Journée des méso-centres

16 Mai 2013, Rouen – France

Micro-organismes dans un écoulement turbulent : effet de la gyrotaxie sur l'accumulation préférentielle

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De nombreux micro-organismes qui forment le plancton ont la faculté de se déplacer de façon autonome. Nous avons étudié l'interaction entre cette nage directionnelle (gyrotaxie) et les structures turbulentes de petite échelle que l'on trouve dans l'océan.
Ceci nous a conduit à démontrer l'existence d'un mécanisme physique original conduisant à l'accumulation préférentielle de ces micro-organismes dans des régions bien identifiées de l'écoulement. La base de notre modèle de simulation est constituée du couplage entre la résolution numérique directe des équations de Navier-Stokes 3D instationnaires et d'un suivi Lagrangien des micro-organismes. L'ensemble des simulations a été conduit sur le supercalculateur Hyperion de CALMIP.

Turbulent eddies and Motility generate small-scale phytoplankton patchiness

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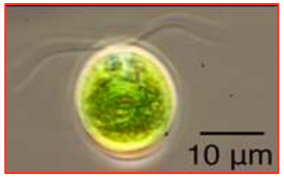
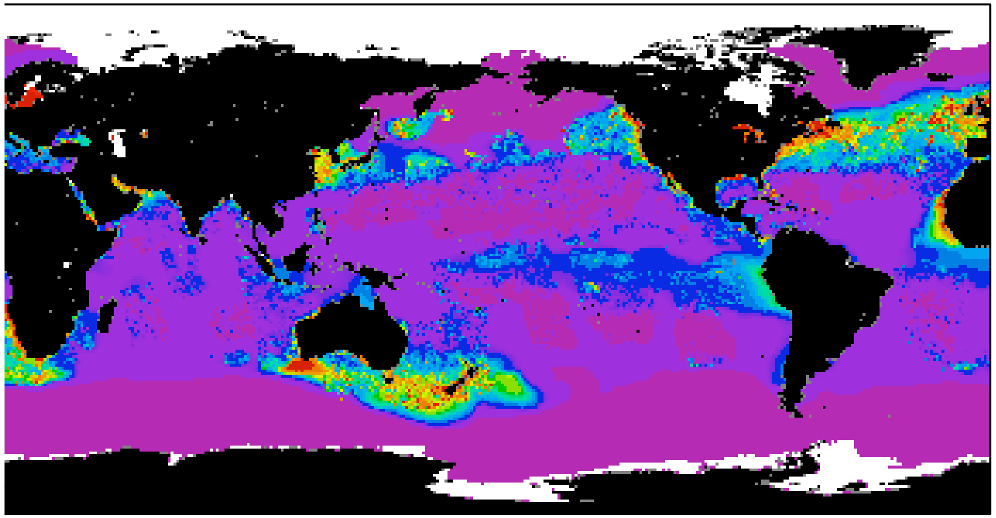
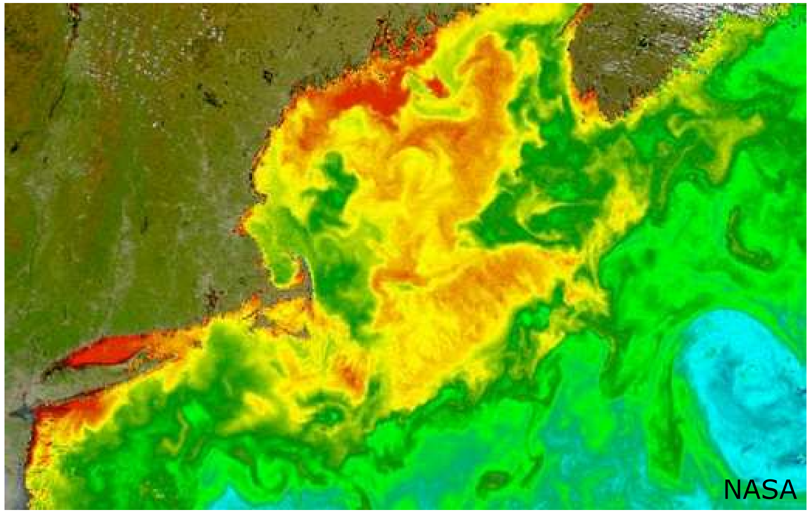
Phytoplankton patchiness



