Olfactory searches and turbulent transport

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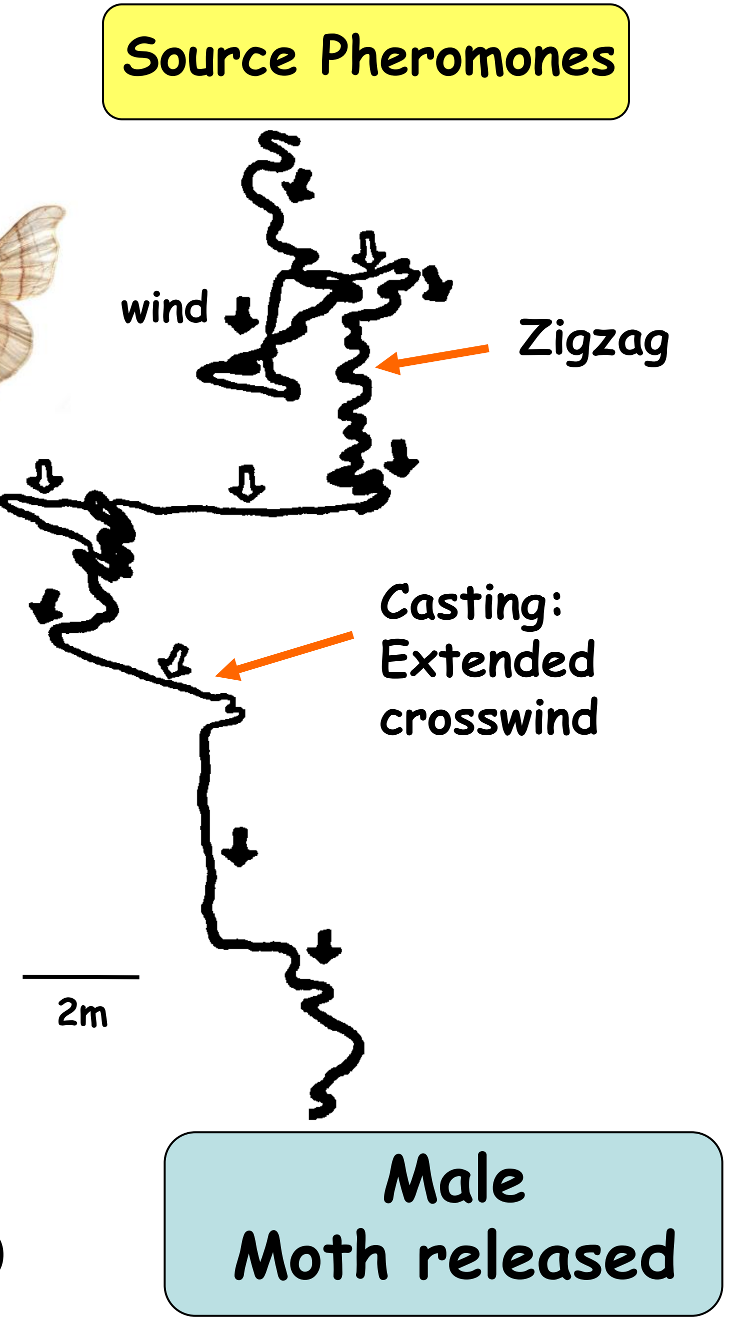
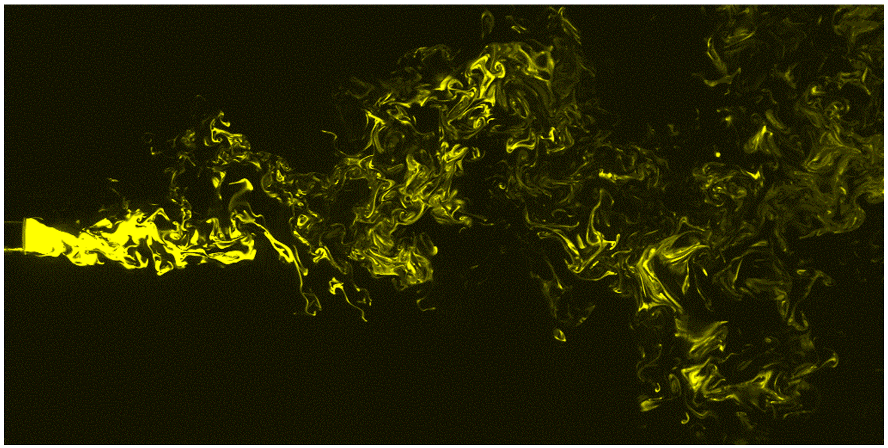
Olfactory searches by insects

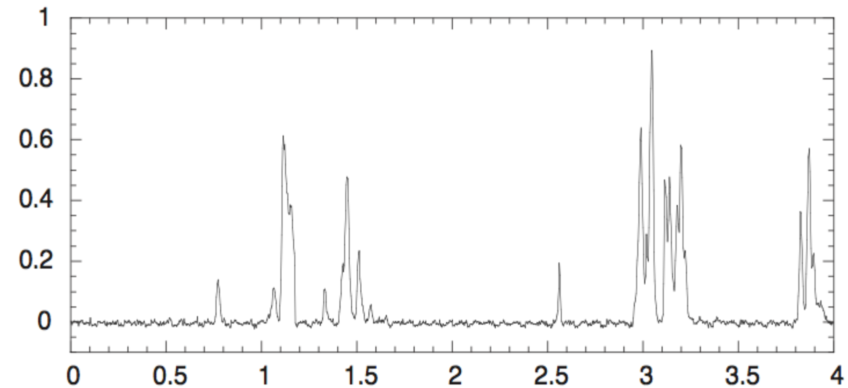


Rates for the emission of pheromones by female moths are in the order of a few picograms/s. Typical molecular weight of pheromone components is a few hundred Daltons.

Kennedy, *Physiol Entomol* (1983)
Murlis et al., *Annual Review of Entomology* (1992)

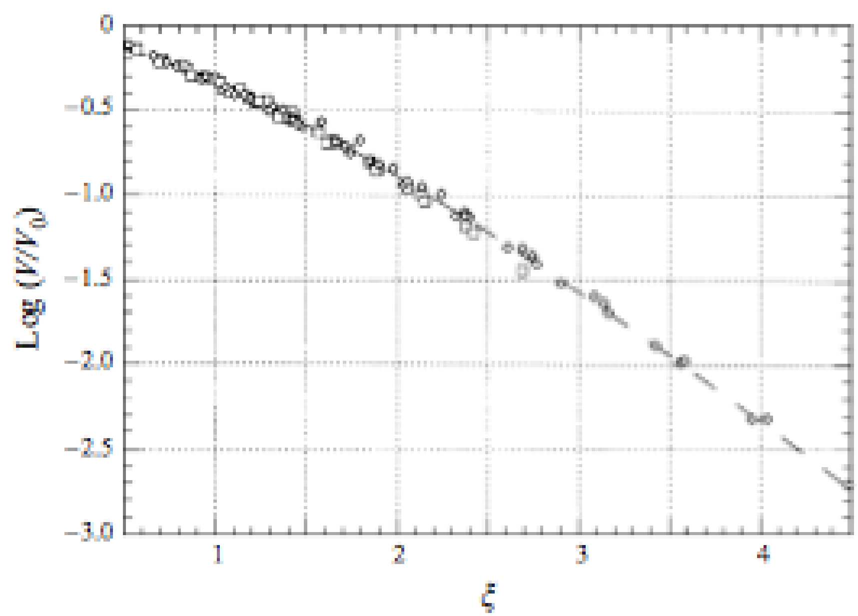
The signal sensed by insects is shaped by turbulent transport





