Random Search Principles in Foraging Ecology

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MPI-Physics of complex Systems
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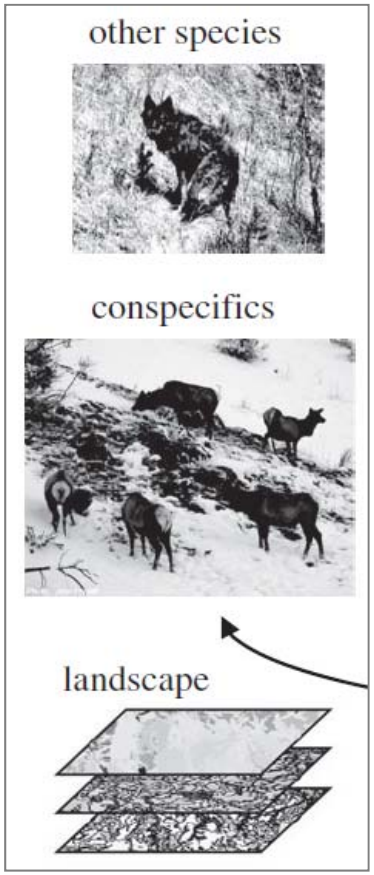
*iCrea
INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

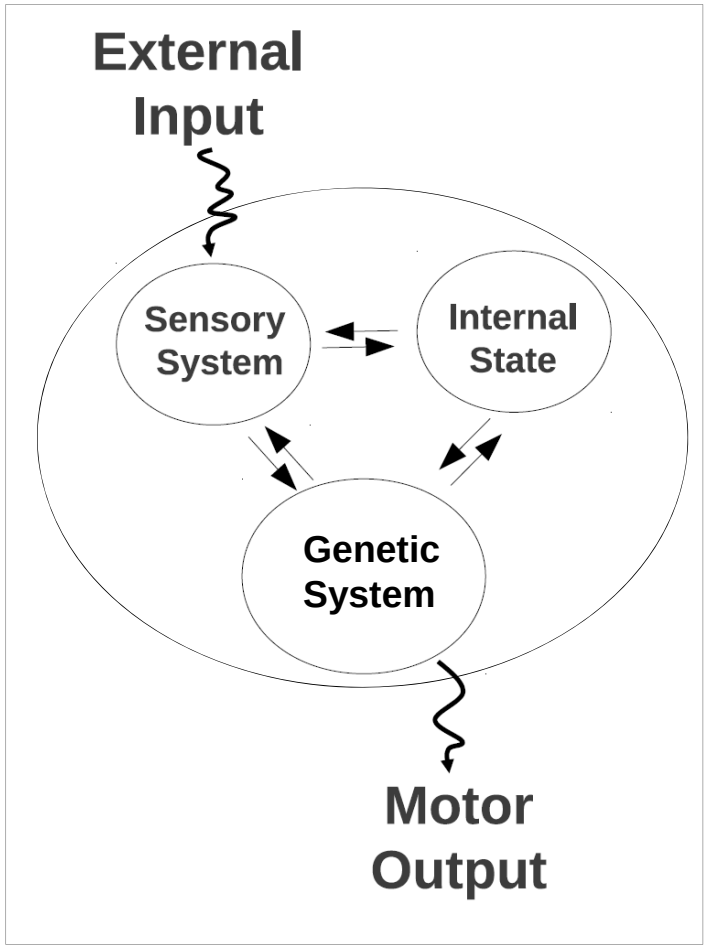
CEAB CENTRE D'ESTUDIS AVANÇATS DE BLANES
CSIC

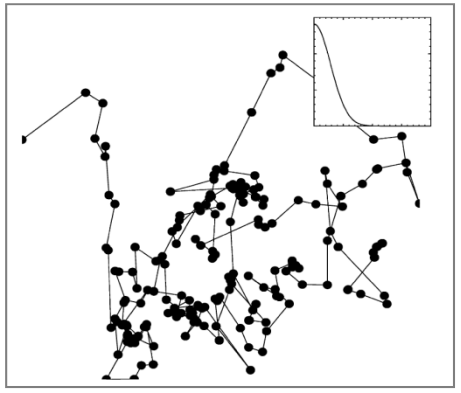
CREAF 25 YEARS

MovementEcologyLab
...understanding organisms in motion

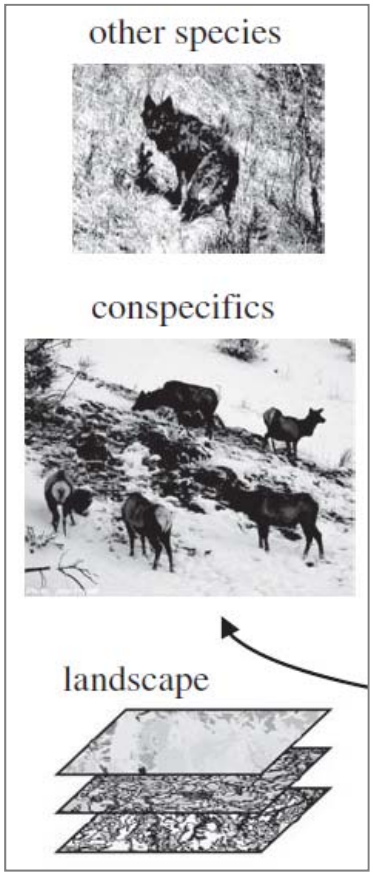
Movement (foraging) Ecology: Concept

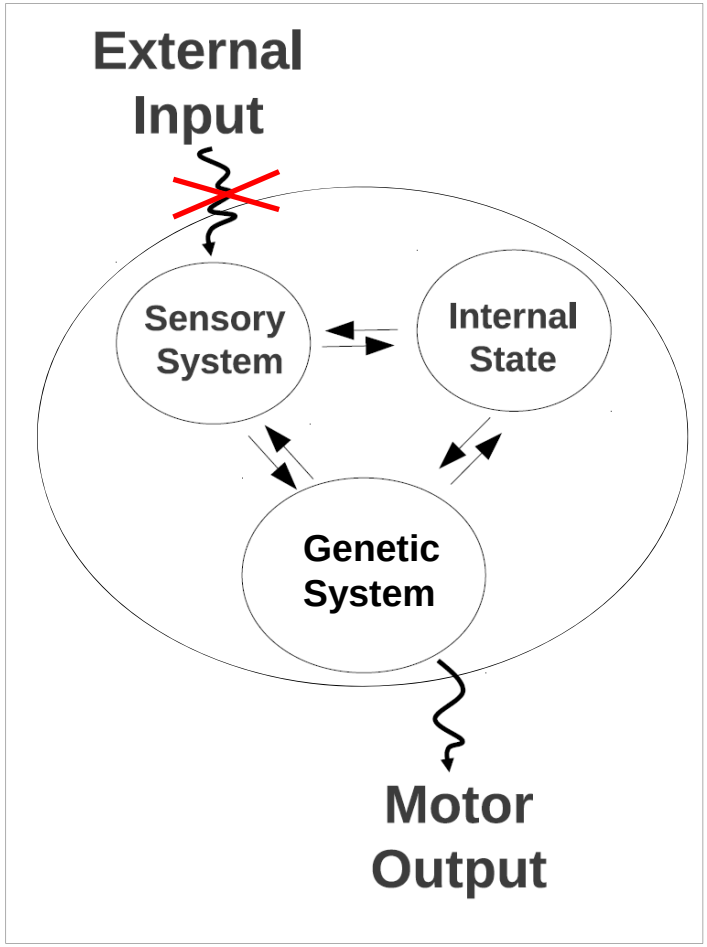


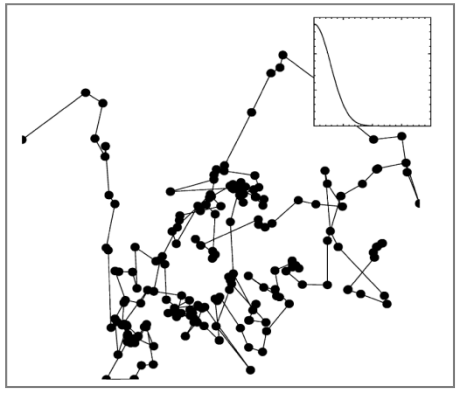




Search: Foraging “under uncertainty”







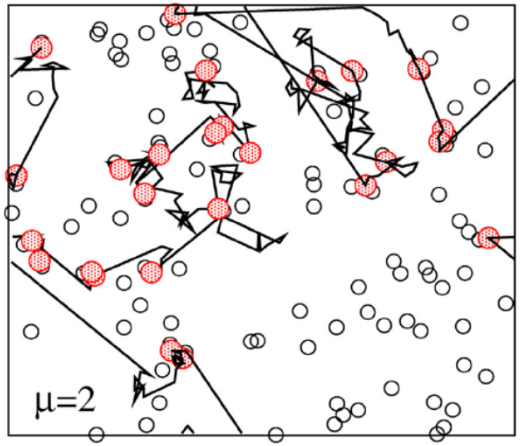
Search efficiency: things to take into account

Different ways to measure efficiency!

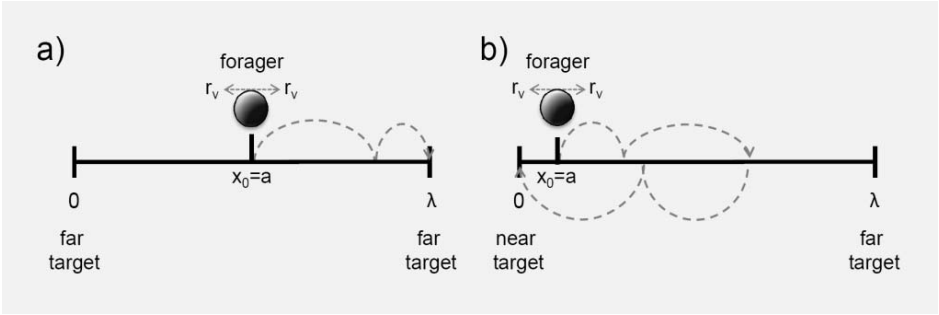
$$\eta = \frac{N_{\text{found}}}{L_{\text{tot}}}$$

1. Target density
2. Target spatial distribution
3. Target mobility
4. Searcher mobility
5. Searcher perception (rv)
6. Searcher x0
7. Encounter dynamics