L > 1000 km



L ≈ 100 km



NASA

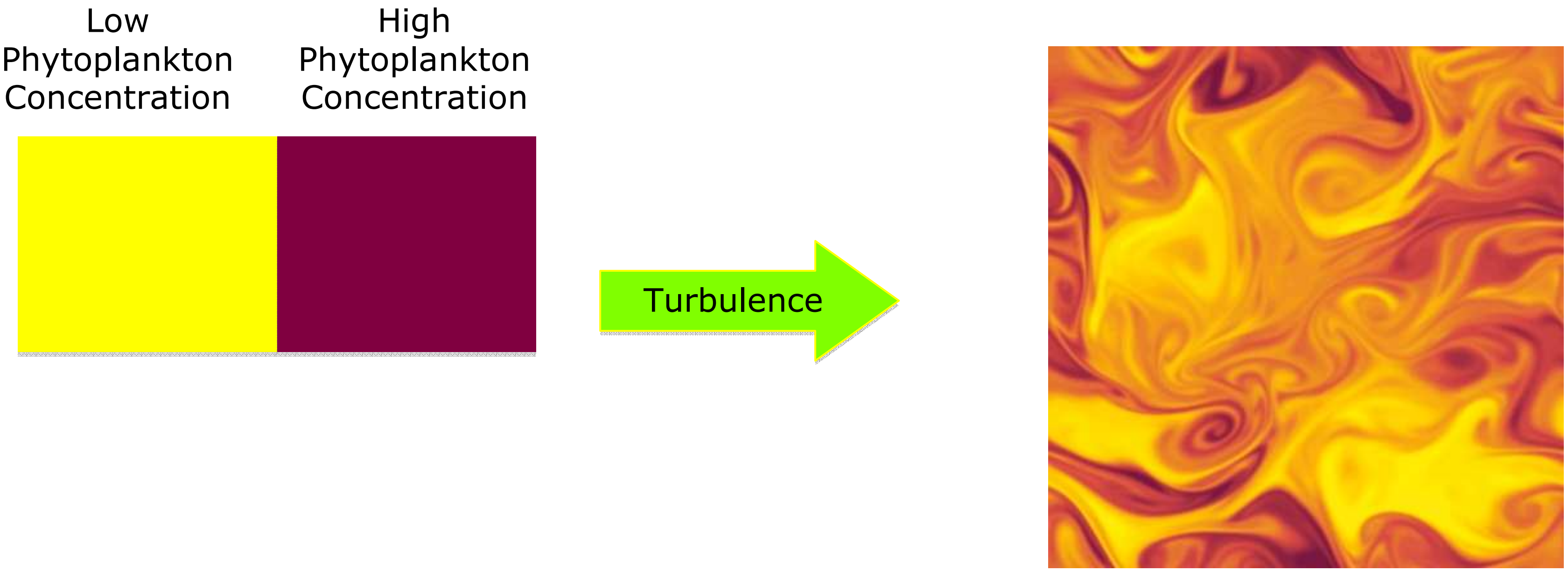
L ≈ 10m

M. Godfrey, NIWA

- The primary producers of the Ocean
- Form the base of the marine food web
- 50% of the global production of oxygen
- Form Harmful Algal Blooms (HABs)

What may cause small-scale heterogeneity ?

Stretching and folding of large scale heterogeneities
by turbulent eddies => plankton is a passive tracer of the fluid



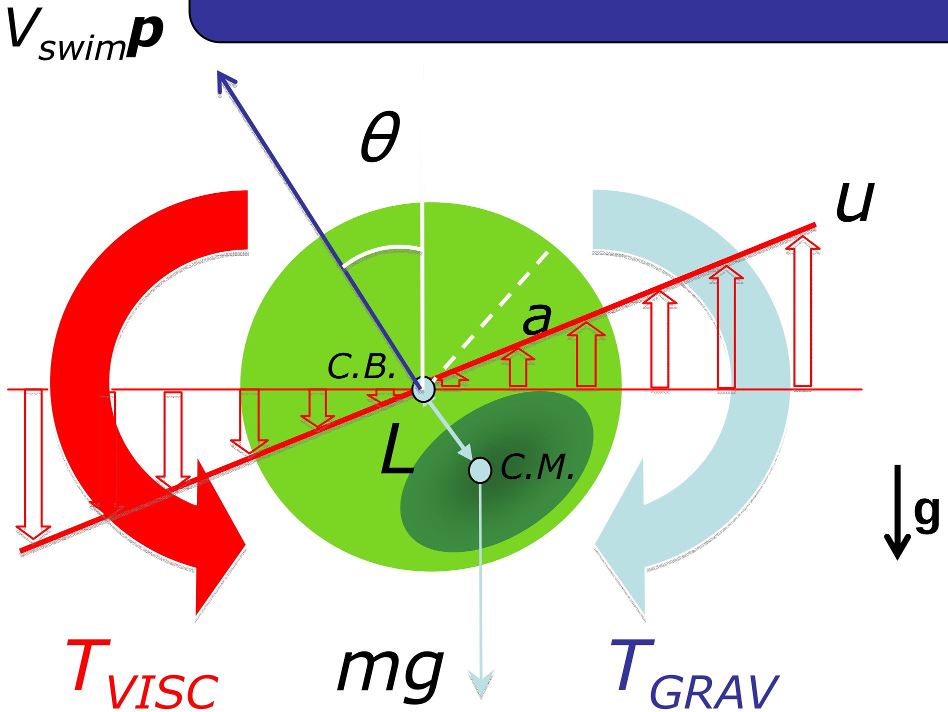
Low Phytoplankton Concentration

High Phytoplankton Concentration

Turbulence

but the micro-organisms are motile (swimming) !!!

Gyrotaxis

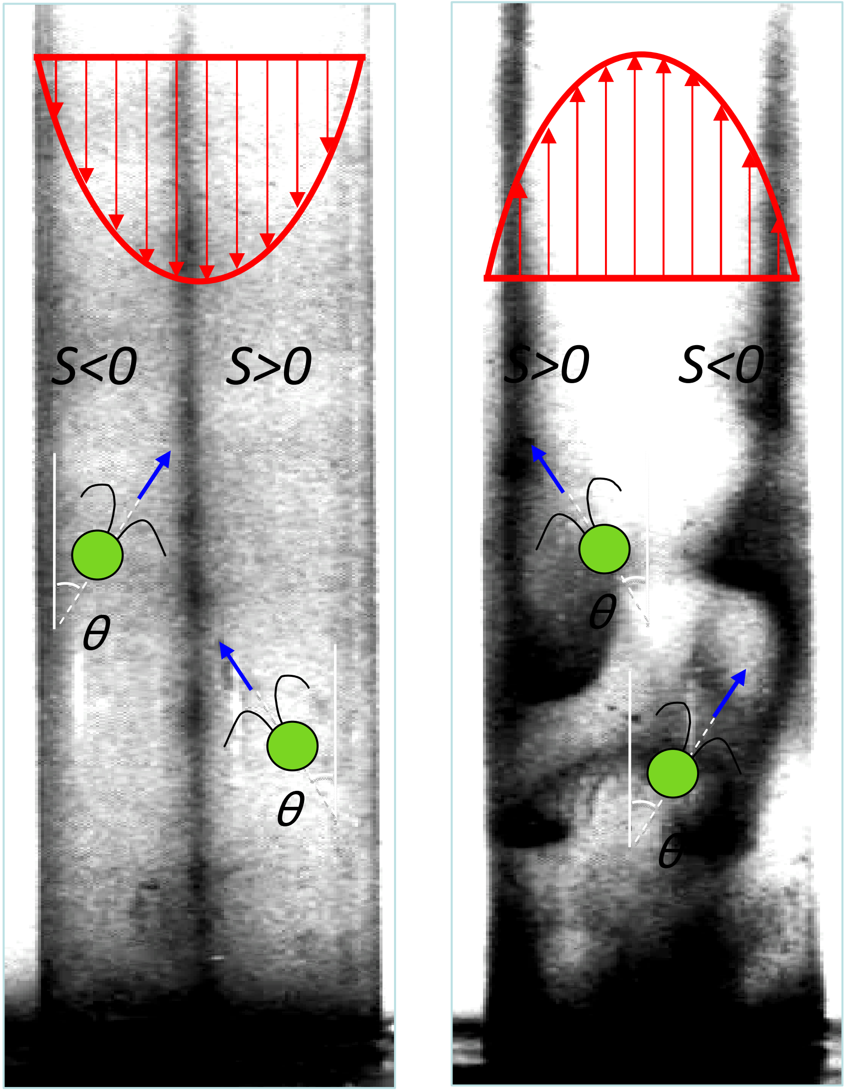


$$\frac{\partial \mathbf{p}}{\partial t} = \frac{1}{2B}\left[\mathbf{k}-(\mathbf{k}\cdot\mathbf{p})\mathbf{p}\right]+\frac{1}{2}(\boldsymbol{\omega}\times\mathbf{p})$$