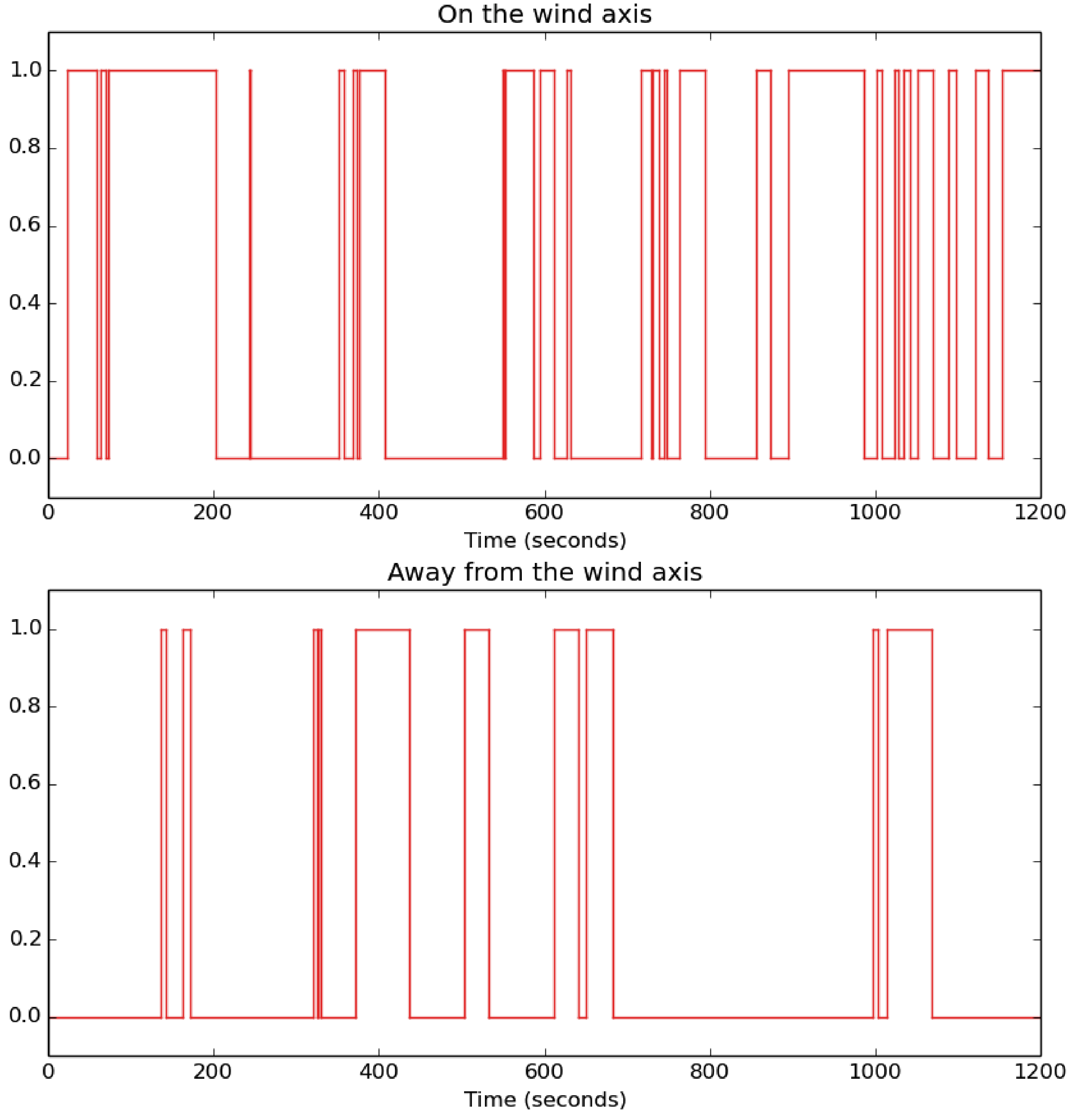
Probability to detect a local concentration higher than a threshold C_s at a distance *ut*

Data by E. Villermaux (IRPHE)



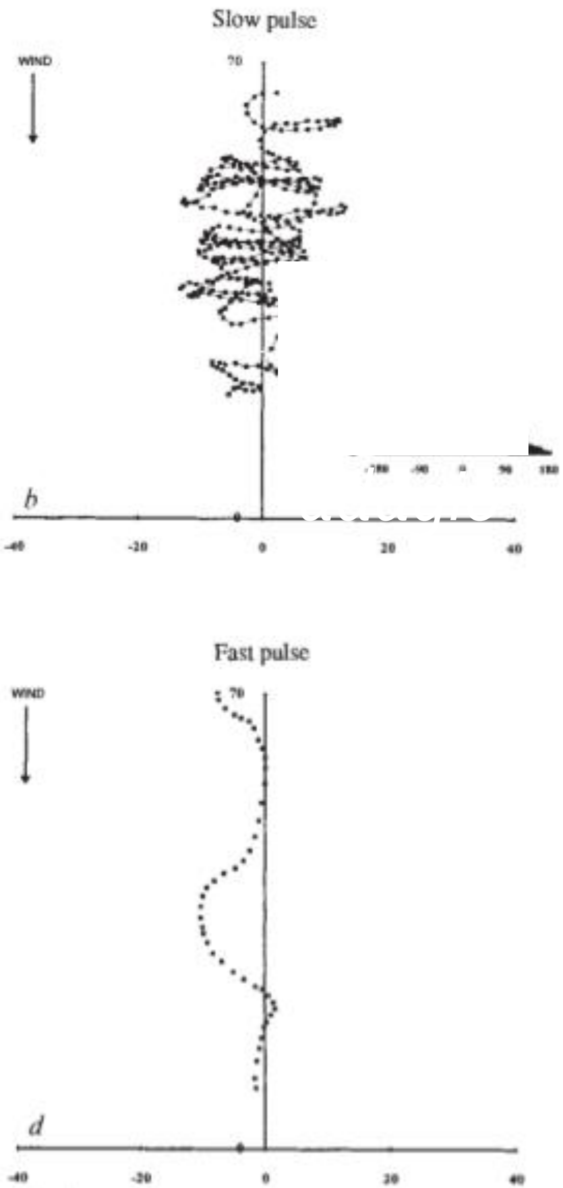
$$x = \frac{ut}{d}\frac{C_s}{C_0}$$

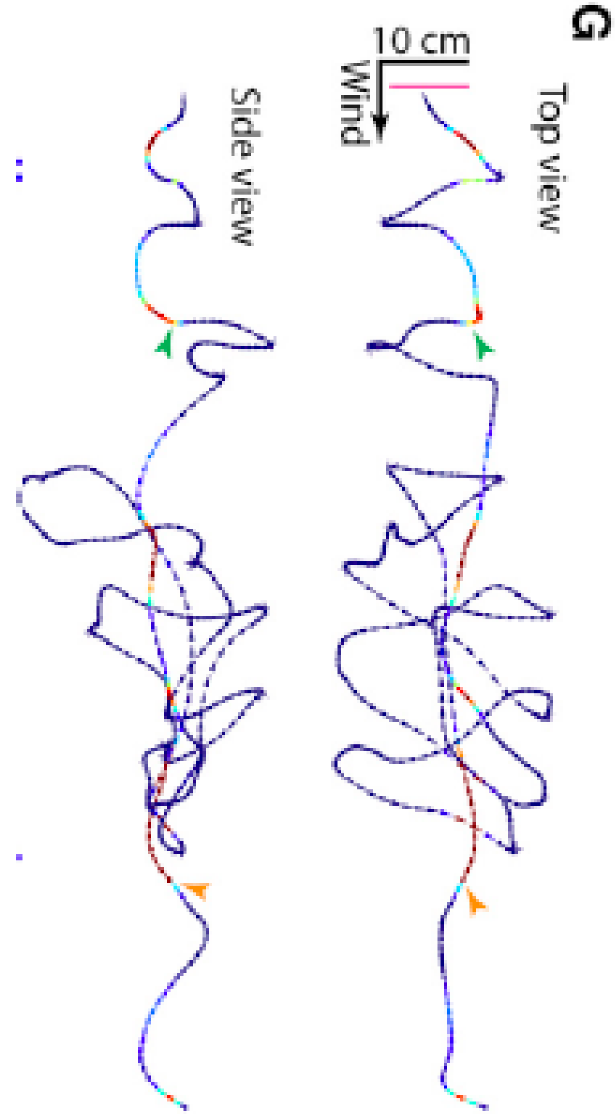
Typical time series 100m from the source