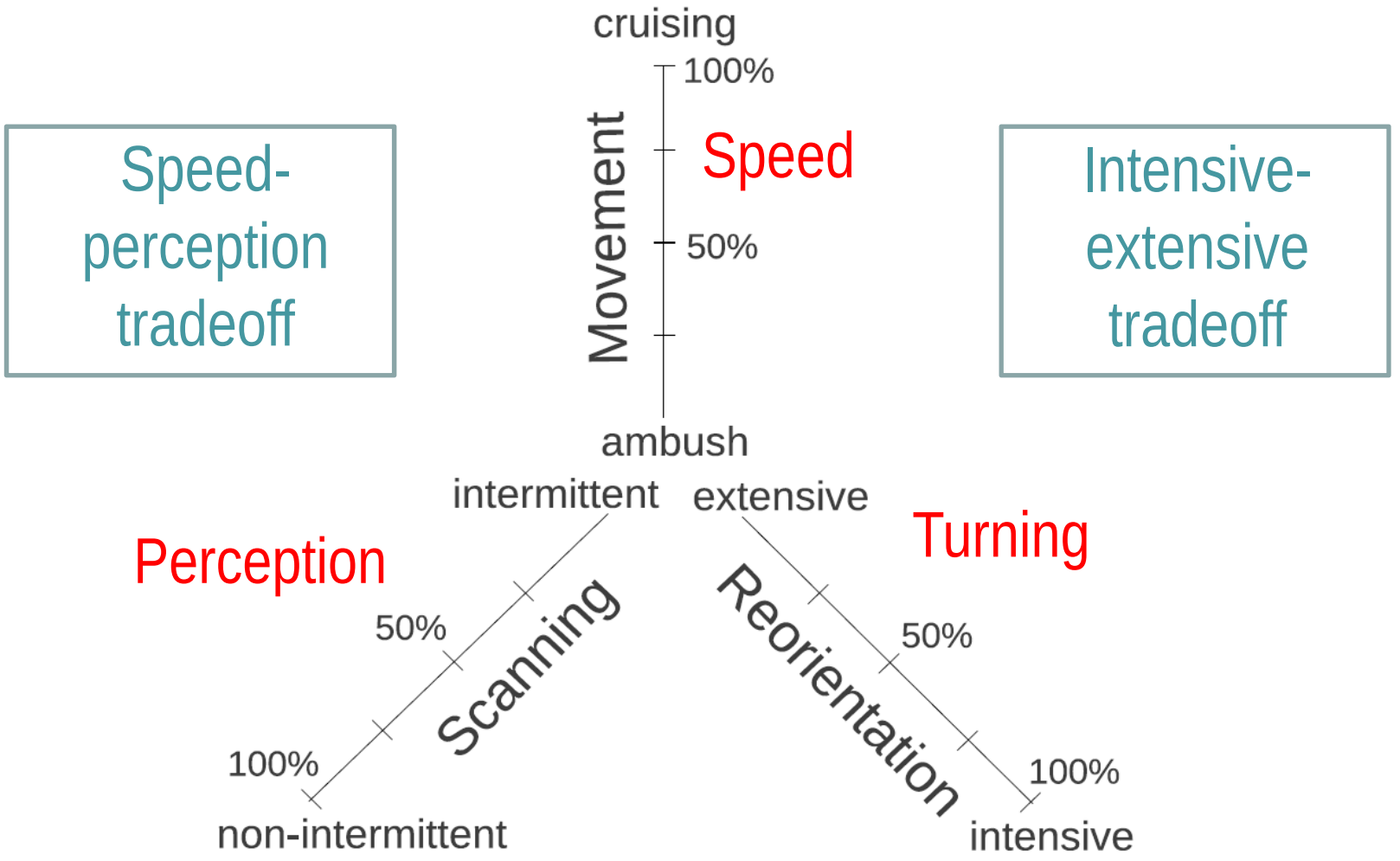
Computer Simulations



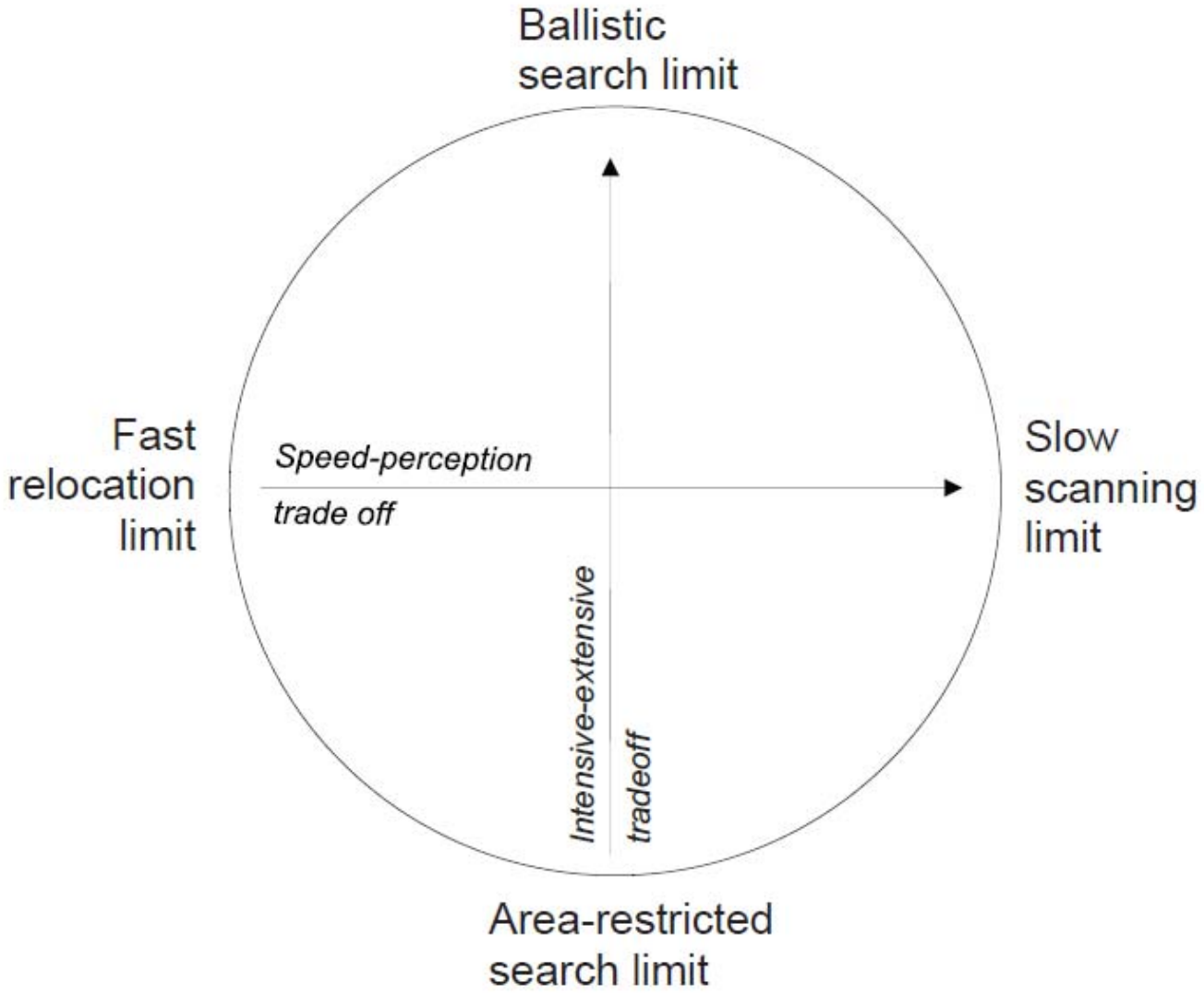
Random Walk & Diffusion Theory



Searcher perspective: search tradeoffs



Searcher perspective: search tradeoffs



Factoring the time to find a target: MFPT ⟶ MFDT

mobility *perception*

$$\langle T \rangle = T_1 + T_2$$

Mean time needed to approach a target

$T_1 = f_1(x_0, D, L)$

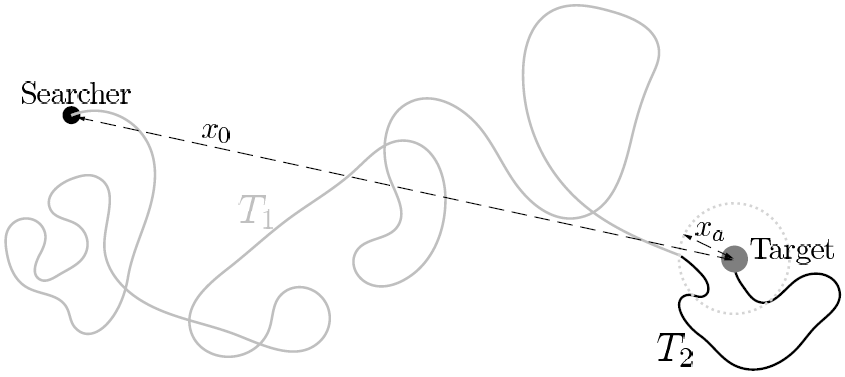
$D(v, \alpha, \varphi(t))$

(intensive-extensive)

Mean time needed to detect a target

$T_2 = f_2(v, p(v), L)$

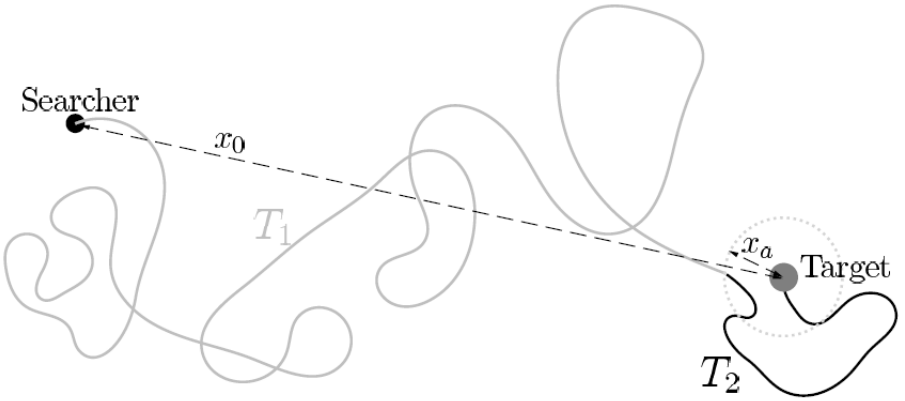
(speed-percpetion)



Campos et al. PRE 2013
Méndez et al. 2014 (Springer)

Factoring the time to find a target: MFPT ⟶ MFDT

1D-Correlated Random Walk



$$\langle T \rangle = \overbrace{\frac{x_0(L-x_0)}{2D}}^{T_1} + \overbrace{\frac{L}{vp(v)}}^{T_2}$$

$$D(v, \alpha, \varphi(t))$$

Campos et al. PRL 2012
Méndez et al. 2014 (Springer)
Weiss J.Chem.Phys .1984

Keys to effective search strategies

TRADEOFF	COMPROMISE	INGREDIENTS
Speed/perception	Optimal Crusing Velocity Optimal Intermittence	• Max. velocity but without perceptual impediments • Run and pause mixtures
Intensive/extensive	Mixture of scales or Lévy “signatures”	• Some directional correlation • Multi-scale turn interevents • Small Diffusion Constant • Super (enhanced) diffusion

Bartumeus et al. PLoSONE 2014; Méndez et al. 2014; Viswanathan et al. 2011;

Diffusion or space use

$$D(v, \alpha, \varphi(t))$$

Exponential

$$D_{corr} = D(v, 0, \varphi_{corr}(t)) = \frac{v^2 \langle t \rangle}{d}.$$

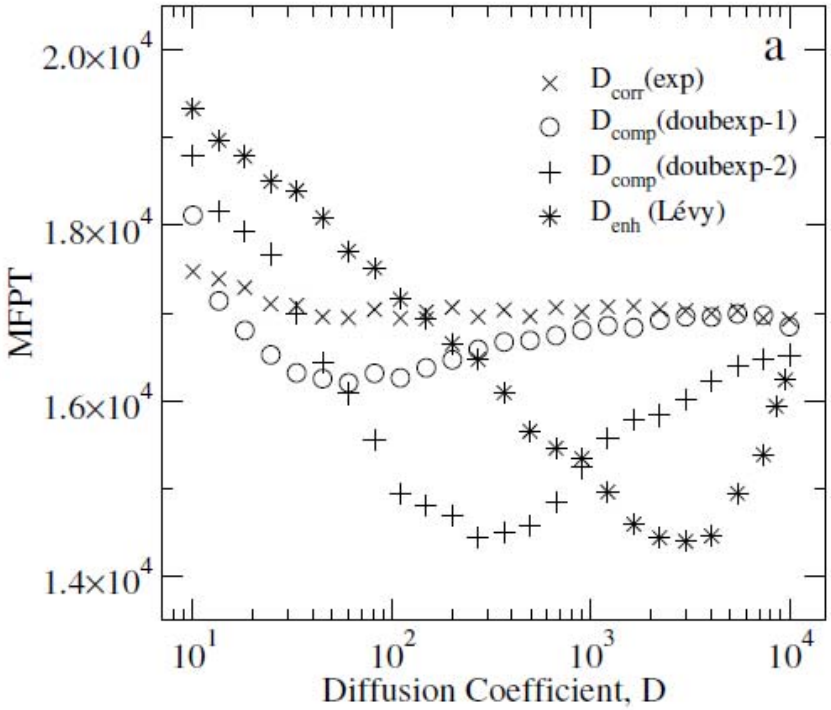
Composite/Hyperexponential

$$D_{comp} = D(v, 0, \varphi_{comp}(t)) = \frac{v^2 \left(w\langle t_1 \rangle^2 + (1-w)\langle t_2 \rangle^2\right)}{d\left(w\langle t_1 \rangle + (1-w)\langle t_2 \rangle\right)}.$$