Equilibrium orientation: $T_{VISC} = T_{GRAV}$

$$\boxed{\mathbf{sin}\theta = B\omega}$$

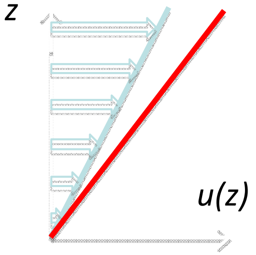
$$\boxed{B = \frac{4\pi\mu a^{3}}{mgL}}$$



(Kessler, 1985)

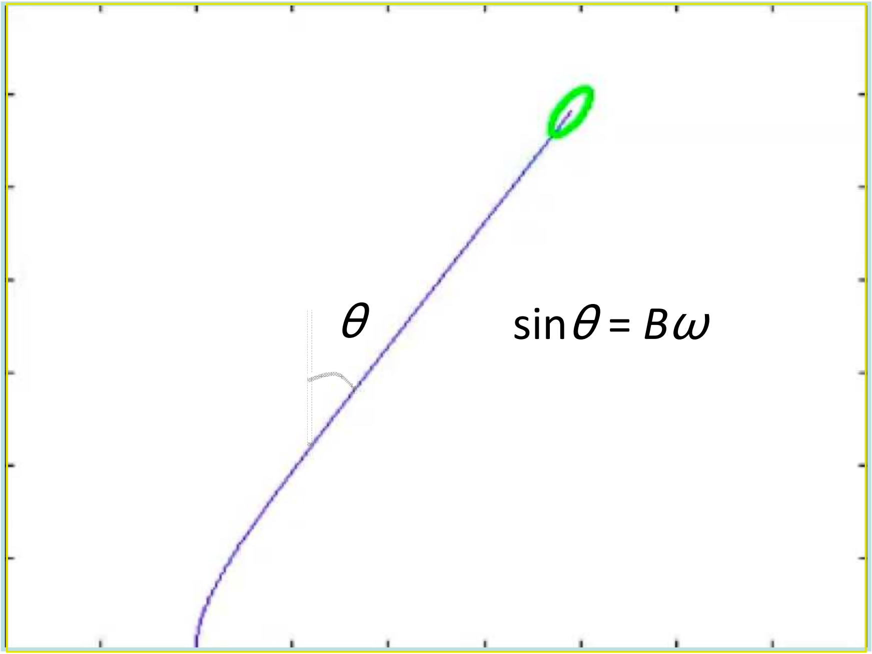
Equilibrium regime

$\sin\vartheta = B\omega$



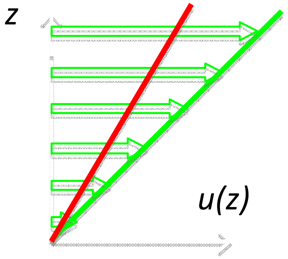
$\omega < \omega_{cr} = B^{-1}$

cells swim up



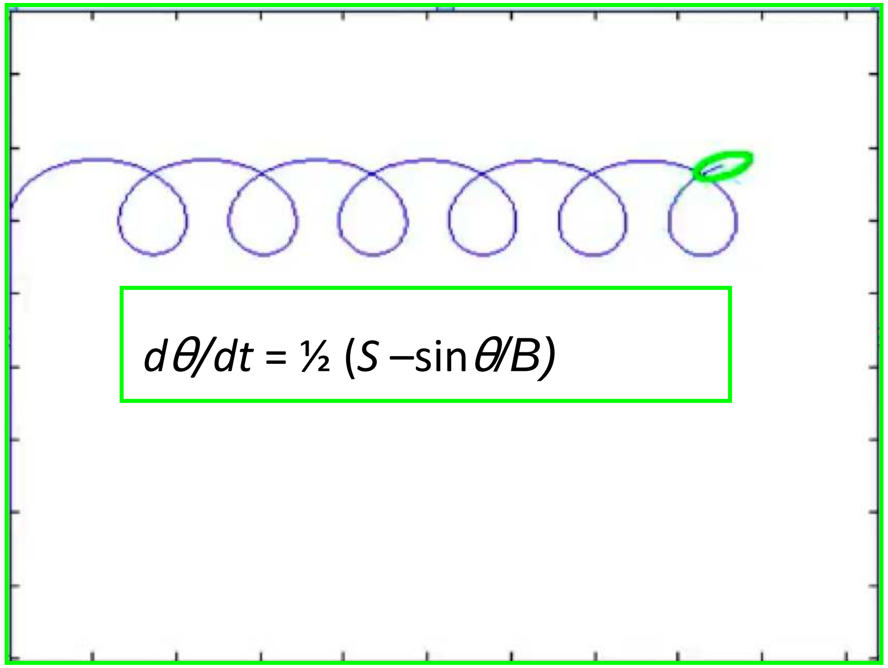
$\sin\theta = B\omega$

Tumbling regime



$\omega > \omega_{cr} = B^{-1}$

cells tumble

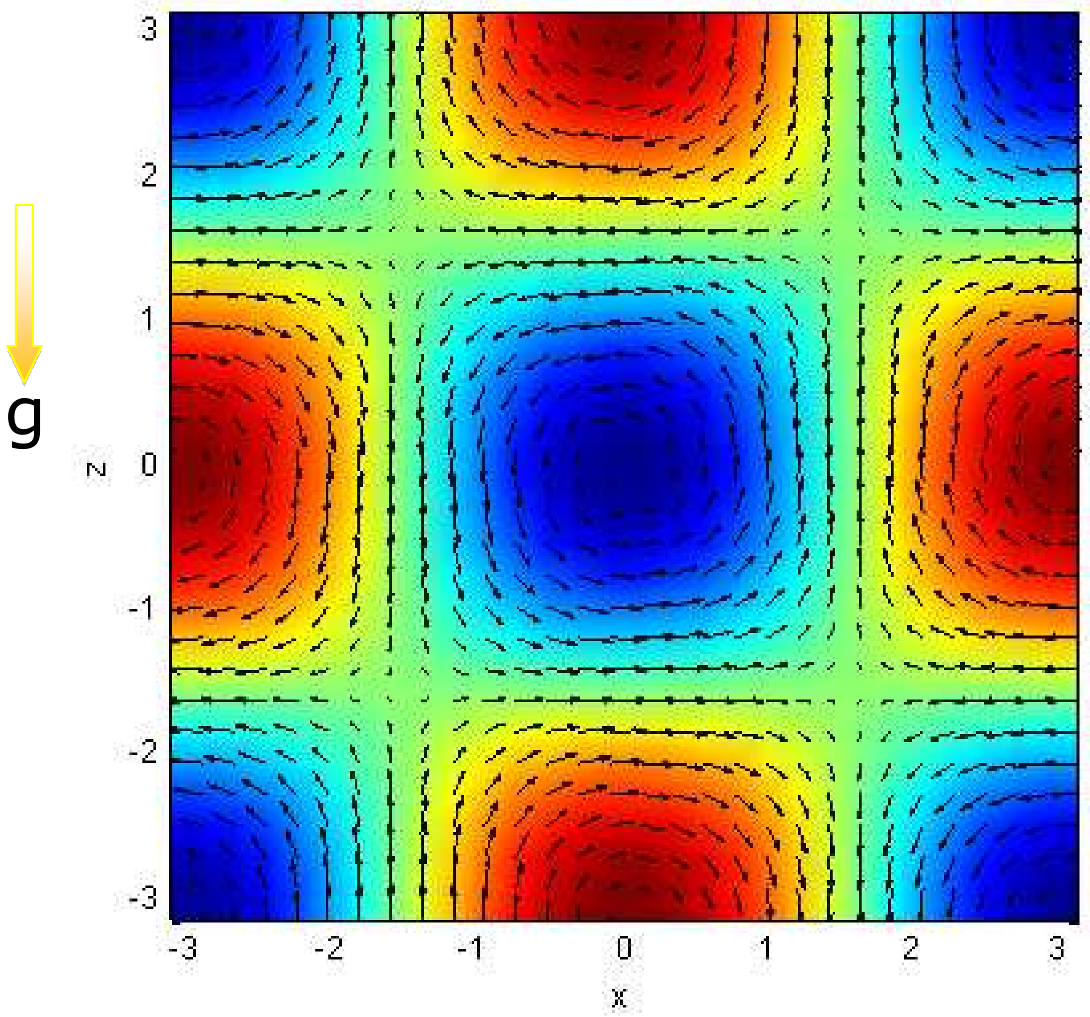


$d\theta/dt = \frac{1}{2}\,(S - \sin\theta/B)$

Transition occurs at $\omega_{cr} = B^{-1}$

Durham, Kessler & Stocker, *Science* 2009

A simple model:
Taylor-Green Vortex (steady)



periodic array of 2D, alternate vortices