Behavior is sensitive to the structure of the signal

Mafra-Neto & Cardé, Nature 1994

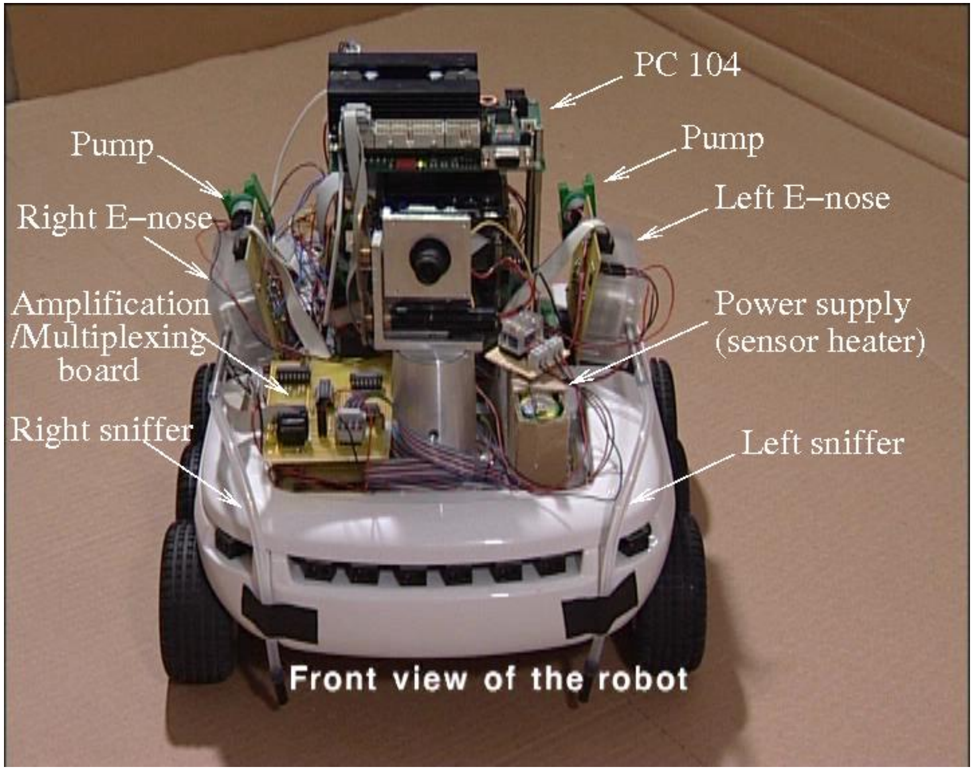


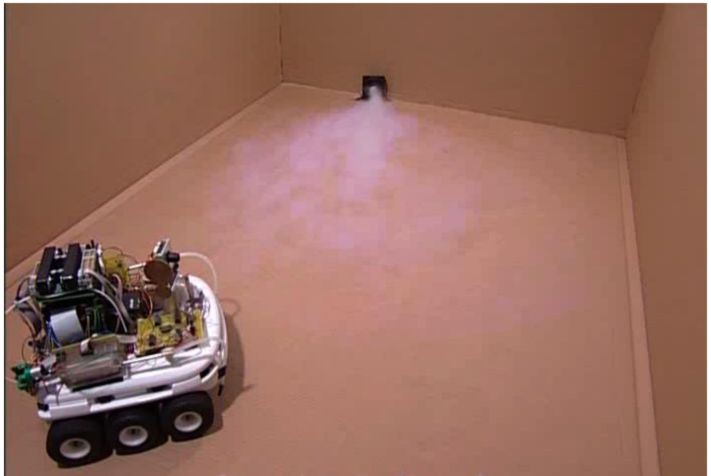


Van Breugel, Dickinson Curr Biol, 2014

Sniffers

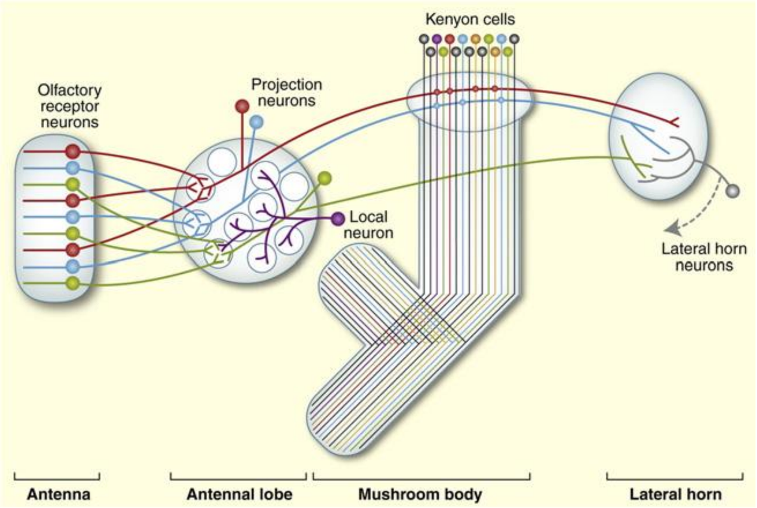
Olfactory robots: applications to detection of chemical leaks, drugs, bombs, land and/or sea mines, sources of toxic substances, etc.





- What are the properties of the natural signals that insects have to process?

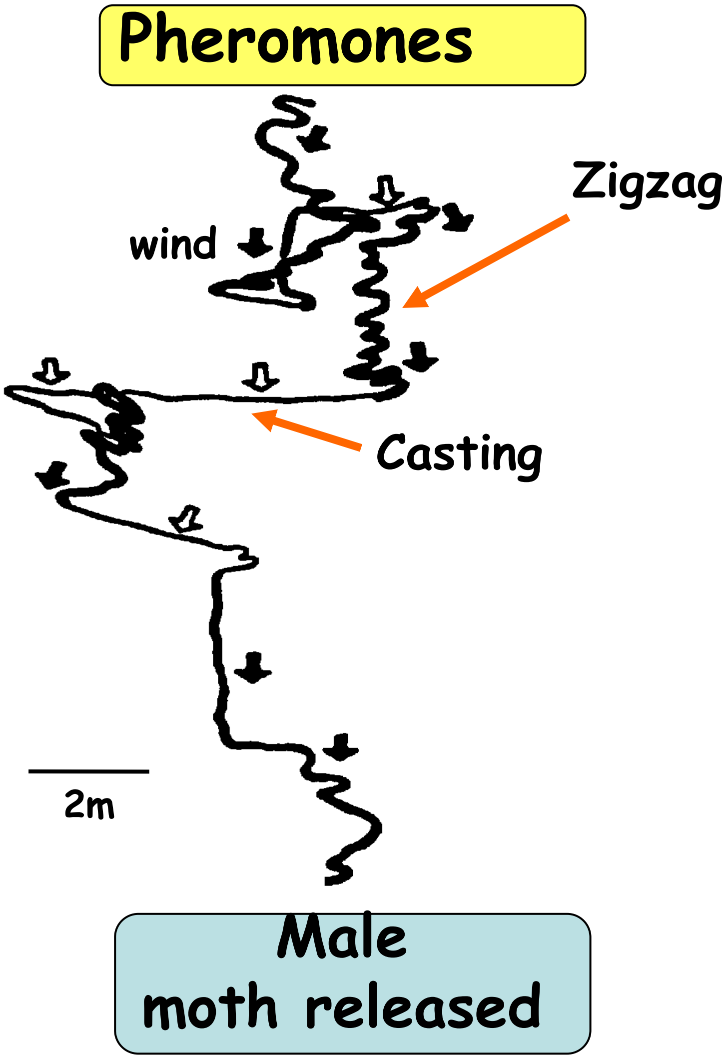
- What is the “algorithm” controlling olfactory searches?