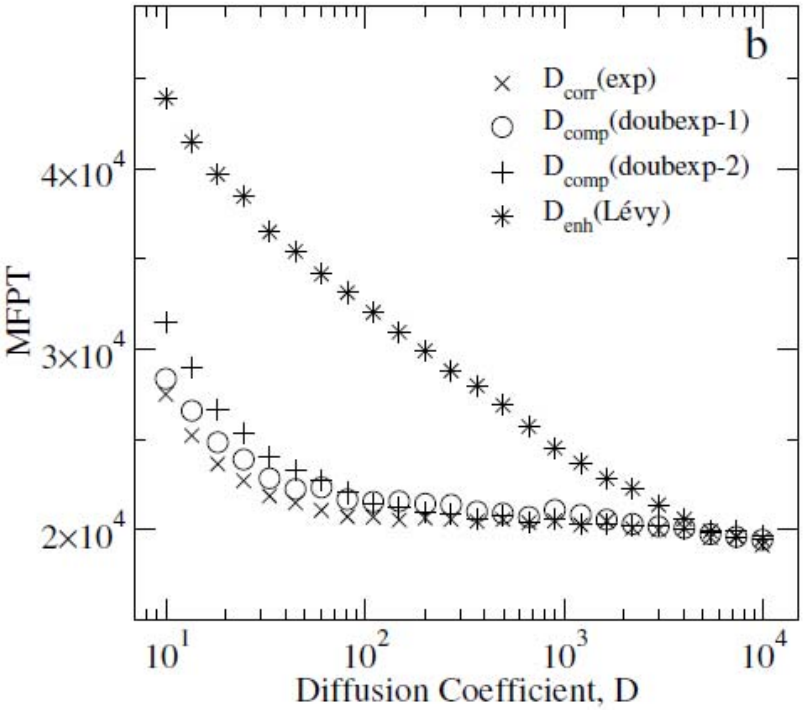
Truncated Lévy

$$D_{enh} = \begin{cases} \frac{v^2}{2d}\left(\frac{1-\mu}{2-\mu}\frac{t_{max}^{2-\mu} - t_{min}^{2-\mu}}{t_{max}^{1-\mu} - t_{min}^{1-\mu}} + \frac{2\alpha}{1-\alpha}\frac{-\mu}{1-\mu}\frac{t_{max}^{1-\mu} - t_{min}^{1-\mu}}{t_{max}^{-\mu} - t_{min}^{-\mu}}\right) & \mu \neq 1, \mu \neq 2 \\ \frac{v^2}{2d}\left(\frac{1-\mu}{2-\mu}\frac{t_{max}^{2-\mu} - t_{min}^{2-\mu}}{t_{max}^{1-\mu} - t_{min}^{1-\mu}} + \frac{2\alpha\mu}{1-\alpha}\log\frac{t_{max}}{t_{min}}\right) & \mu = 1 \\ \frac{v^2}{2d}\left[(1-\mu)\log\frac{t_{max}}{t_{min}} + \frac{2\alpha}{1-\alpha}\frac{-\mu}{1-\mu}\frac{t_{max}^{1-\mu} - t_{min}^{1-\mu}}{t_{max}^{-\mu} - t_{min}^{-\mu}}\right] & \mu = 2. \end{cases}$$

Asymmetric regime
(heterogeneity)



Symmetric regime
(diluted,homogeneous)

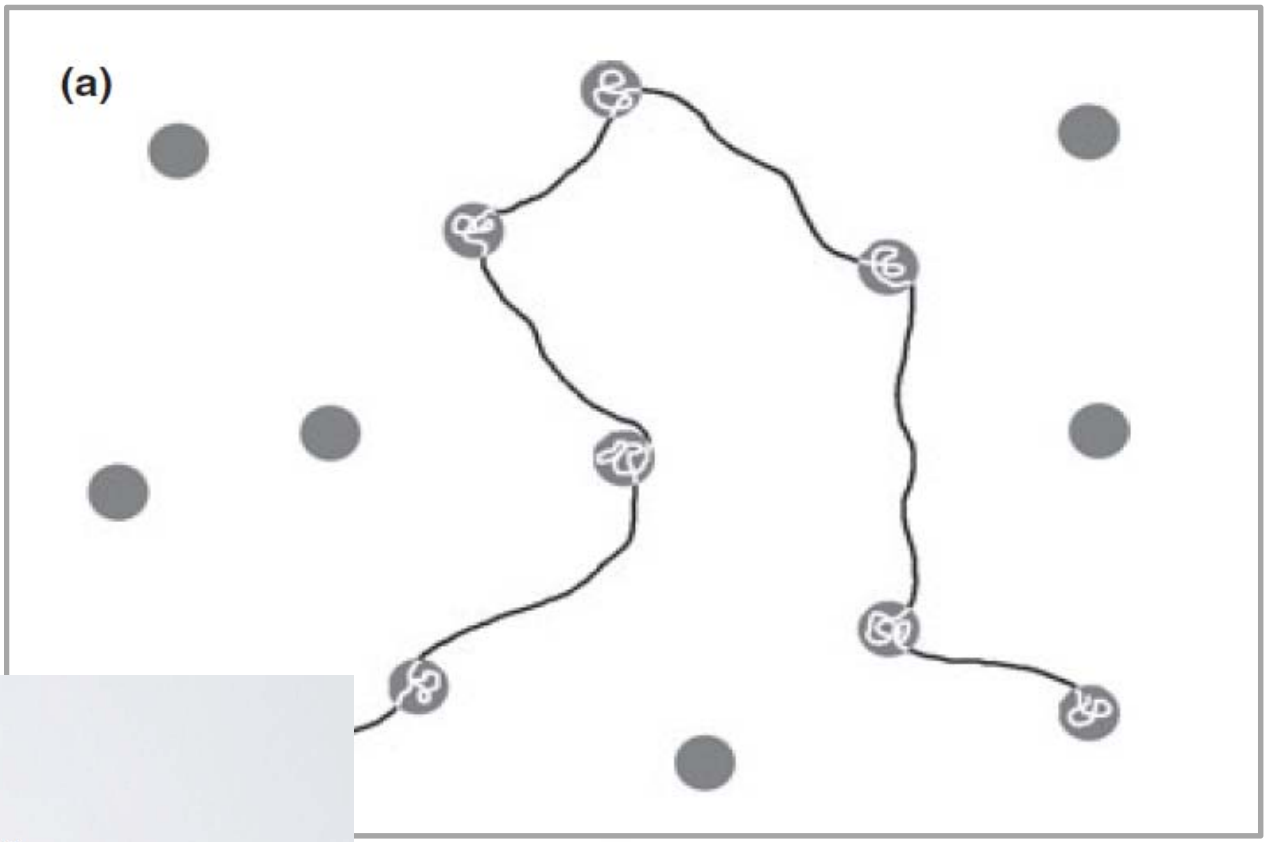


“mixture of scales/persistence”

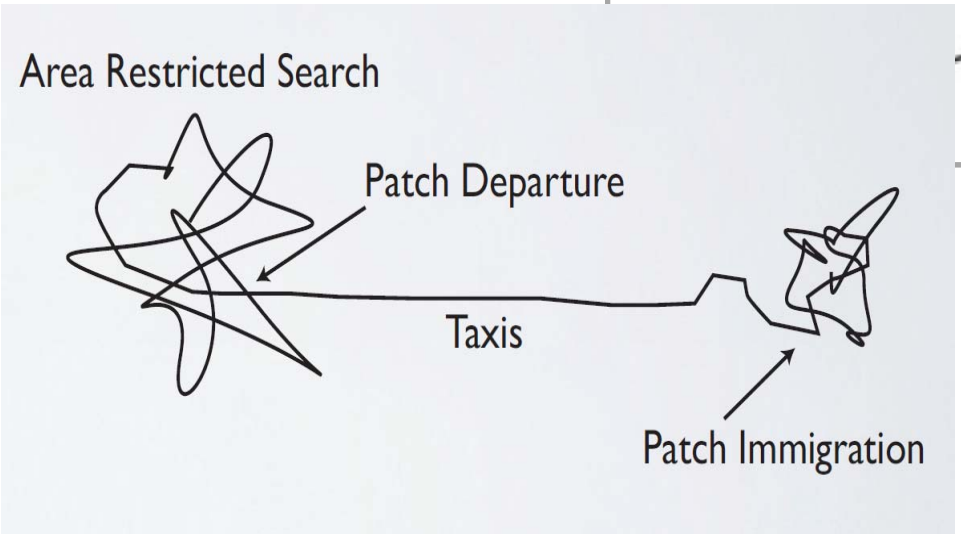
“large scale/persistence”

Current Paradigm of inter-patch Motion

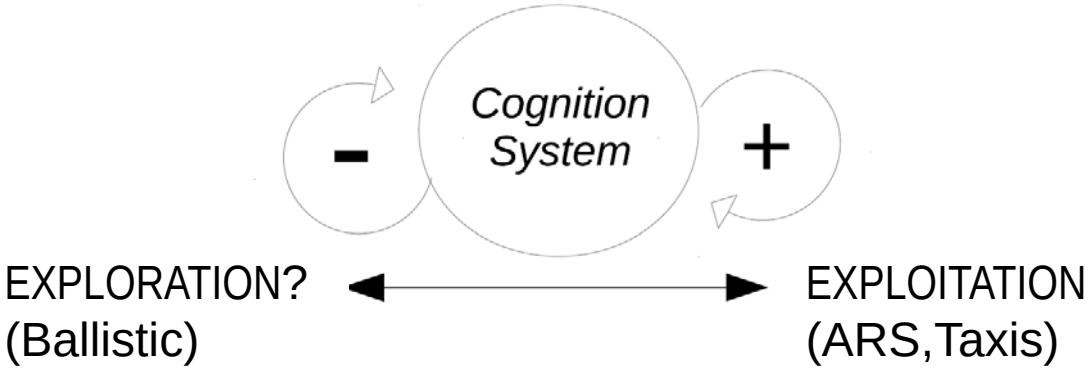
R.S. Schick et al. (2008)
Ecology Letters