x-velocity $$u = -\frac{\omega_o}{2k}\cos(kx)\sin(kz)$$

z-velocity $$w = \frac{\omega_o}{2k}\sin(kx)\cos(kz)$$

vorticity $$\omega = -\omega_o \cos(kx)\cos(kz)$$

Gyrotaxis in Vortical Flow

$$\frac{\partial \mathbf{p}}{\partial t} = \frac{1}{2B}\left[\mathbf{k} - (\mathbf{k}\cdot\mathbf{p})\mathbf{p}\right] + \frac{1}{2}(\boldsymbol{\omega}\times\mathbf{p}) + \cancel{\alpha_0 \mathbf{p}\cdot\mathbf{E}\cdot(\mathbf{I}-\mathbf{pp})}$$

Stability imparted by bottom heaviness

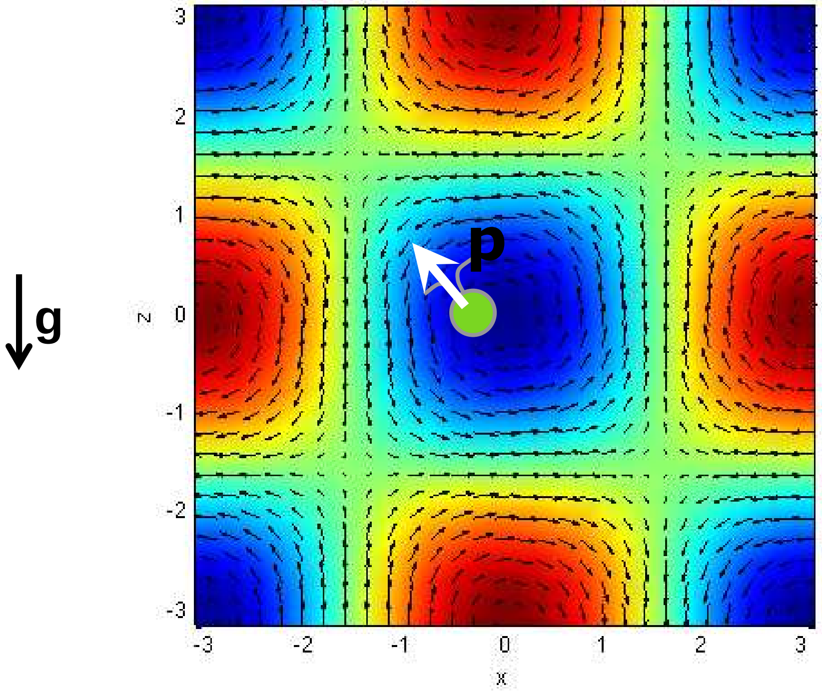
Overturning by vorticity

Alignment with principal strain

Spherical cells

$\mathbf{p}$ = unit vector of swimming direction
$\mathbf{k}$ = unit vertical vector
B = gyrotactic reorientation time
α_0 = cell aspect ratio
$\mathbf{E}$ = rate of strain tensor