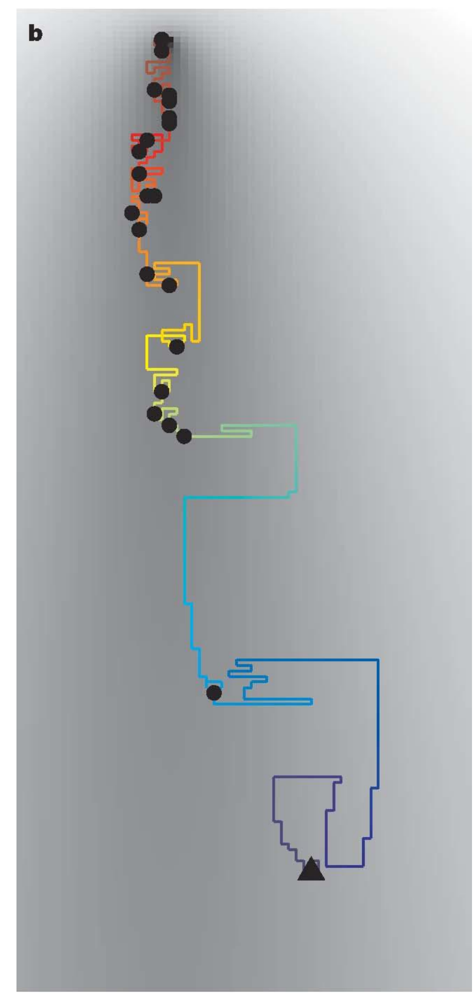
Nobody is able yet to track trajectories ***and*** measure concentrations of sensed odors in natural conditions.

How to perform olfactory searches in those conditions, with sporadic detections?

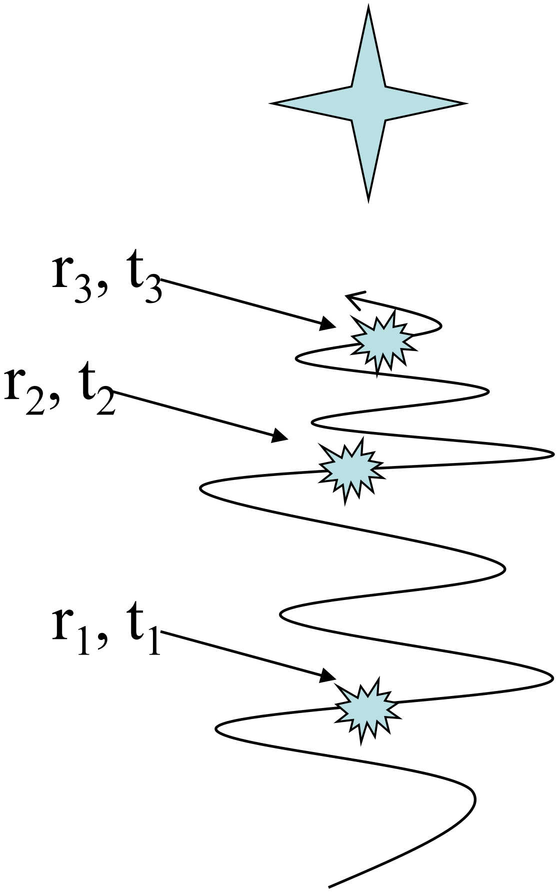
(MV, Villermaux, Shraiman, Nature 07)



Infotaxis



Olfactory searches: Decoding the message of pheromone concentration



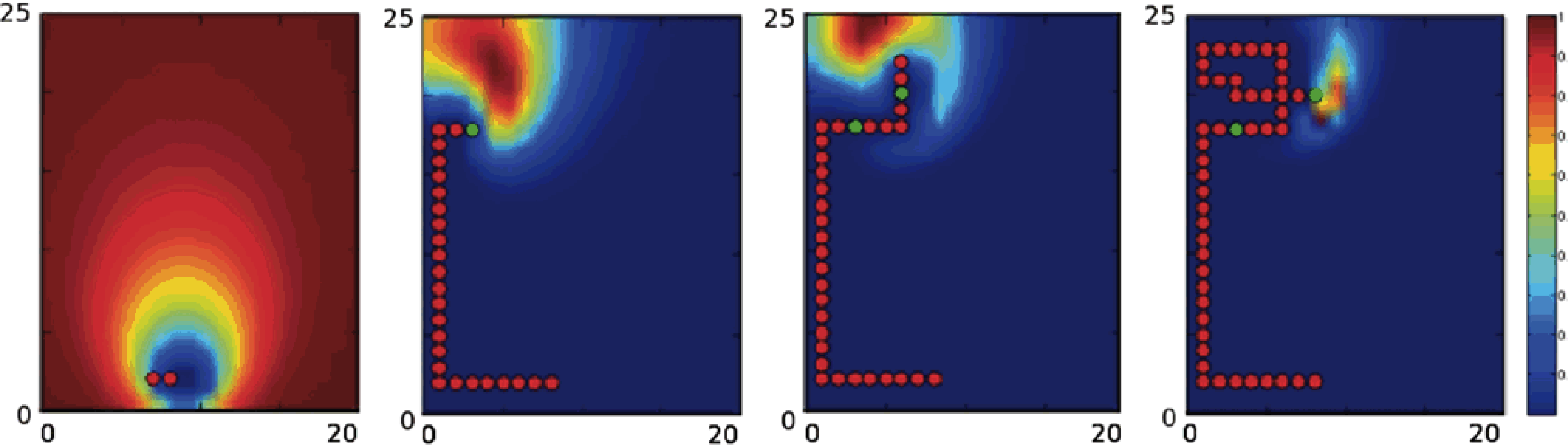
The source emits particles that are transported in the (random) environment.

Consider them as a message sent to the searcher.

Message in a random medium.

Use the trace of odor encounters experienced by the searcher to build a probability map of where the source might be located

Example of dynamics of the probability map



t_1 t_2 t_3 t_4

The map is initially almost flat and its uncertainty (quantified by Shannon's entropy) is maximal.

Detections concentrate the map around the detection location while their absence spreads the map out.

At the end of the search, the map is very peaked, i.e. its Shannon entropy is minimal.

Infotaxis

Move so as to maximize the rate of information acquisition:

i.e. maximize the expected reduction <ΔS> of the entropy of the field $P_t(\bullet)$.

$$\langle \Delta S \rangle \left(r \to r_j \right) = P_t\left(r_j\right)\left[0 - S\right] + \left(1 - P_t\left(r_j\right)\right)\left[\rho_0 \Delta S_0 + \rho_1 \Delta S_1 + \ldots\right]$$

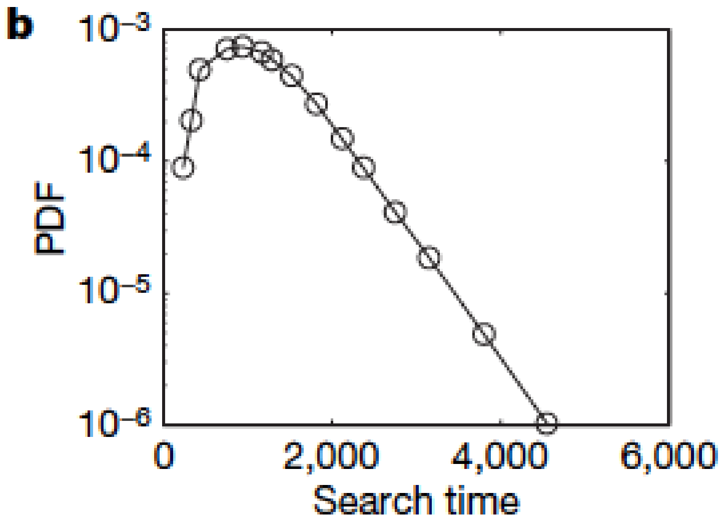
source found at r_j

no source but k=0,1,2,.. odor encounters

Pure Exploitation: maximum likelihood.

