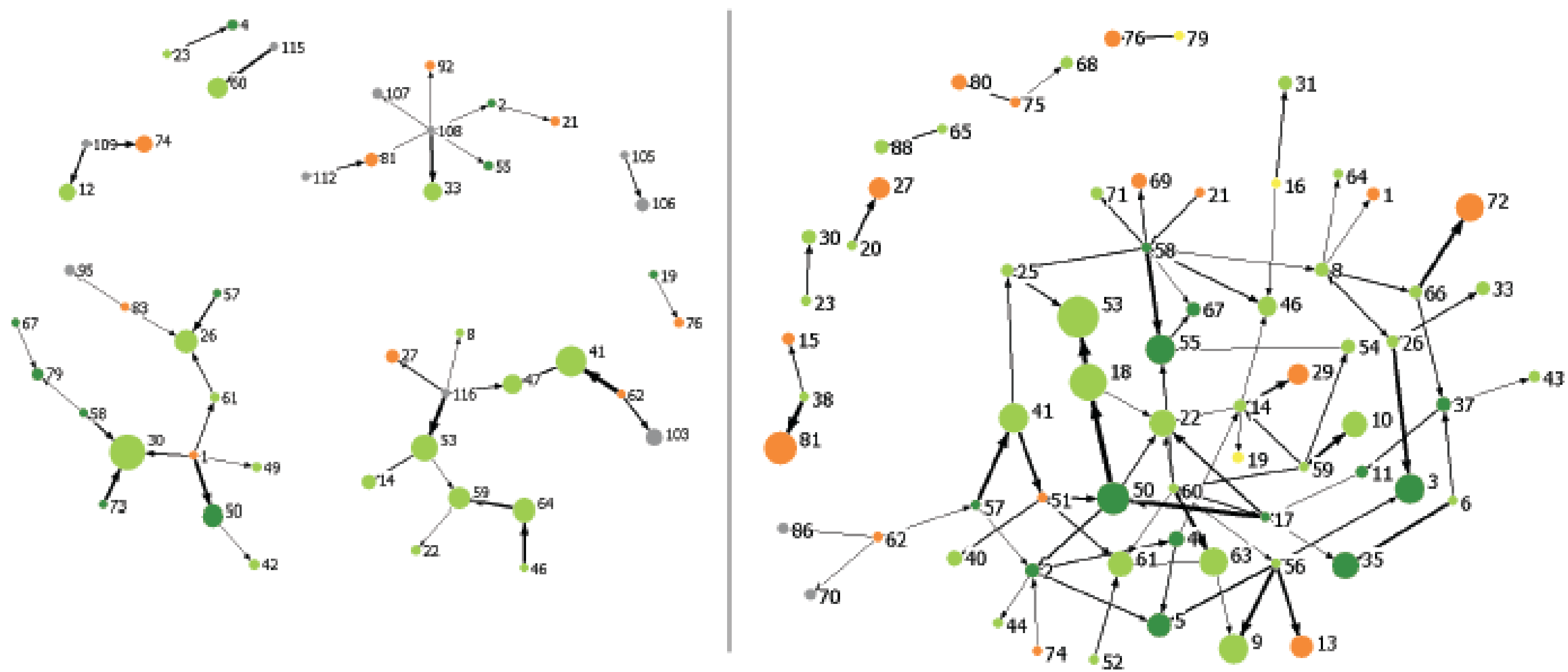