Leal and Hinch, 1972
Pedley and Kessler, 1992



Steady flow

$$\mathbf{V}(t) = \mathbf{u}(\mathbf{x}) + V_{swim}\mathbf{p}(t)$$

$$\frac{d\mathbf{x}}{dt} = \mathbf{V}(t)$$

Two dimensionless parameters

$$\Psi = B\,\omega_0$$

$$\Phi = \frac{V_C}{V_{VORTEX}} = \frac{V_C k}{\omega_0}$$

Gyrotaxis in Vortical Flow

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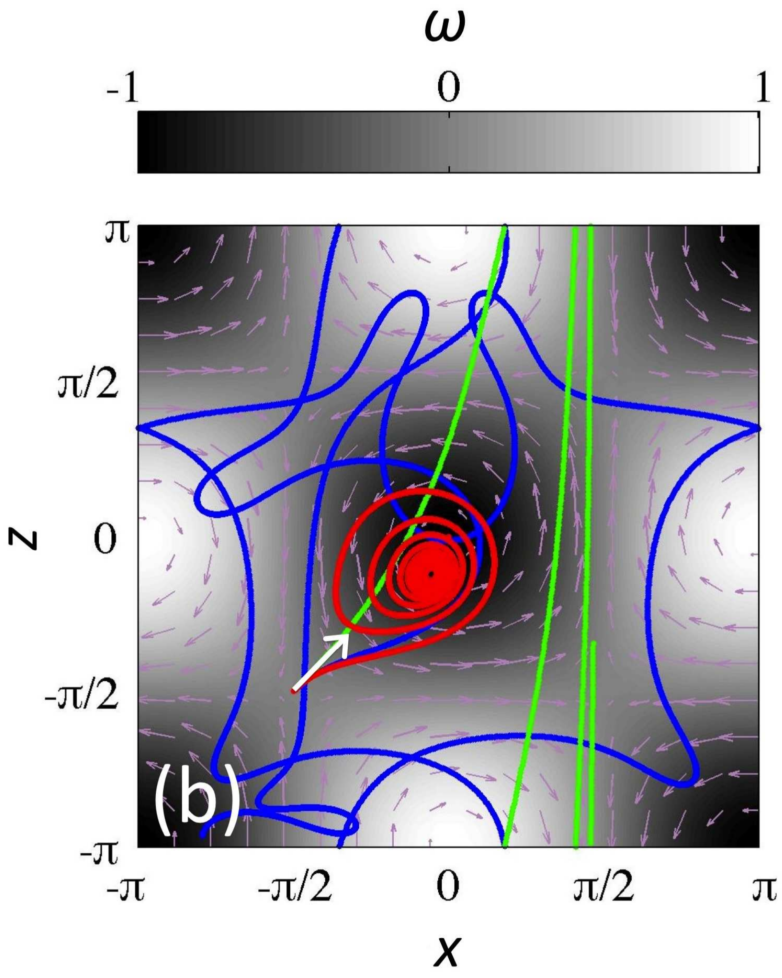