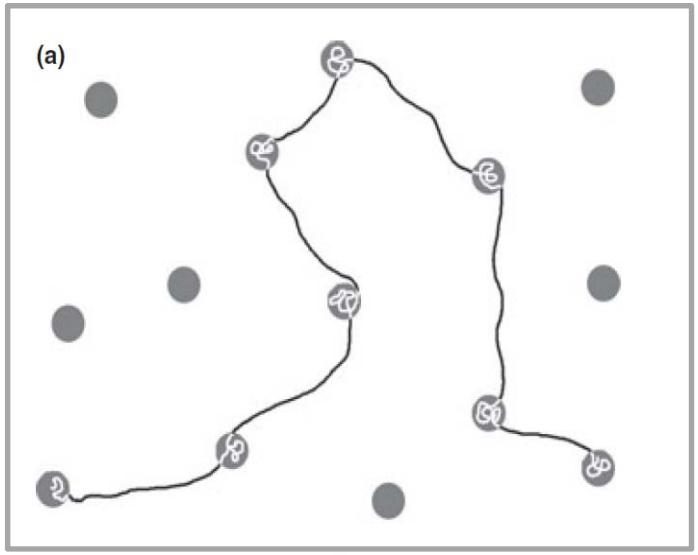


S. Benhamou 2014
Ecology Letters



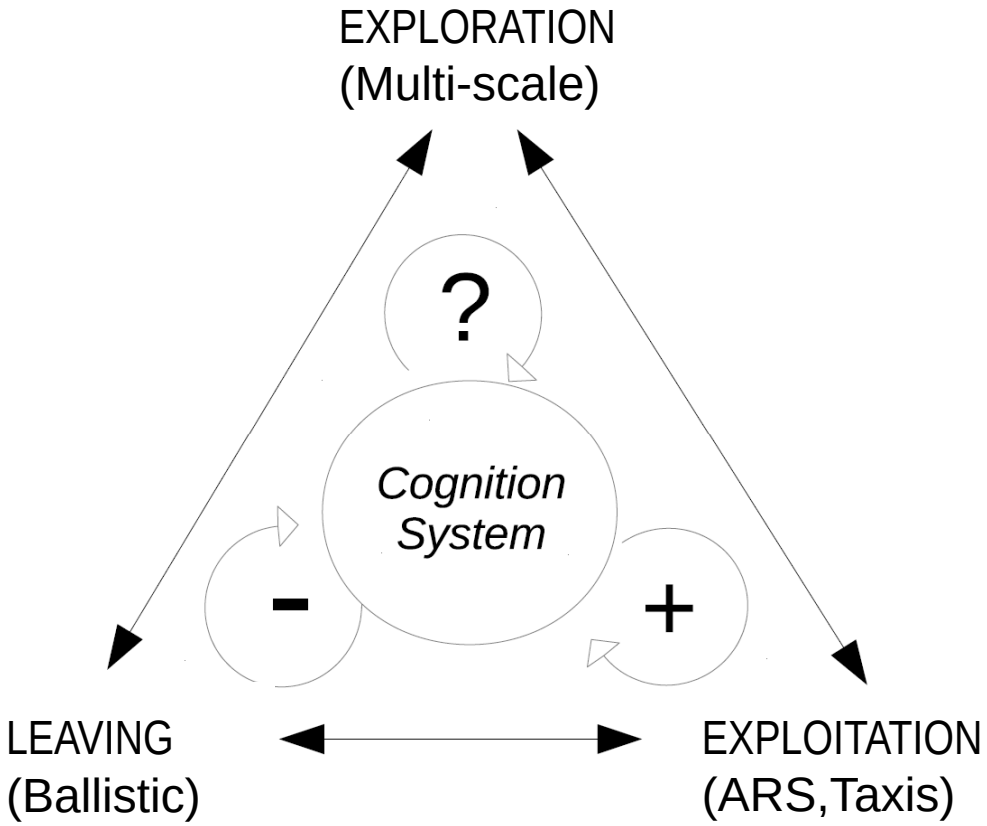
Current Paradigm of inter-patch Motion



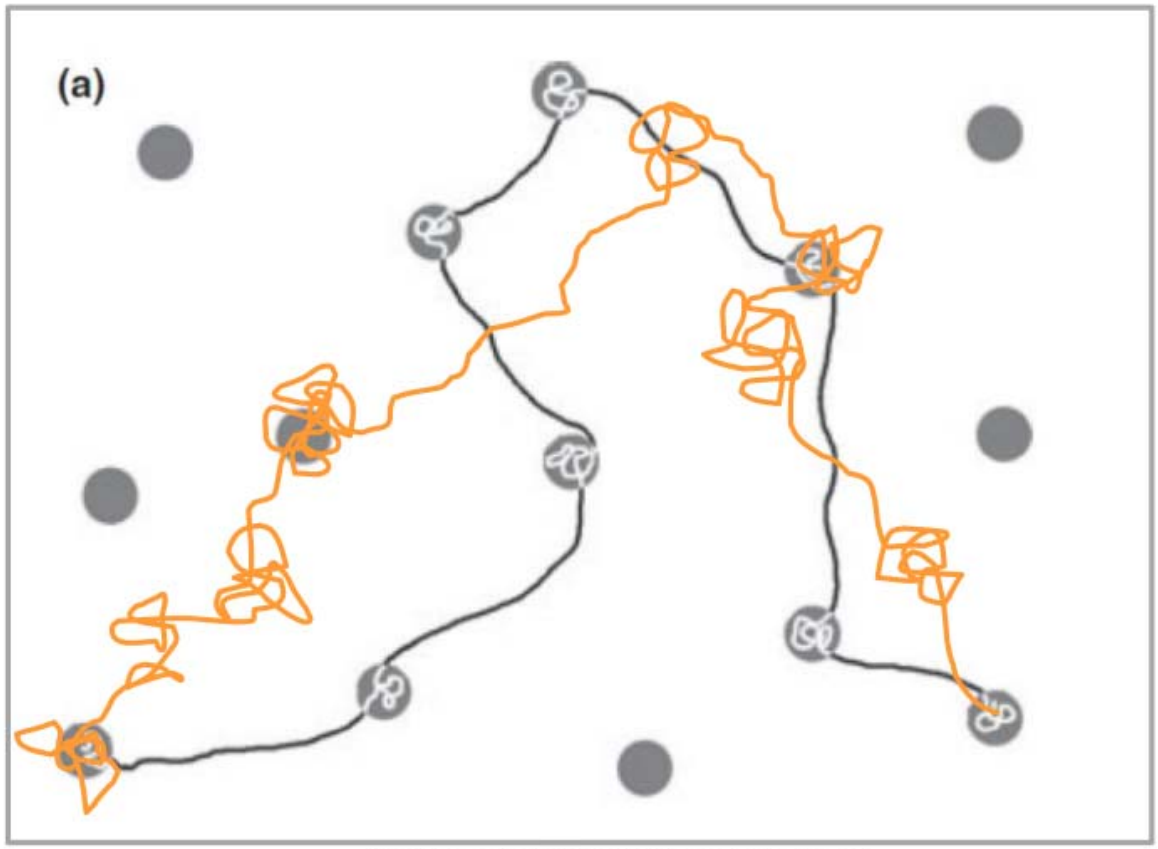


Perfect mapping

New paradigm of inter-patch motion



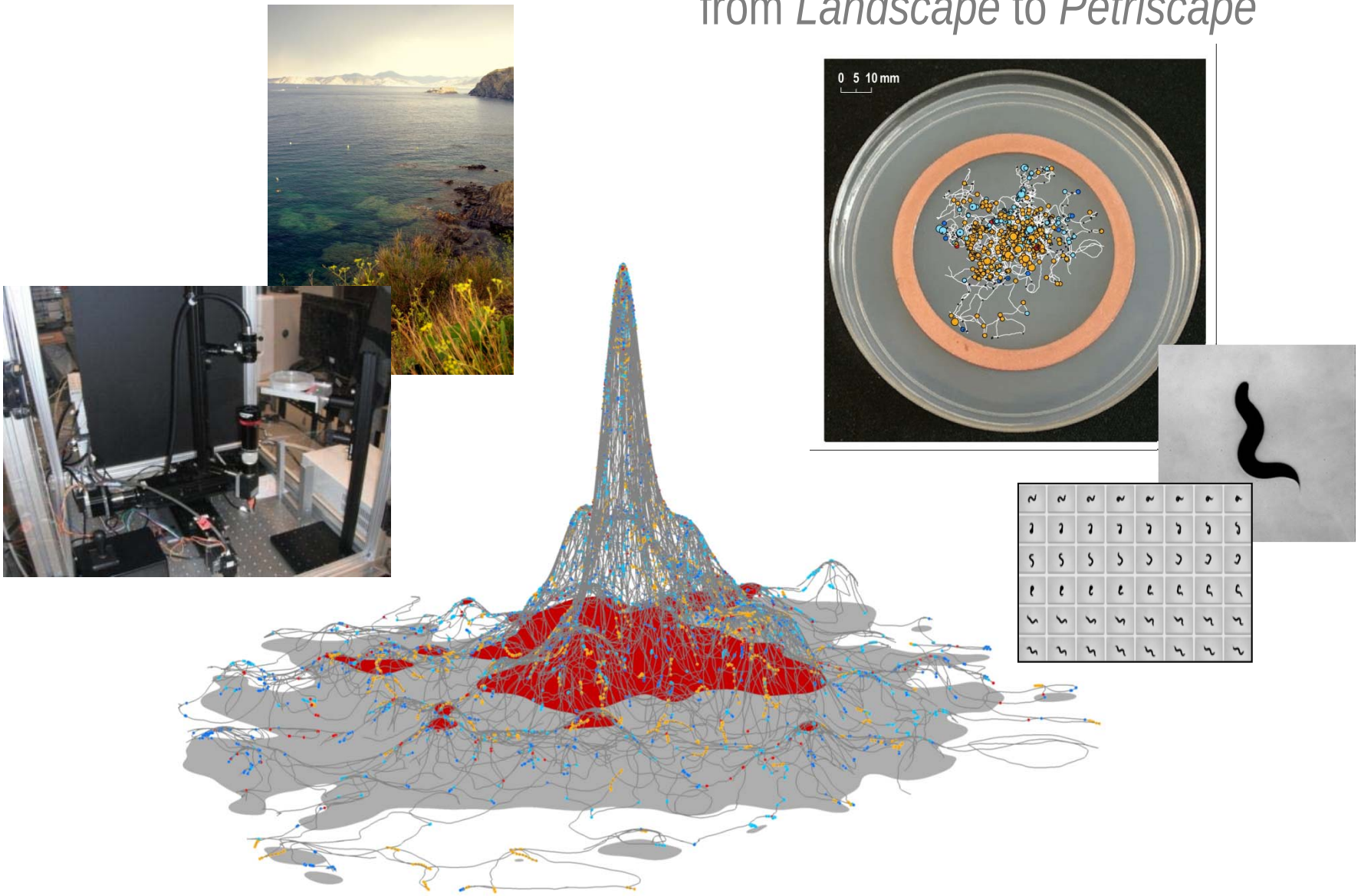
New paradigm of inter-patch motion



Impertect mapping

Search Ecology with Model Organisms

from *Landscape* to *Petriscape*



Model Organisms

Temnothorax albipennis

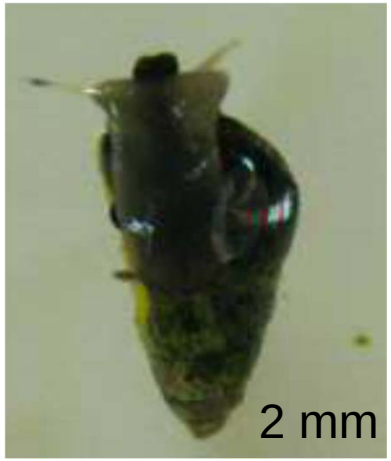
Hydrobia ulvae

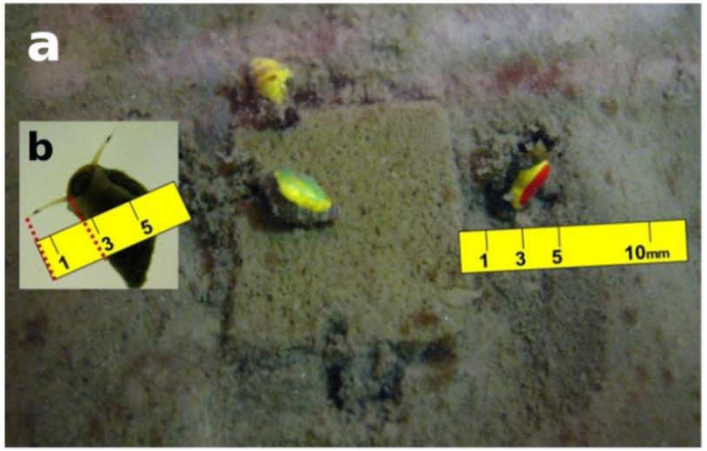
Schistocerca gregaria

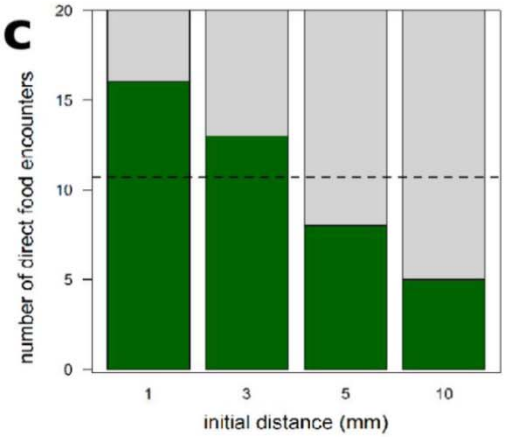
Aphaenogaster senilis

Mytilus edulis

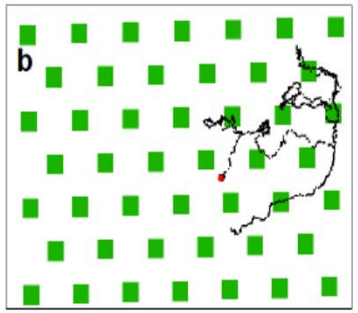
Perception Scales < 3 mm



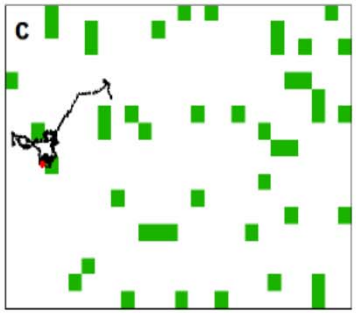