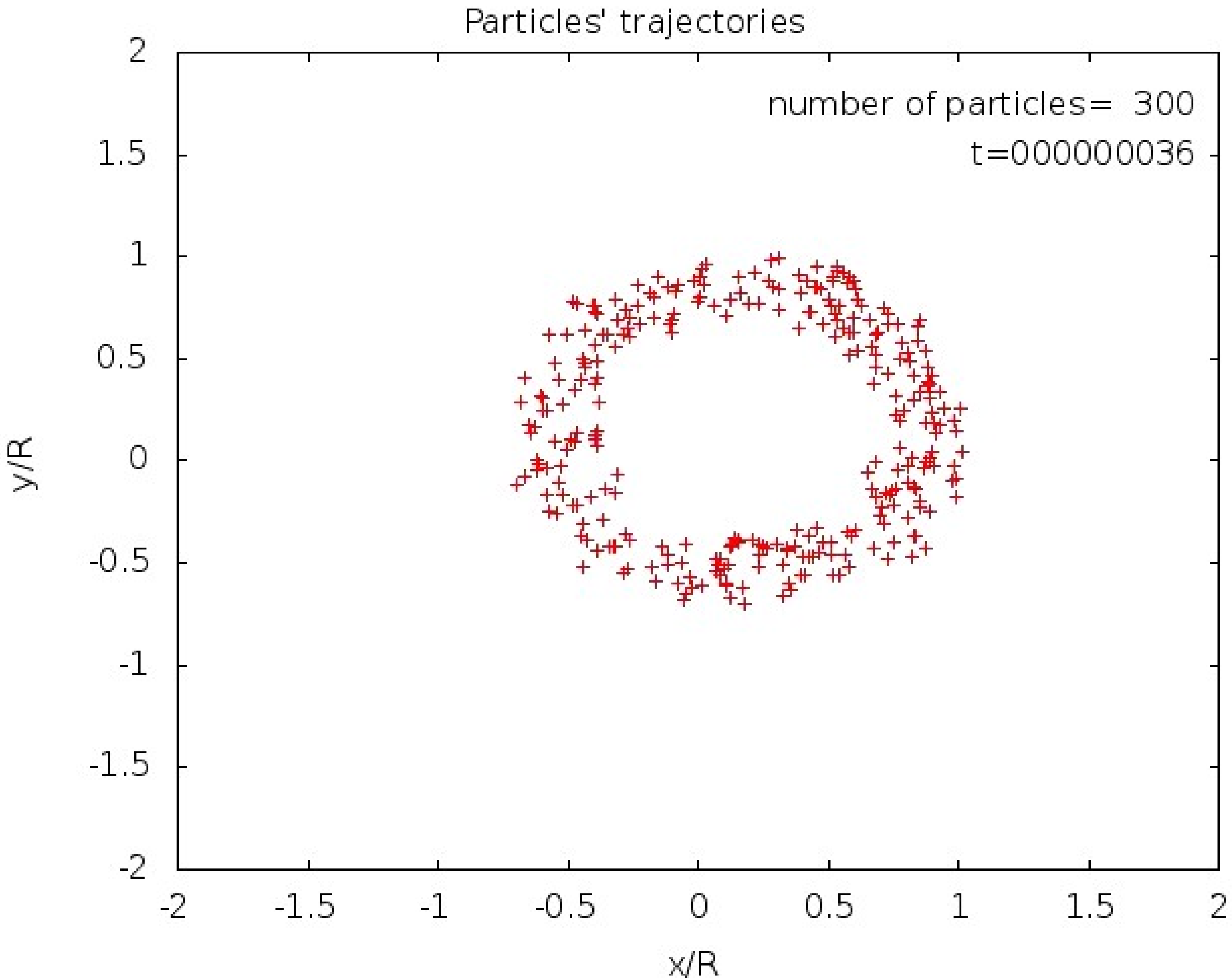
4)