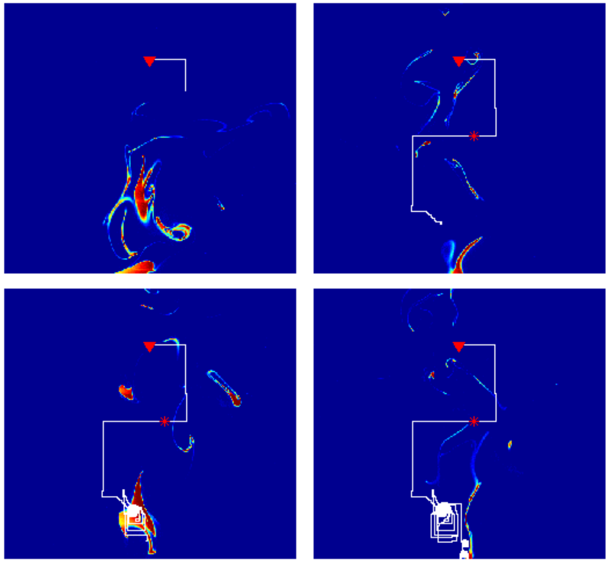
Exploration: passive gathering of information.

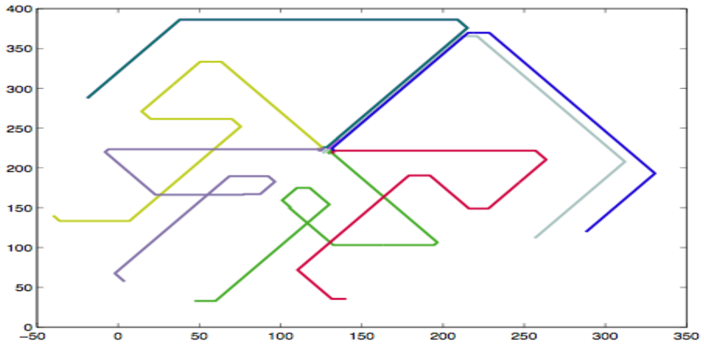
RS Sutton, AG Barto *Reinforcement Learning* MIT Press, 1998.



Searches are fast, reliable…

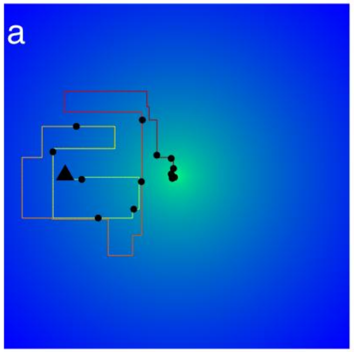
robust to inaccuracies of the environmental transport model and noise…





can be upgraded to swarm searches and to 3D…
(Masson et al., J. Phys. A ‘09; Barbieri et al., EPL, ‘11)

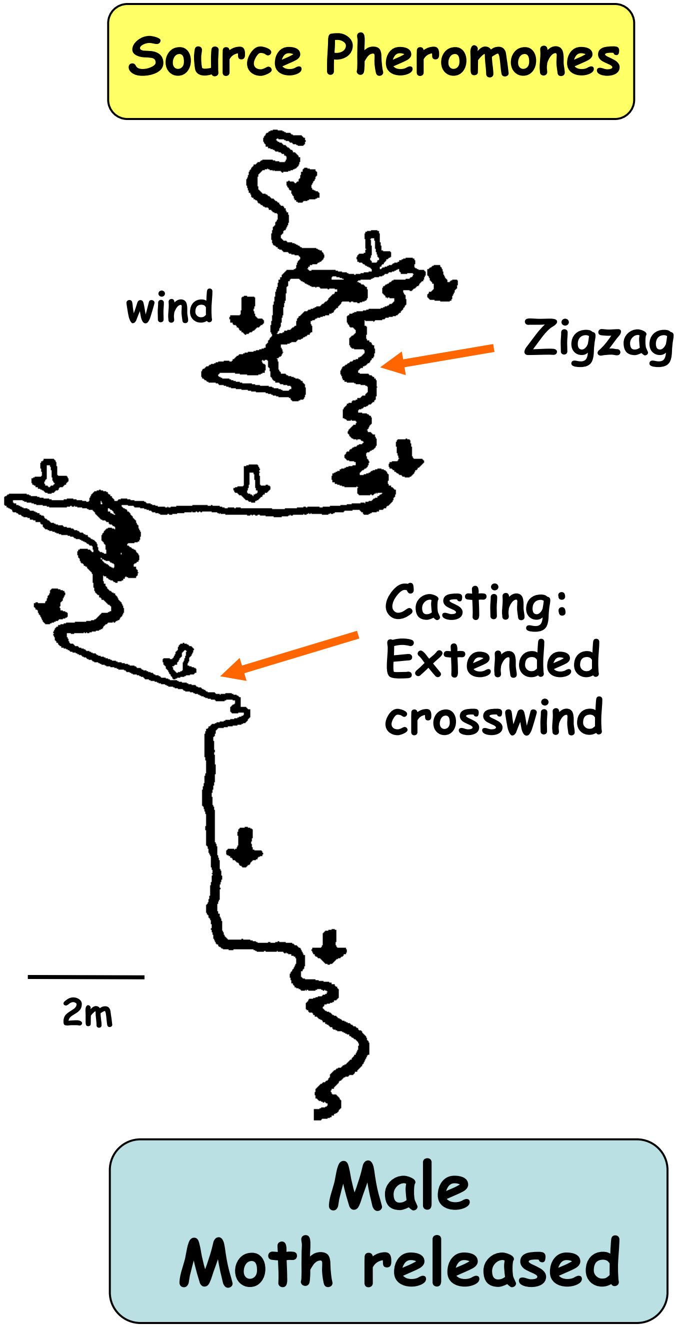
and work even in the absence of mean wind



Getting to realistic distances…

Khepera robot moving with the infotaxis strategy and equipped with temperature sensors (Masson, PNAS, 2013).

Requirements on space representation and calculations involved in the search can be reduced.



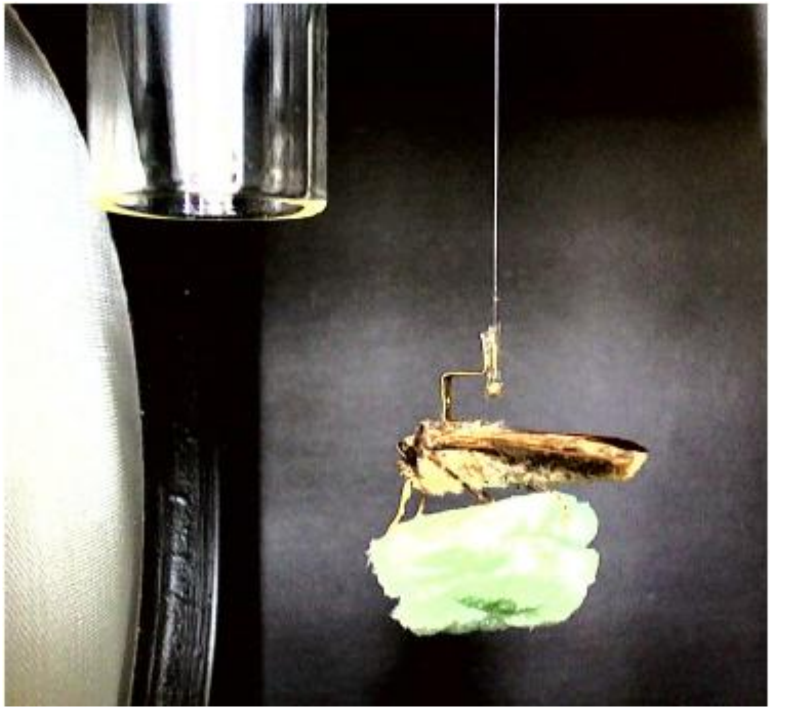
How is casting structured and decided by the moth?

What is the extension (and angle wrt the wind) of casting phases?