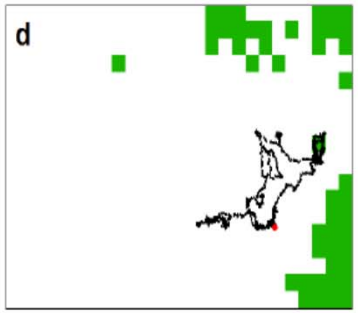
Landscapes 400x600 mm



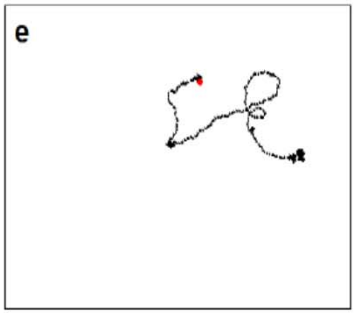
Regular



Homogeneous



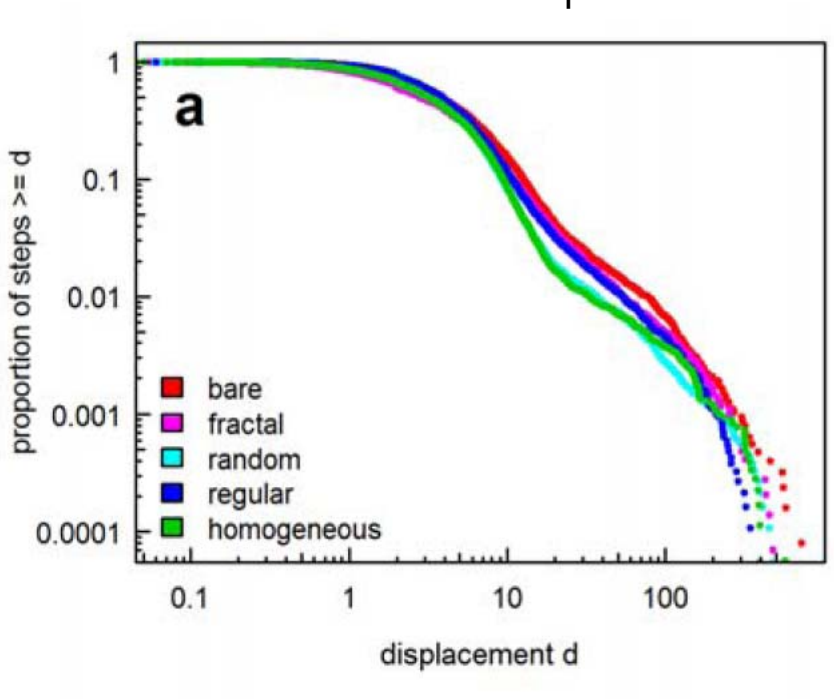
Fractal/Patchy

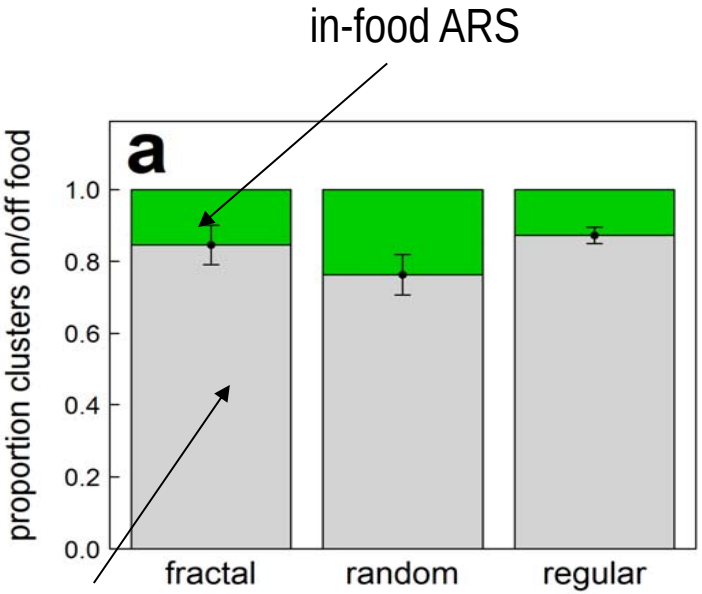


Bared

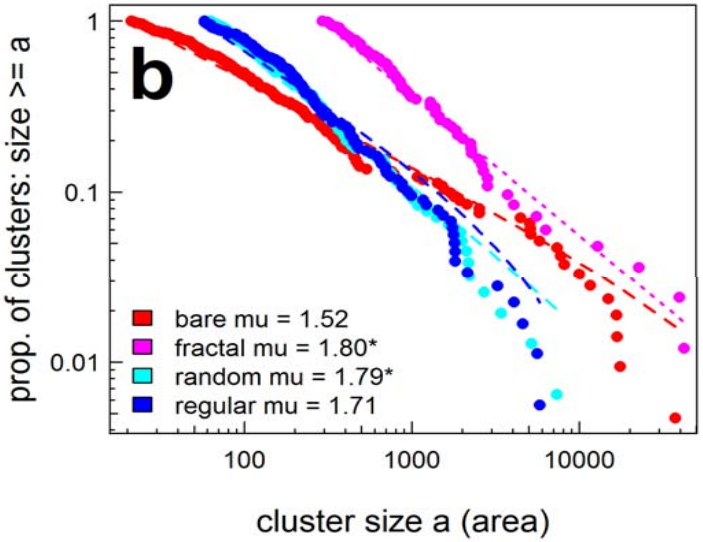
Inherent Multi-scale Search

Mixture of scales in displacements



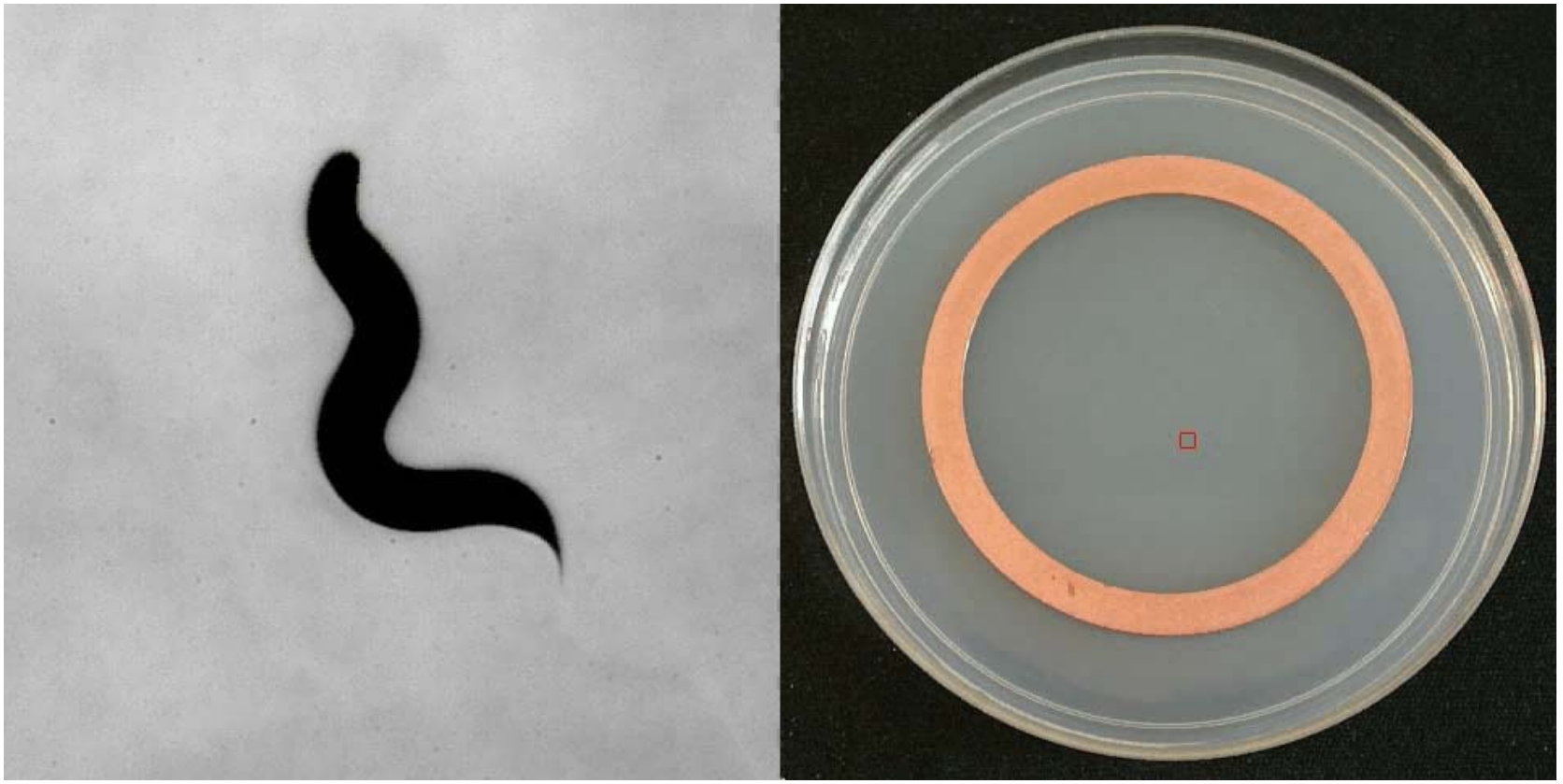


Multiscale ARS cluster sizes



Koelszch et al. 2015

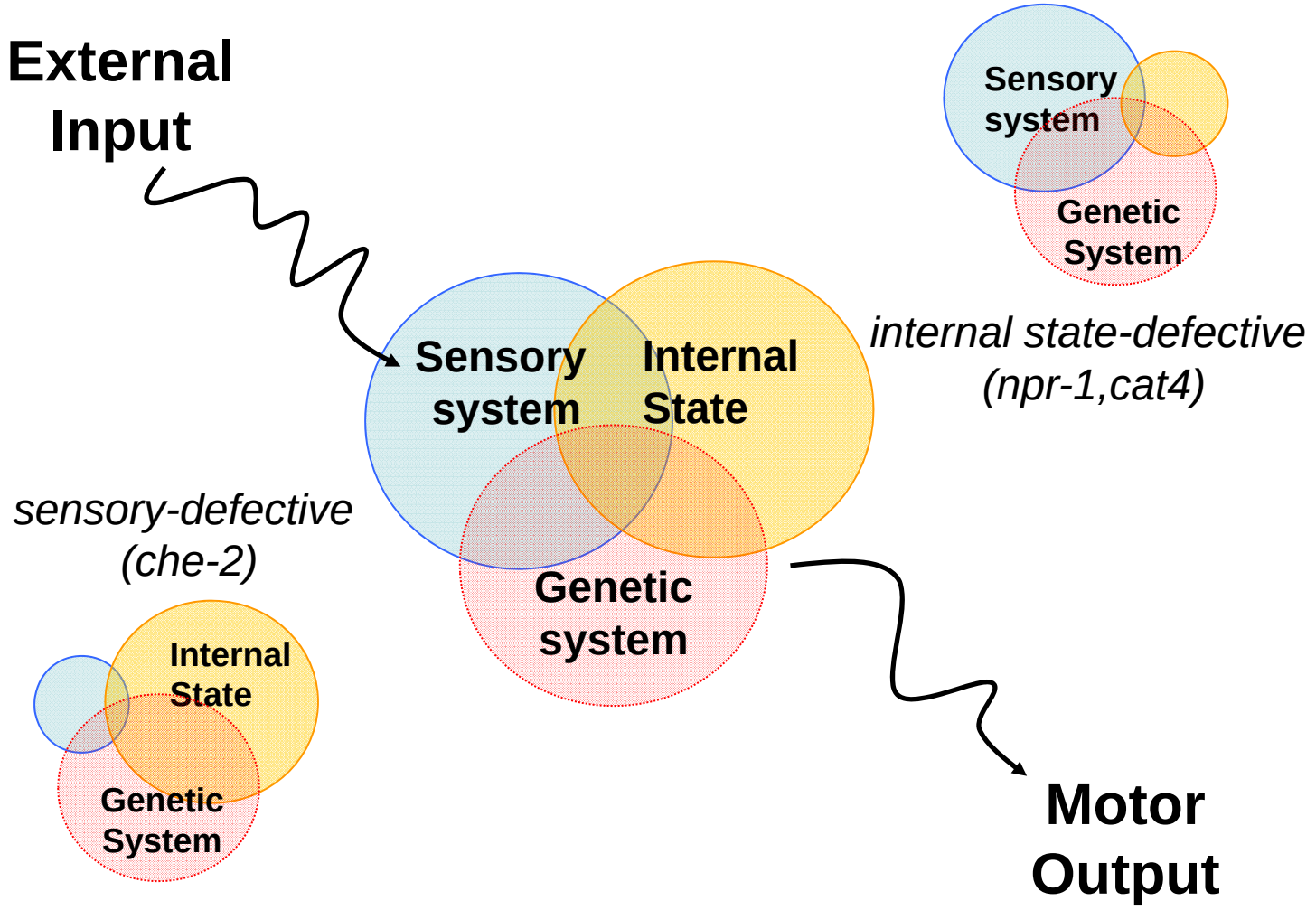
Chaenorabditis elegans



> Locomotion includes crawling or swimming and they perform stereotyped turns
  Omega / Reversals / Pirouettes / Pauses
> Evidence of random movements and chemotaxis
> Mutants (sensorial and motor) and engineering genetic techniques