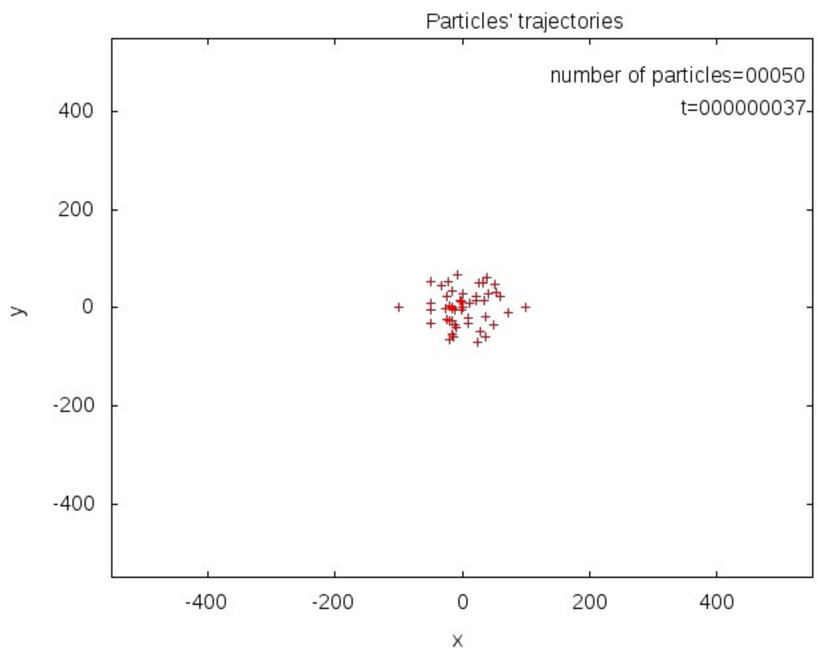


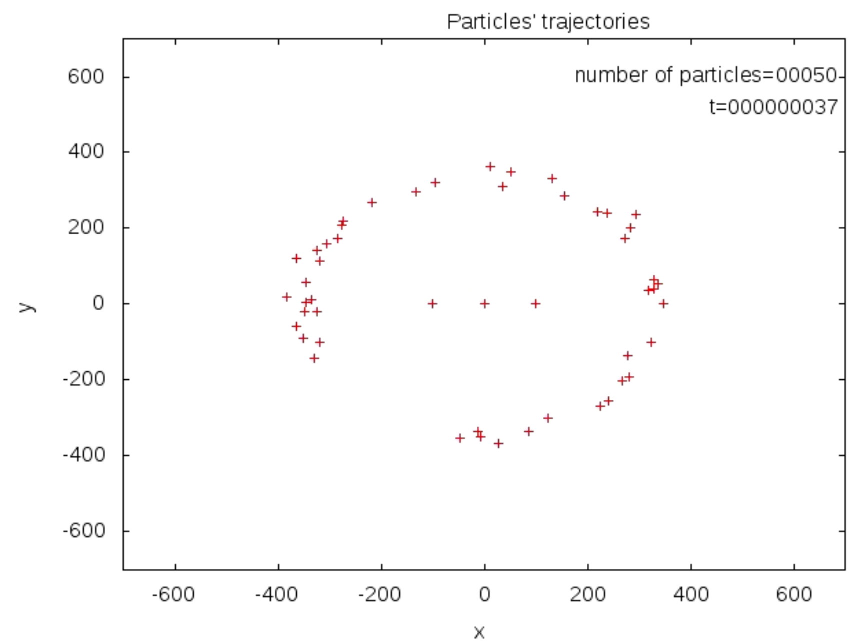
next step:

TIME-Varying Networks & Aggregation




Particles' trajectories
number of particles= 300
t=000000036
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
y/R
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
x/R


Particles' trajectories
number of particles=00050
t=000000037
y
x
400
200
0
-200
-400
-400
-200
0
200
400


Particles' trajectories
number of particles=00050
t=000000037
y
x
600
400
200
0
-200
-400
-600
-600
-400
-200
0
200
400
600

Thanks to collaborating teams

▪ USE equipe ▪ USE index

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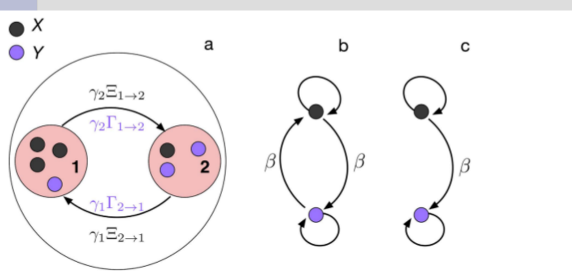

Figure 1. Experimental setup for the study of aggregation/segregation dynamics in an environment containing two equal patches and its relationship with the model defined by eq. (4) (a). Positive feedback networks of conspecific and heterospecific interactions : symmetrical (b) and asymmetrical (c) case.

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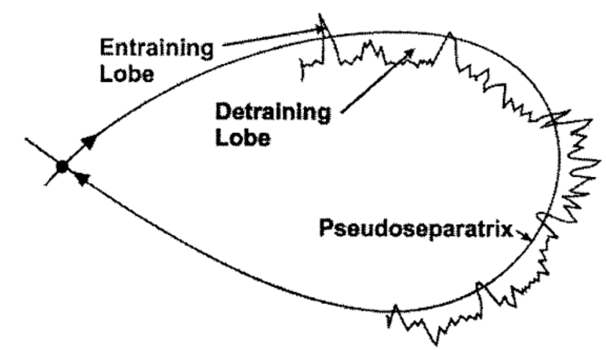

Figure 5.5. Schematic of phase space slice through intersecting manifolds of stochastic system.

"Coordinated aggregation in complex systems", V. Basios, S.C. Nicolis, JL Deneubourg, Eur. Phys. J. ST 225 (6-7), 1143-7, 2016

"Strong perturbations in nonlinear systems", V. Basios
Eur. Phys. J. ST 6 (225), 1219-29, 2016