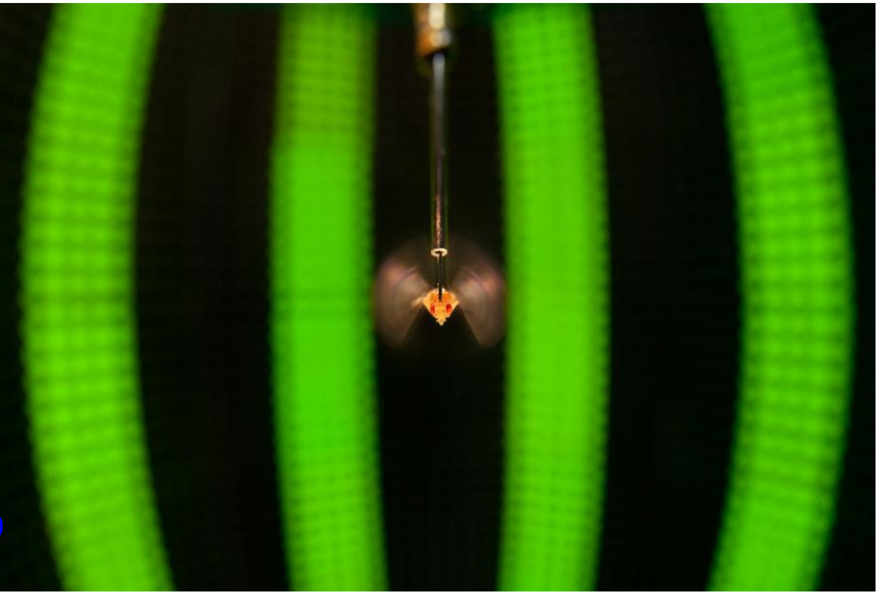
How do decisions depend on the memory of past detections and how far back in time does it go?

Is there any sense of space, i.e. where past detections were made?

Tethered insect experiments

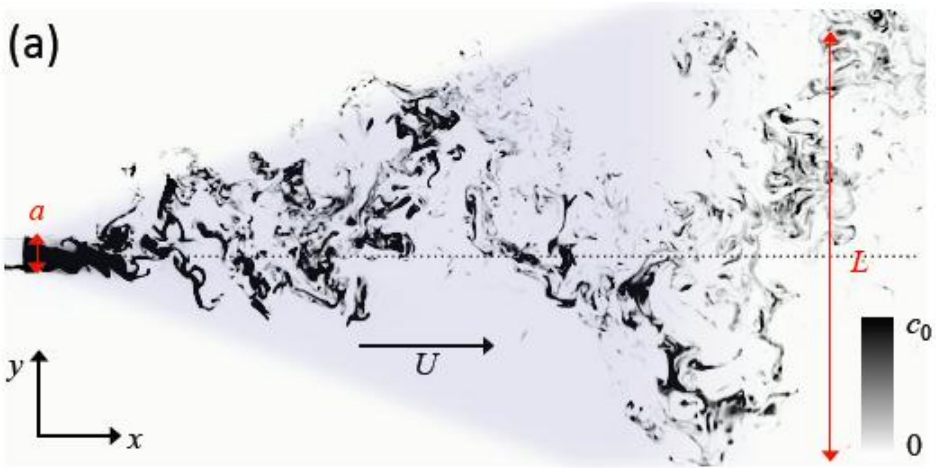


Manduca. Gray et al. 2002. J Neur. Meth.
Locust. Mappes & Homberg 2004. J. Comp. Physiol. A
Monarch butterfly. Mouritsen & Frost 2002. PNAS
Drosophila. Yamaguchi et al. 2008. PNAS ; Bhandawat et al. 2010. J. Exp. Biol.

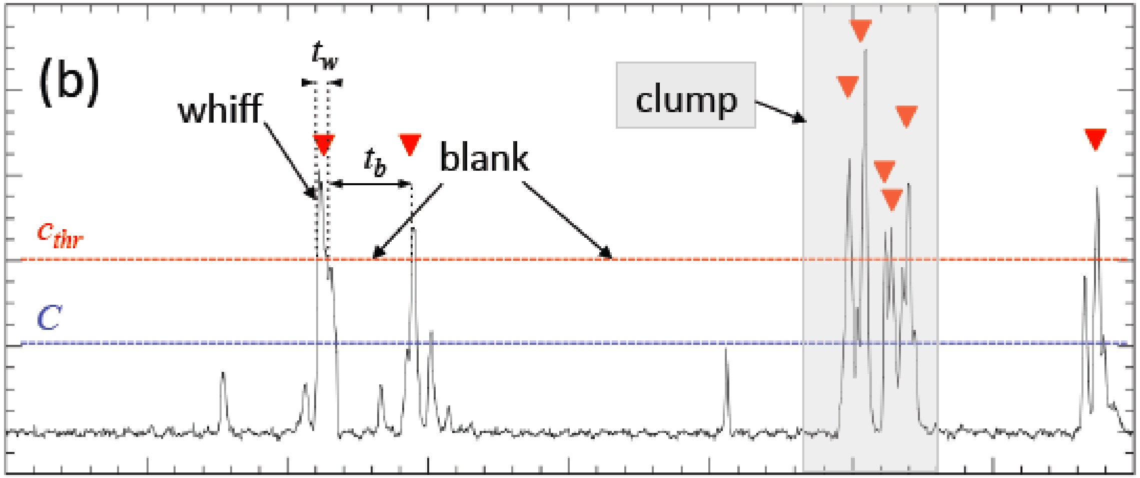


What kind of stimuli should be delivered?

Statistics of concentration field and odor detections



We (Celani et al., Phys. Rev. X, '14; APS Physics Synopsis, Oct 28, 2014) calculate the dependency on x and y of



χ: the fraction of time the signal is non-zero

C: the average concentration when the signal is non-zero

The Lagrangian approach

$$\frac{\partial c}{\partial t} + \boldsymbol{v} \cdot \boldsymbol{\nabla} c = \kappa \nabla^2 c + J h_a(\boldsymbol{x})$$

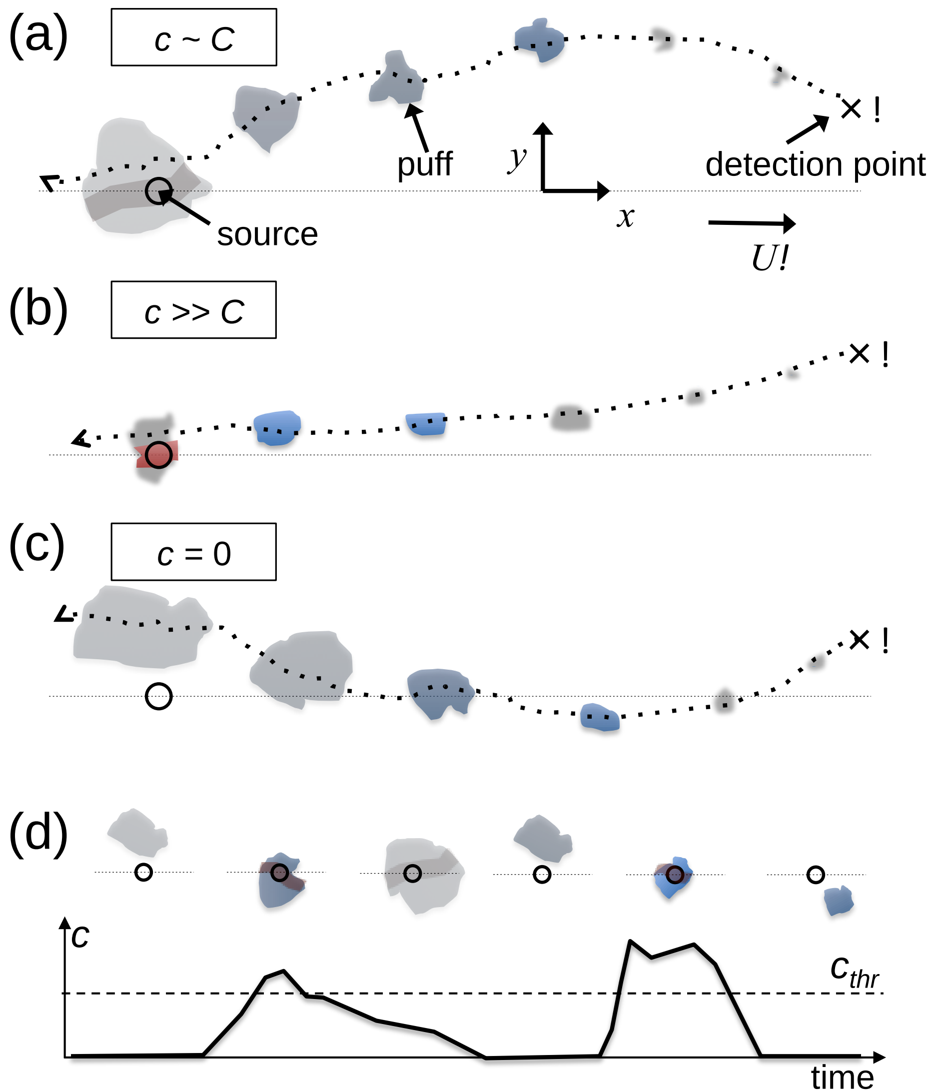
h_a is the characteristic function of the source of size *a (≈ cm)*