Chaenorabditis elegans

"Behaviour comes in modules"
M. Heisenberg 2009 Nature

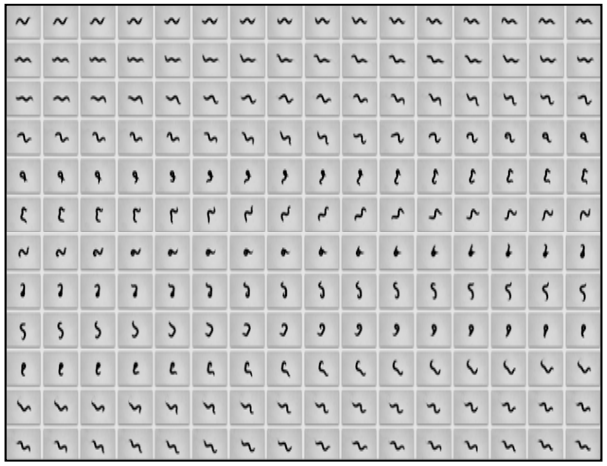


W.Ryu (U.Toronto, Canada)
I.Nemenman (Emory, Atlanta, USA)

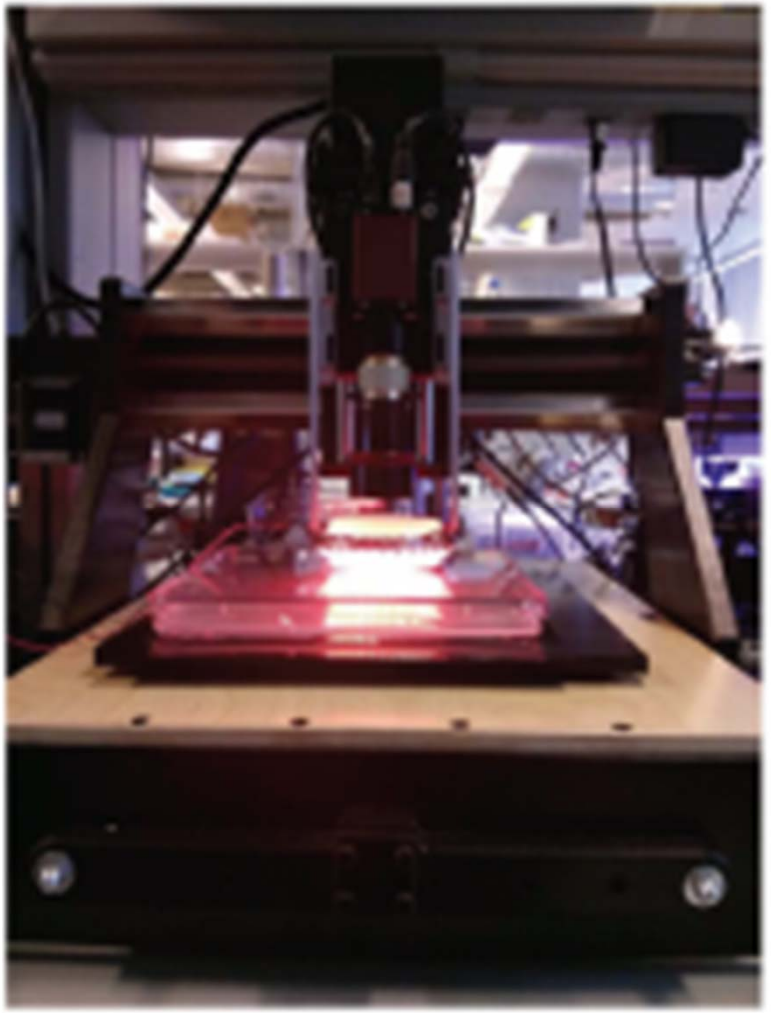
HUMAN FRONTIER SCIENCE PROGRAM
FUNDING FRONTIER RESEARCH INTO COMPLEX BIOLOGICAL SYSTEMS

W.Ryu Lab (U.Toronto, Canada)

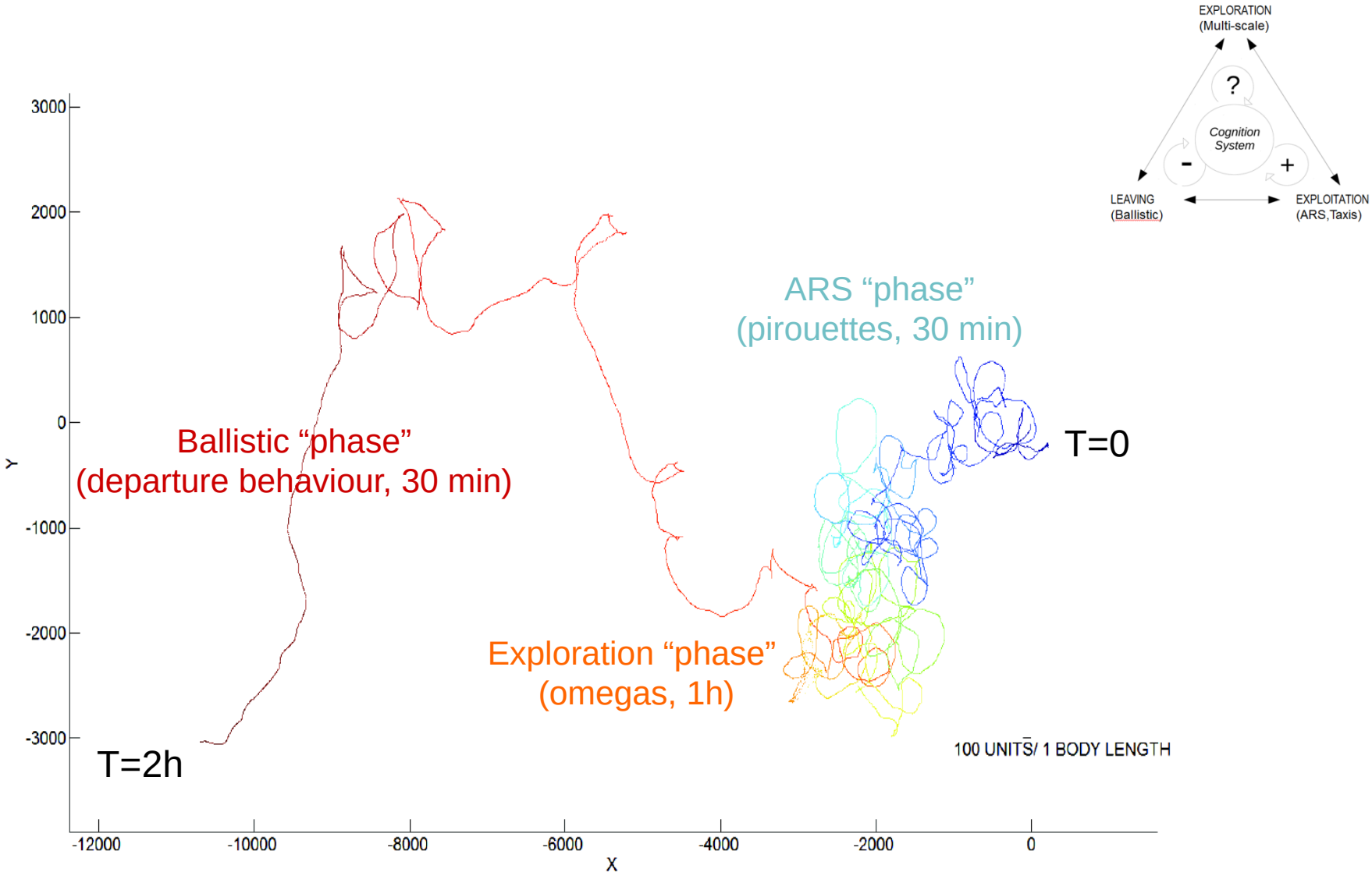
Behaviour



25x25cm,32 frames sec^{-1}



Caenorhabditis elegans



Behavioural Annotation

Input Features

Coverage

$C_i = \frac{1}{|N_i|} \sum_{j \in N_i} d_{i,j}$

Relocation

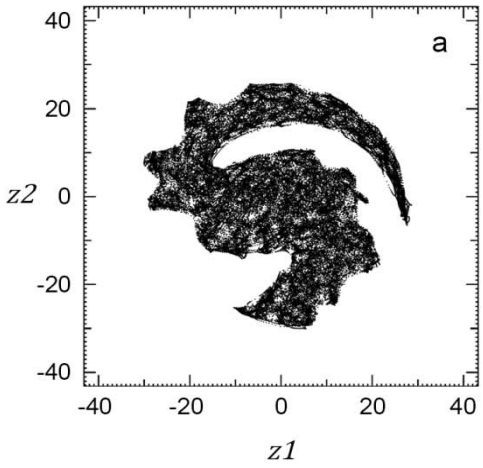
$R_i = d_{l,r}^{(i)}$

Travel

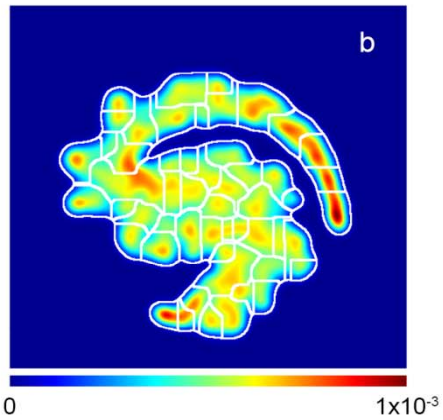
$T_i = \frac{1}{|N_i|} \sum_{j \in N_i} d_{j,j+1}$