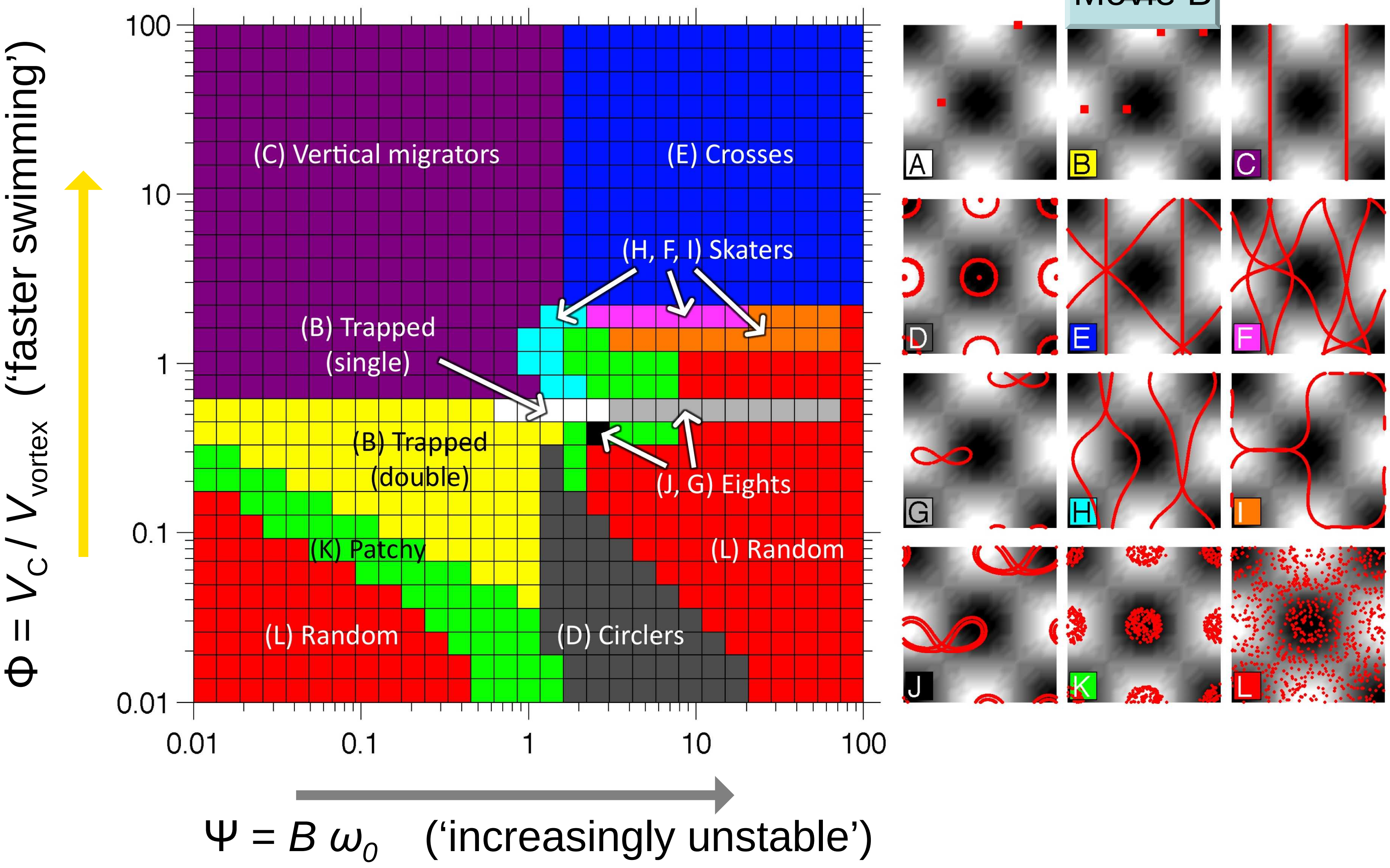
↓ g

Three cell species (different Ψ and Φ) initialized at the same location and orientation ($x = z = -\pi/2$; $\theta = \pi/4$; white arrow)

Trajectories correspond to
(Ψ=0.1 , Φ=20) 🟩
(Ψ= 1, Φ= 0.2) 🟥
(Ψ= 100, Φ= 0.5). 🟦

Diagram of accumulation patterns

Movie B



Description of the numerical modelling

- **Continuous phase :** Newtonian fluid (**Direct Numerical Simulation**)

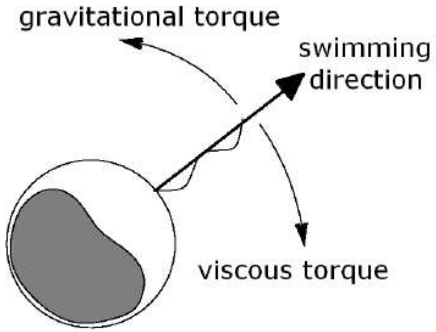
$$\nabla.\mathbf{u} = 0$$

ρ_f, μ : constant physical properties

$$\rho_f\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}.\nabla\mathbf{u}\right) = -\nabla P + \mu\Delta\mathbf{u} + f$$

Large scale forcing
to sustain turbulence

- **Trajectory of motile gyrotactic spherical micro-organisms**



$$\mathbf{V}(t) = \mathbf{u}(\mathbf{x},t) + V_{swim}\mathbf{p}(t)$$

$$\frac{d\mathbf{p}}{dt} = \frac{1}{2B}\left(\mathbf{k} - (\mathbf{k}.\mathbf{p})\mathbf{p}\right) + \frac{1}{2}\boldsymbol{\omega}(\mathbf{x},t)\wedge\mathbf{p} + \cancel{\alpha\,\mathbf{p}.\mathbf{E}.(\mathbf{I} - \mathbf{pp})}$$

Stability imparted by bottom heaviness

Overturning by vorticity

Alignment with principal strain

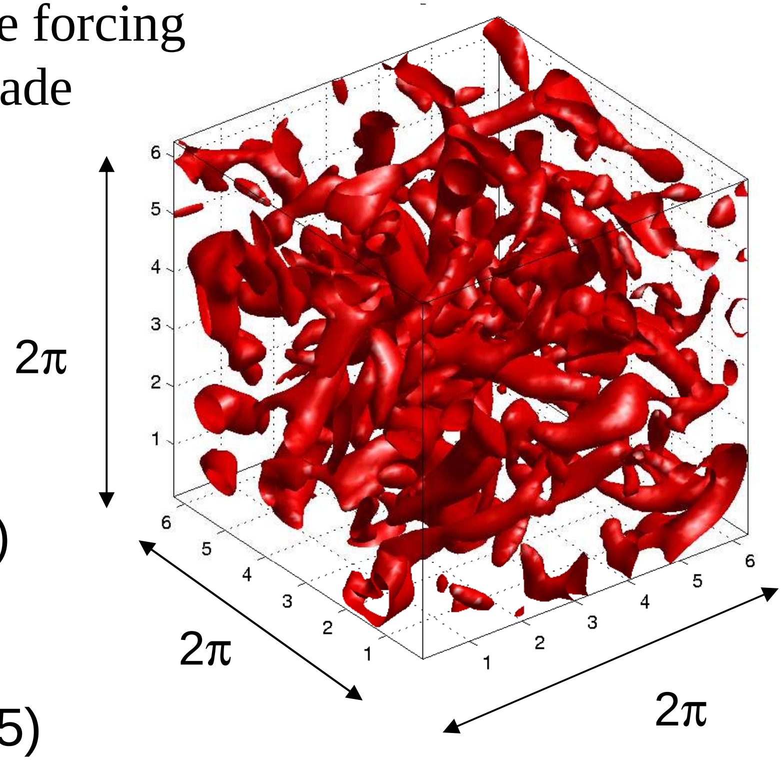
$\mathbf{p}$ = unit vector of swimming direction
$\mathbf{k}$ = unit vertical vector
B = reorientation time
α = cell aspect ratio
$\mathbf{E}$ = rate of strain tensor

Leal and Hinch, 1972
Pedley and Kessler, 1992

Characteristics of the flow

Homogeneous isotropic turbulence with large scale forcing

=> sustaining turbulence and energy cascade



Fourier pseudo-spectral resolution

=> Parallel computing using FFTW_MPI

Tri-periodic domain

calmip

Fully resolved DNS: 128^3 grid points ($k_{max}\eta_k=1.4$)

Characteristic scales of the turbulent flow ($Re_\lambda=55$)

Velocity fluctuations $u_{rms}=19.256$

Taylor micro-scale $\lambda=0.3405$

Kolmogorov scales

$\tau_K=0.0046$; $v_k=5.087$; $\eta_k=0.0234$

Two dimensionless numbers

Characteristics of the swimming micro-organisms

-Time scale of reorientation B

-Swimming speed V_{swim}

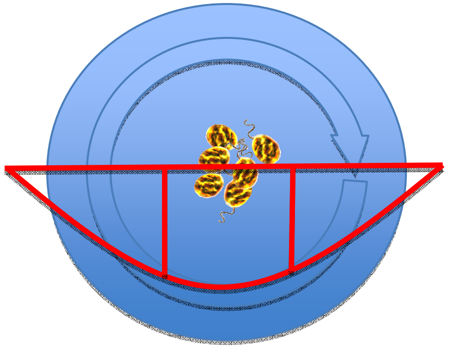
$$\Psi = B/\tau_K = B/\text{Kolmogorov time}$$

$$\Phi = \frac{V_{Swim}}{v_K} = \frac{\text{Swimming velocity}}{\text{Kolmogorov velocity}}$$