$$\begin{cases} \dfrac{d\mathbf{x}}{dt} = \mathbf{v}(\mathbf{x},t) + \sqrt{2k}\,\mathbf{w}(t) & \text{Lagrangian trajectories} \\[2ex] \dfrac{dc(\mathbf{x}(t),t)}{dt} = J h_a(\mathbf{x}(t)) & \text{Scalar concentration} \end{cases}$$

c is proportional to the residence time at the source

$$c(\boldsymbol{x},t) = J \int_{-\infty}^{t} dt' \int d\boldsymbol{x}'\, h_a(\boldsymbol{x}')\, p(\boldsymbol{x},t|\boldsymbol{x}',t')$$

Why can we solve the problem?



(see Falkovich, Gawedzki, MV Rev Mod Phys, 2001)

We are interested in the integral over time and the source is larger than the folds. We can try integrating over the internal structure, i.e. track only the size and the position of the puff

Lagrangian scaling exponents

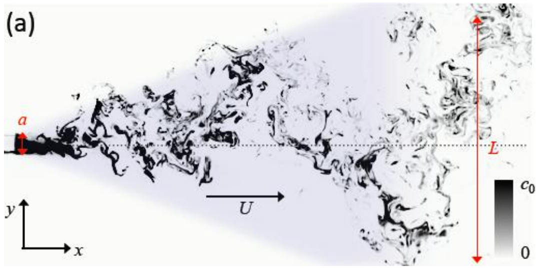
Distance travelled by single particle ~ *time*$^{1/\alpha}$ (e.g. Ut)

Size of a puff *r* ~ *time*$^{1/\gamma}$

Rate-of-growth of the size of a puff $d \log r/dt \sim time^{\beta-1}\ size^{-\beta\gamma}$

Single particle diffusion α=2; ballistic α=1.

Average plume ≈ $x^{1/\alpha}$



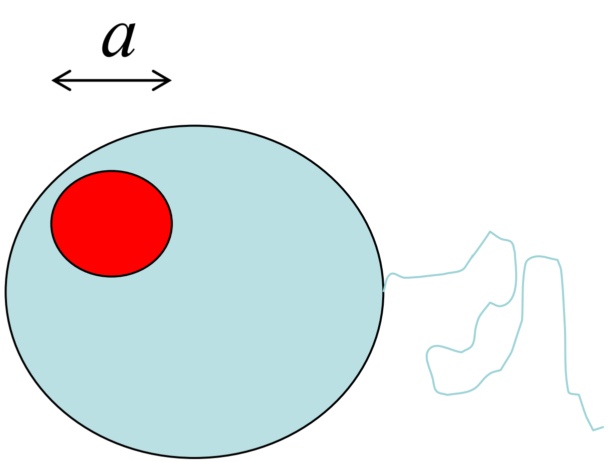
Two-particle Richardson dispersion γ=2/3; ballistic γ=1; diffusion γ=2

β accounts for possible non-stationarity. β=1 for homogeneous and stationary flows; β=2 in atmospheric neutral boundary layer due to non-homogeneity in the vertical direction.

Duration of whiffs and blanks

$$p_b(t_b) \approx \frac{1}{\tau}\left(\frac{t_b}{\tau}\right)^{-3/2} g_b(t_b)$$ Cut-off T_b

$$p_w(t_w) \approx \frac{1}{\tau}\left(\frac{t_w}{\tau}\right)^{-3/2} g_w(t_w)$$ Cut-off T_w

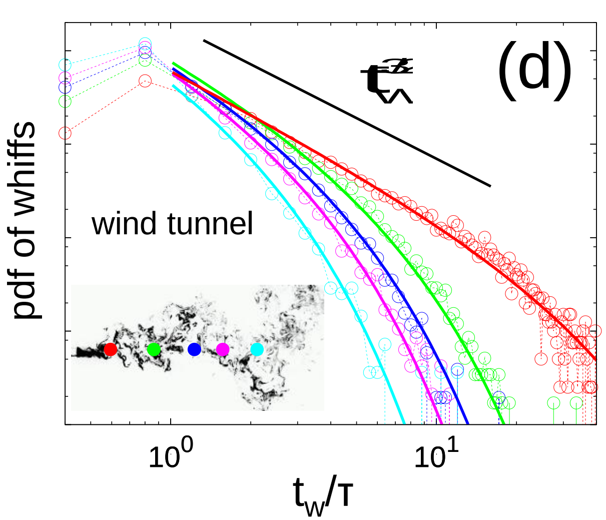


The position of successive puffs diffuses at short times with the turbulent diffusivity *D* due to turbulent small scales

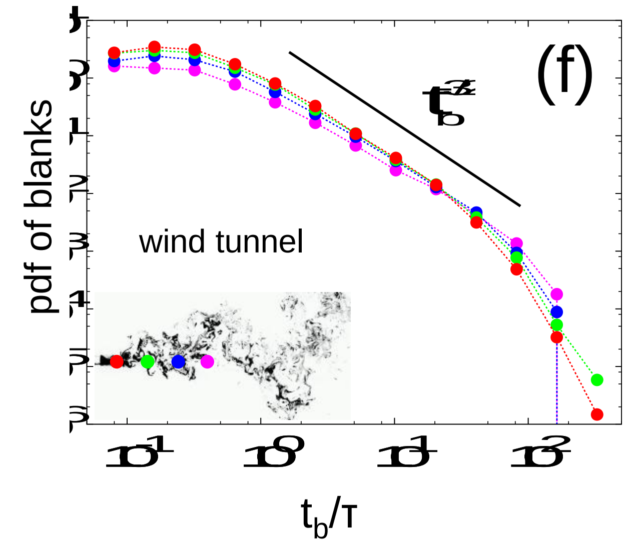
Shortest time $\tau \approx a^2 / D$

Times of overlap (or its loss) are distributed as for a 3D random walk, i.e. they feature a -3/2 power law