t-Stochastic Neighbouring Embedding

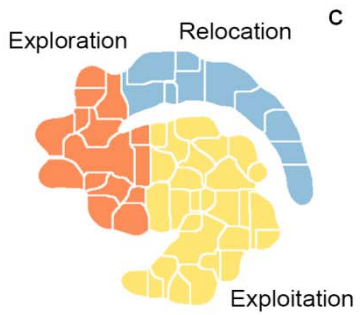
t-SNE



KDE



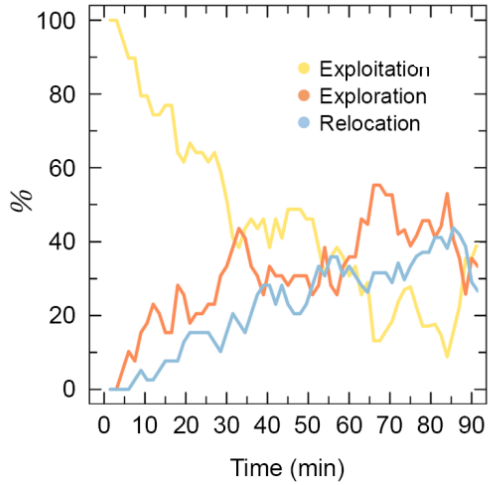
Watershed

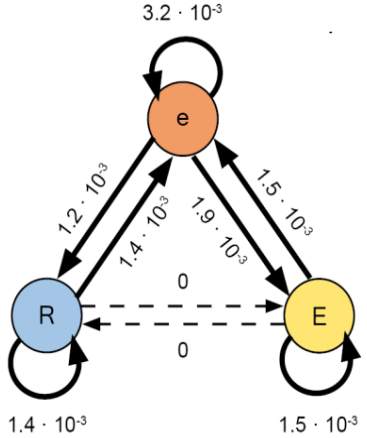


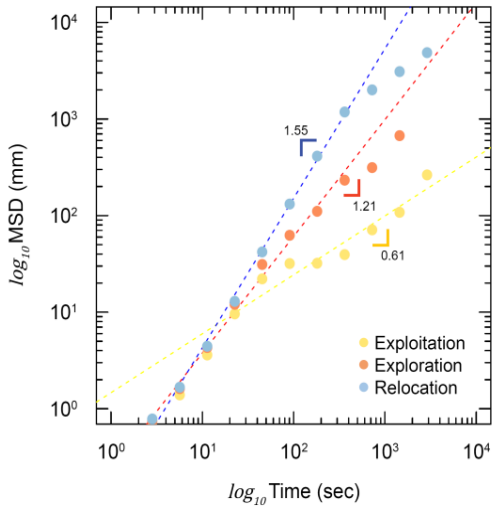
Berman et al. 2014; van Maaten XXX

Behavioural Annotation

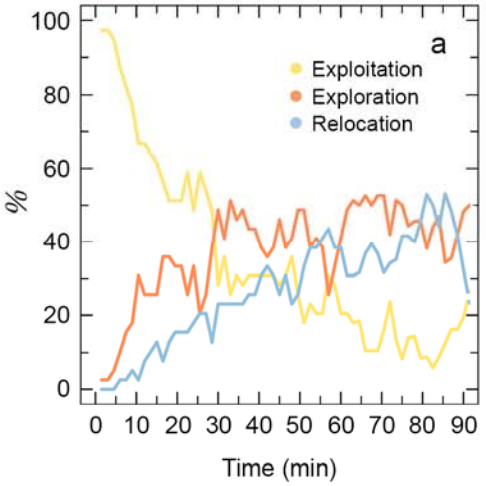
t-SNE + Markov Model

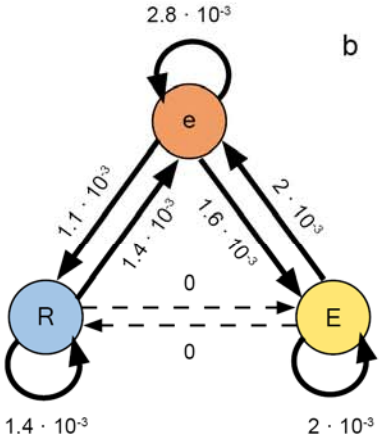


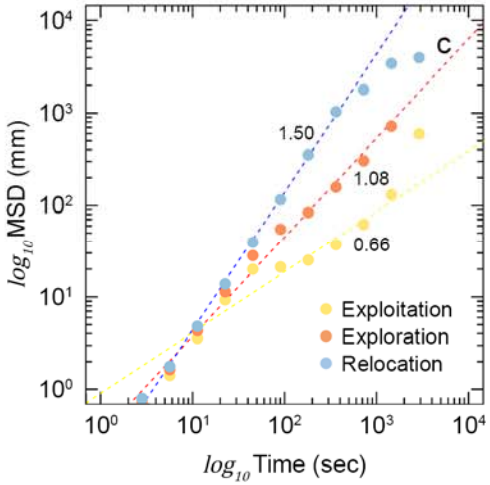




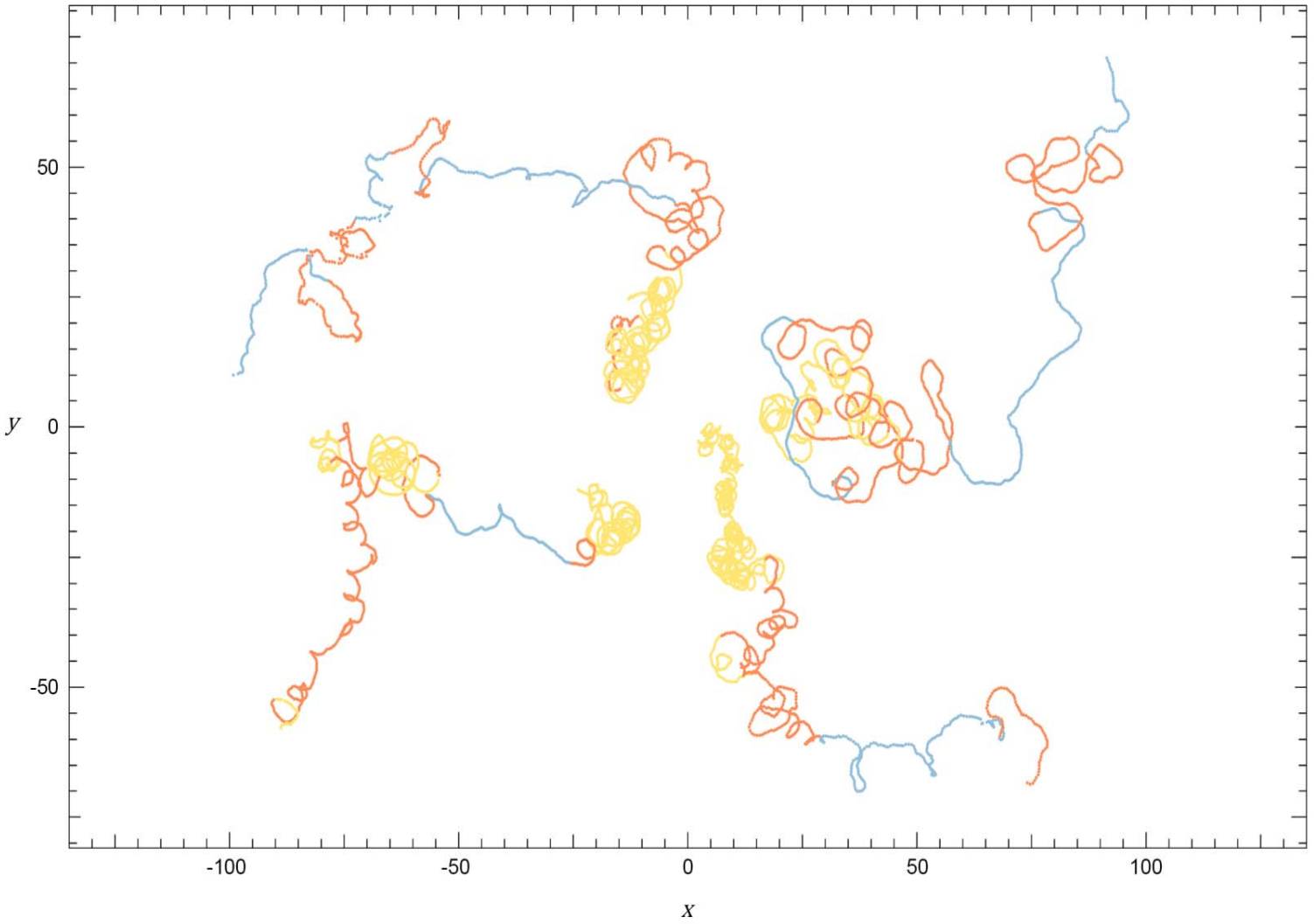
Hidden Markov Models (3-states)





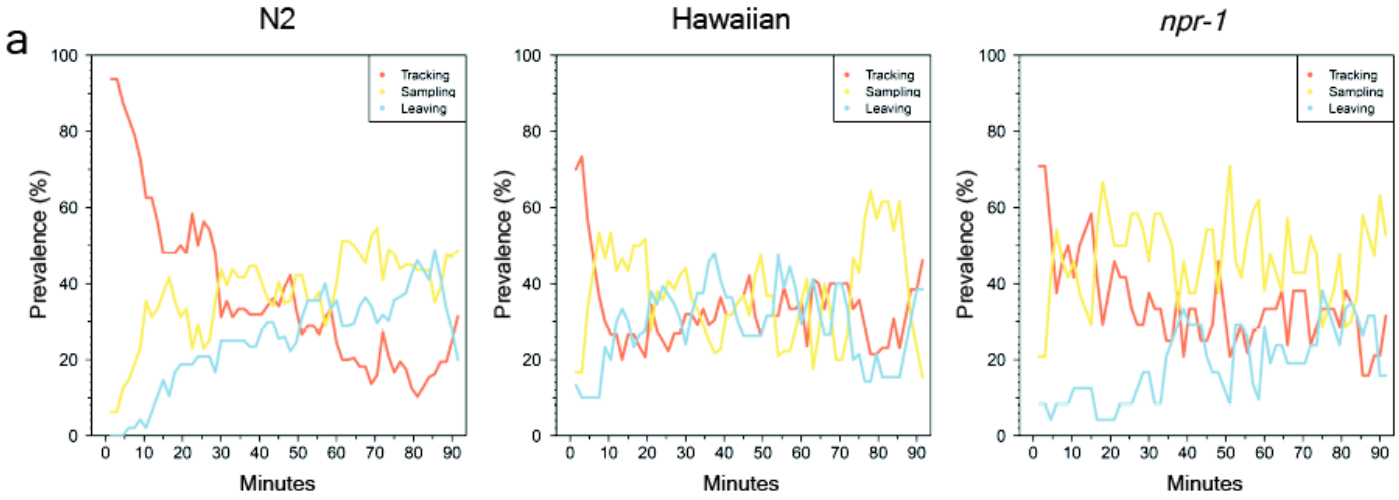


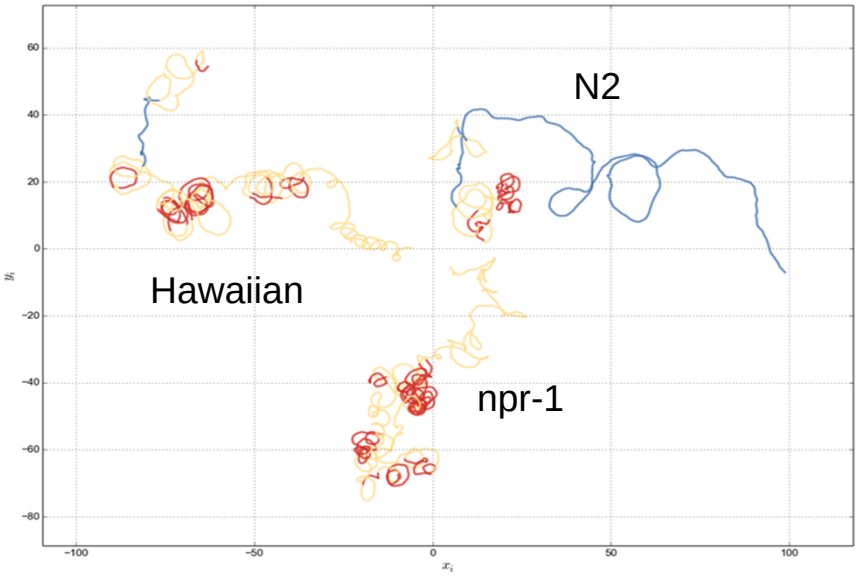
Behavioural Annotation



Other wild types and knocked-out mutants

Hidden Markov Models (3-states)