Characteristic scale of the vorticity : $\Omega \sim (\varepsilon/3\nu)^{1/2} \Rightarrow \Omega\tau_K = 1/3^{1/2}$

Overturning may occur when : $2\Omega B > 1 \Rightarrow B > 3^{1/2}\tau_K/2 \Rightarrow \Psi > 3.5$

Gyrotactic trapping in high vorticity regions ?



Φ and Ψ in the Ocean

Turbulence

	$\varepsilon = 10^{-10}$ W/kg	$\varepsilon = 10^{-4}$ W/kg
$1/\tau_k = S_K = (\varepsilon/\nu)^{1/2}$	$0.01 s^{-1}$	$10 s^{-1}$
$\upsilon_K = (\nu\varepsilon)^{1/4}$	100 µm/s	3000 µm/s

Motility

$B = 0.1 - 100$ s (only known for 3 species)

$V_S = 0 - 1000$ µm/s

	Minimum	Maximum
$\Phi = \frac{V_{swim}}{v_K}$	0	10
$\Psi = B/\tau_K$	10^{-3}	10^{3}

In the simulations, Φ and Ψ were varied independently in the range : 0.1 – 40

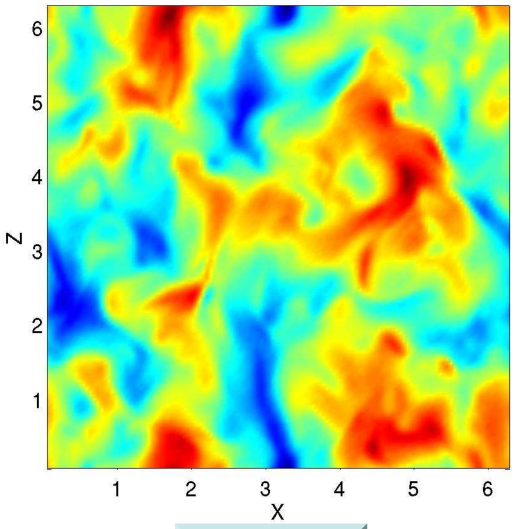
Accumulation does occur !

100,000 particles seeded at initial random positions
Videos over 20 Kolmogorov time scales

Φ=10 and Ψ=1

↓ **g**

Vertical plane

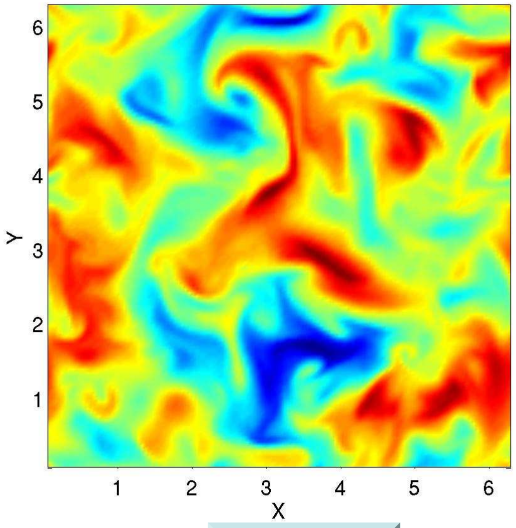


Vertical velocity

Down 🟦

Up 🟥

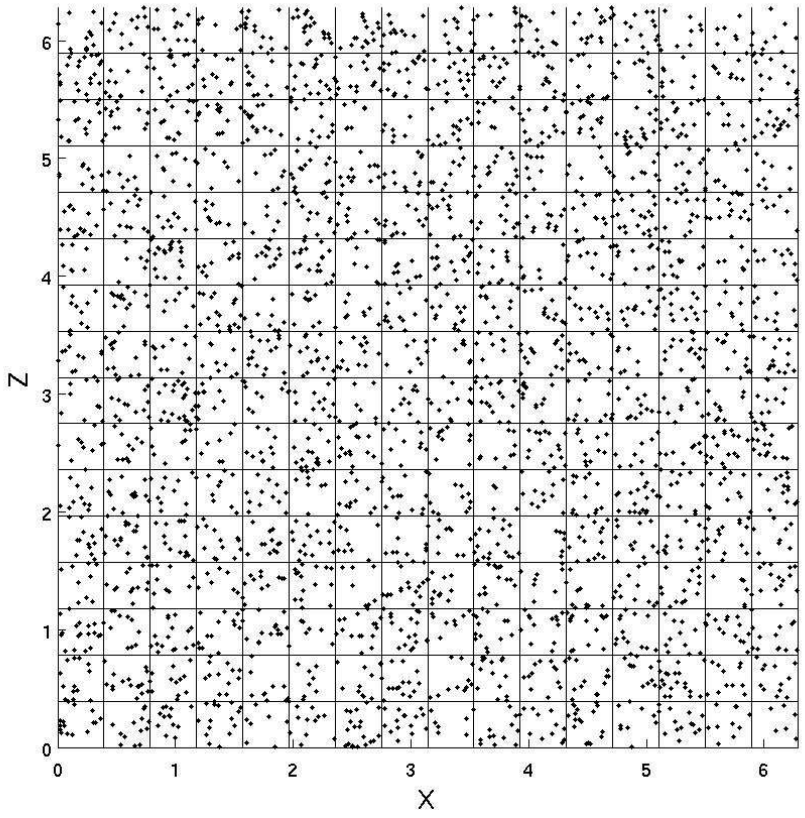
Horizontal plane



⊗ **g**

Tests with different initial random positions
Tests over the three possible orientations of gravity