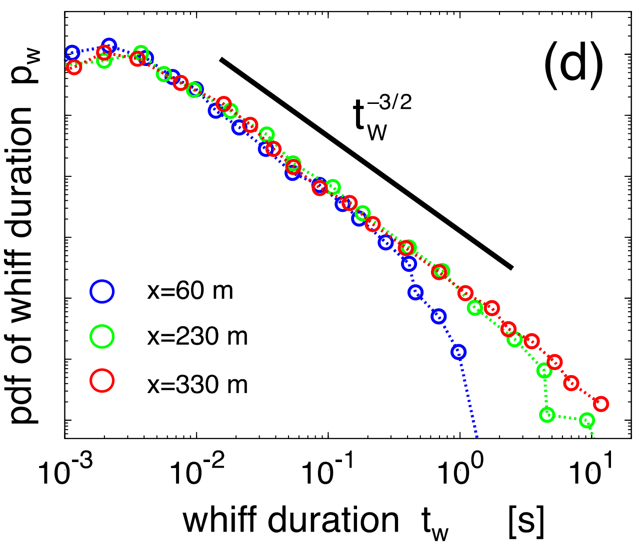
Whiff and blank duration

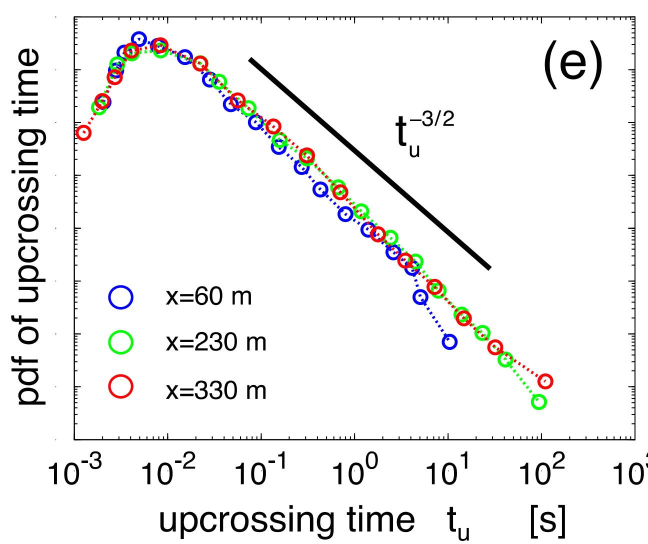


Jet flow



Atmospheric surface layer



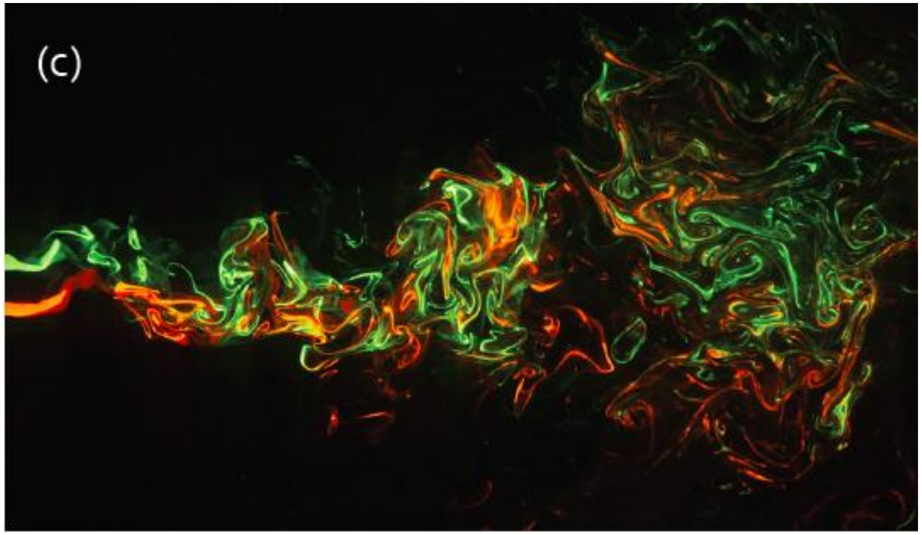


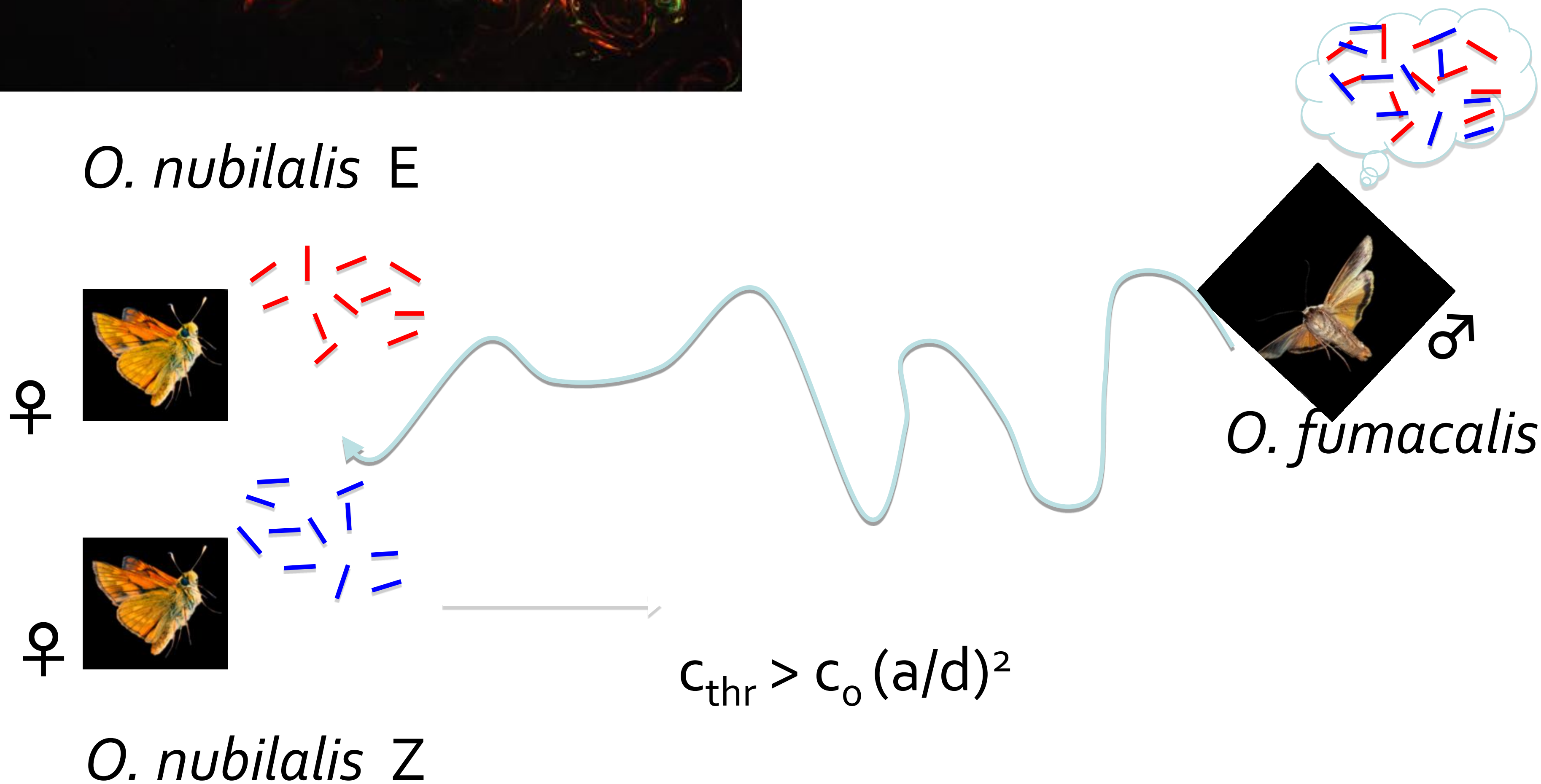
Summary

- attraction range ≈ $a(U/v)(c_{thr}/c_0)^{-1/2}$ ≈ 1000 m
- shortest whiff ≈ $(a/v)(c_{thr}/c_0)^{1/2}$ ≈ 1 ms
- longest whiffs ≈ clumps ≈ $(a/v)\ (c_{thr}/c_0)^{-1/2}$ ≈ 1000 s
- blanks ≈ whiffs [within the cone of the average plume]
- blanks >> whiffs [outside the cone]

The three distributions $p_c(c)$, $p_w(t_w)$ and $p_b(t_b)$ yield a complete protocol of realistic stimulation which can be generated by either mechanical or optogenetic technology

Mixing blends





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