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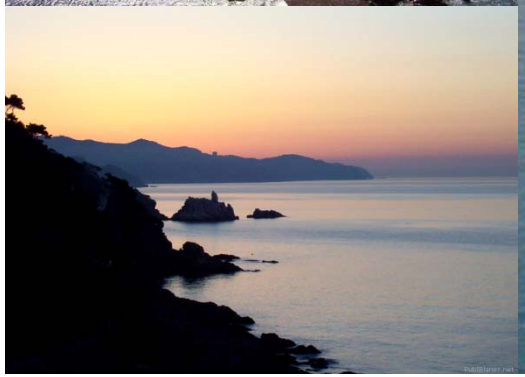
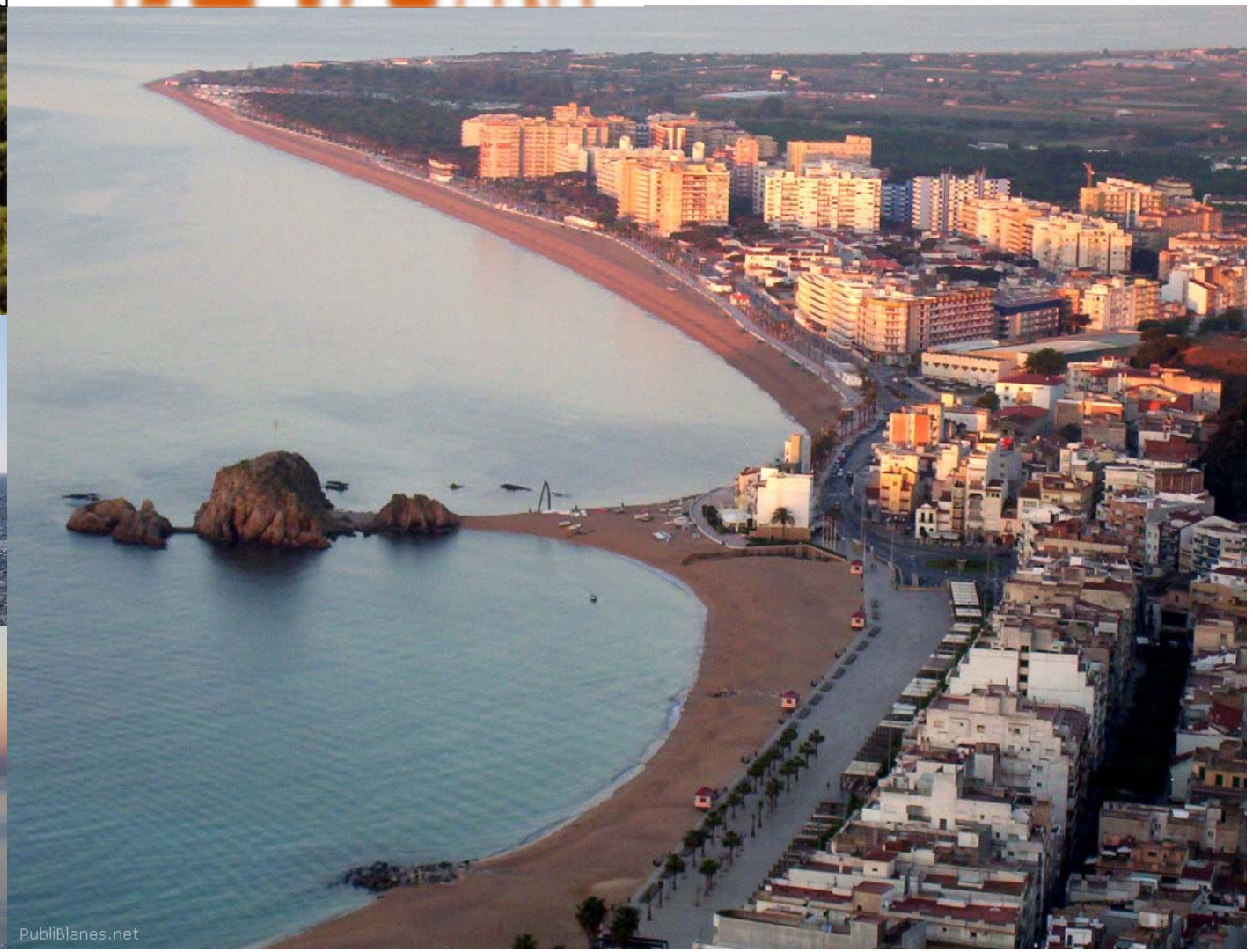
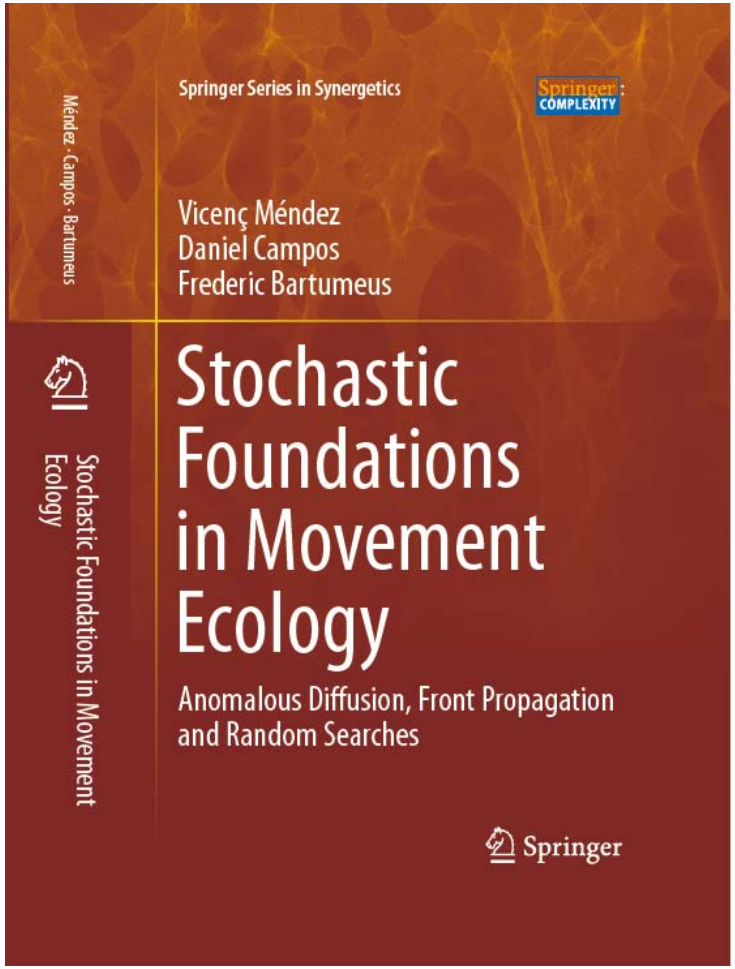
MovementEcologyLab

...understanding organisms in motion





Random Search Strategies



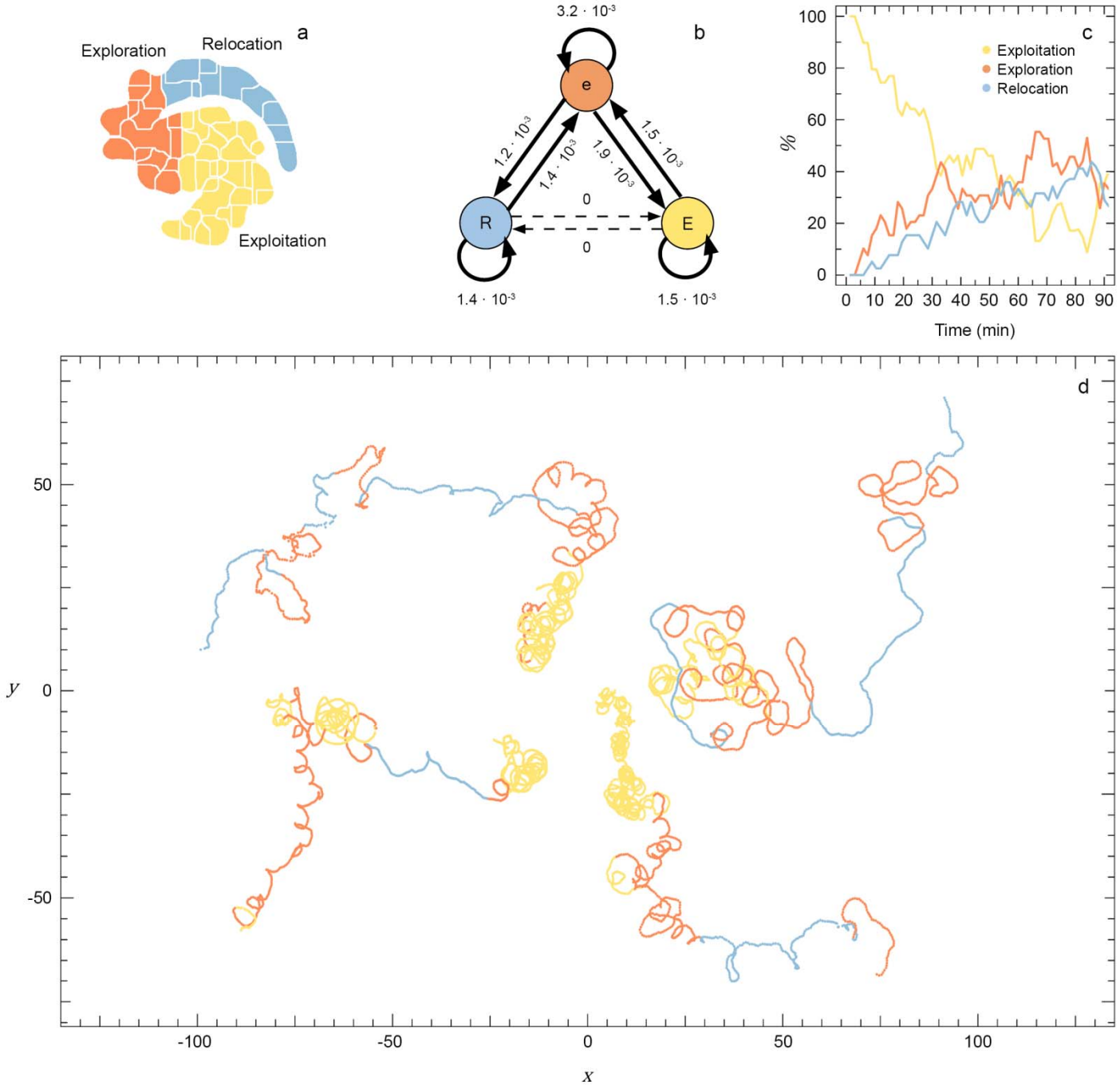
Chapter 9
Biological Searches and Random Animal Motility

. . . Evidence of randomly generated action (action that is distinct from reaction because it does not depend upon external stimuli) can be found in unicellular organisms. Take the way bacterium E. coli moves. It has a flagellum that can rotate around its longitudinal axis in either direction: one way drives the bacterium forward, the other causes it to tumble at random so that it ends up facing in a new direction ready for the next phase of forward motion. This 'random walk' can be modulated by sensory receptors, enabling the bacterium to find food and the right temperature. What this tells us is that behavioural output can be independent of sensory input. This is in line with the fact that in early development of individual organisms the motor system slightly precedes the sensory system. The same may have been true in evolution, as merely being dispersed in space should have been advantageous and should have favoured mobility.
. . . Behaviours in complex organisms typically come in modules. Insufficiently equipped, insufficiently informed, and short of time, animals have to find a module that is adaptive.
. . . The physiology of how this happens has been little investigated. But there is plenty of evidence that animal's behaviour cannot be reduced to responses.

Martin Heisenberg
Nature 459, 164–165 (2009)

An essential focus of experimental and theoretical studies of animal movement is to reveal the underlying drivers (internal and external) of the complex statistical patterns of animal motion that appear in nature [48]. A common and pervasive assumption is that animals are deterministic input/output systems that firmly tie behavioural responses to external stimuli. Once the operating laws of such a system are known, the behaviour of any animal at any time can be predicted from the current environmental situation. This does not necessarily imply that the same

V. Méndez et al., *Stochastic Foundations in Movement Ecology*,
Springer Series in Synergetics, DOI 10.1007/978-3-642-39010-4_9,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