Accumulation statistics



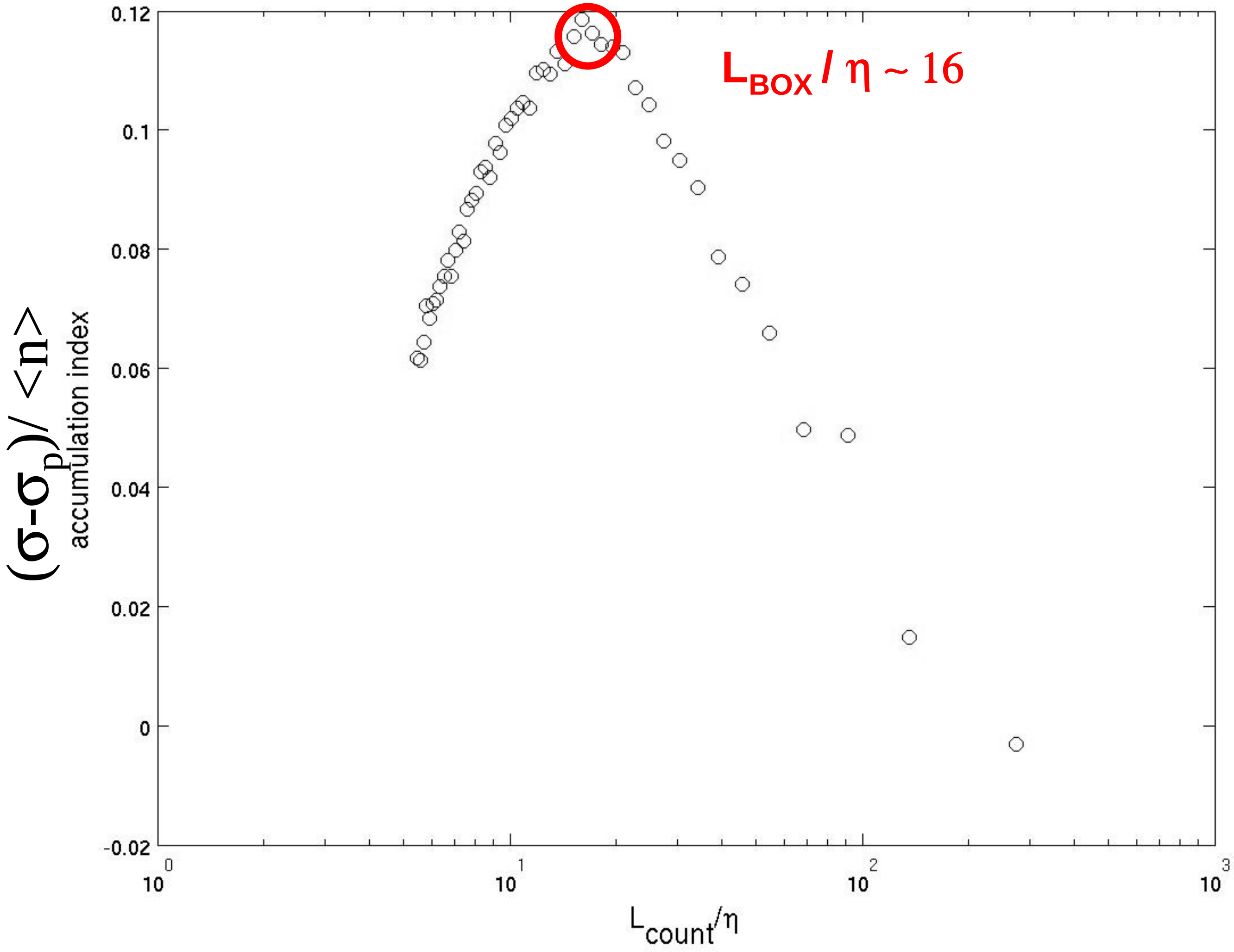
Pdf of the number n of cells in a box
(box counting : L/16)

Random positions : Poisson distribution
100,000 particles => <n> = 25
std deviation σ_p = $\langle n \rangle^{1/2}$ = 5

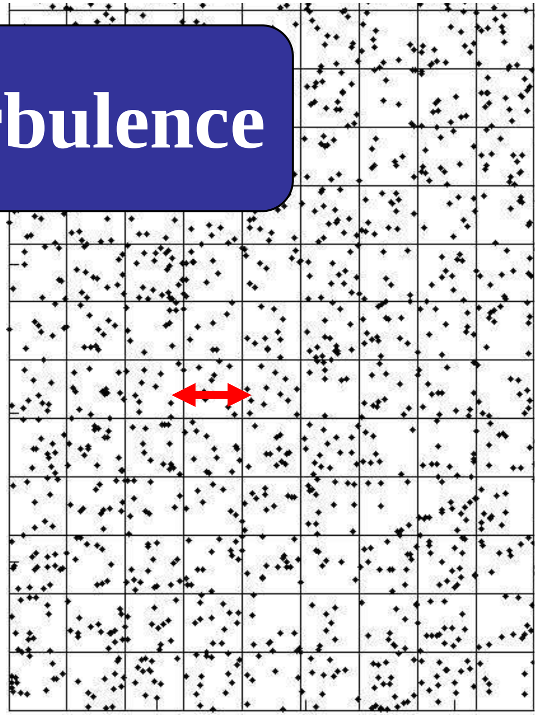
Pdf of n
Accumulation index: N = $(\sigma-\sigma_p)/ \langle n \rangle$

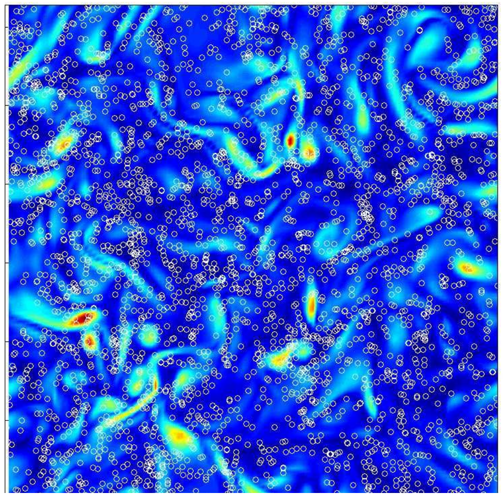
Voronoi tesselation

Accumulation length scale in Turbulence

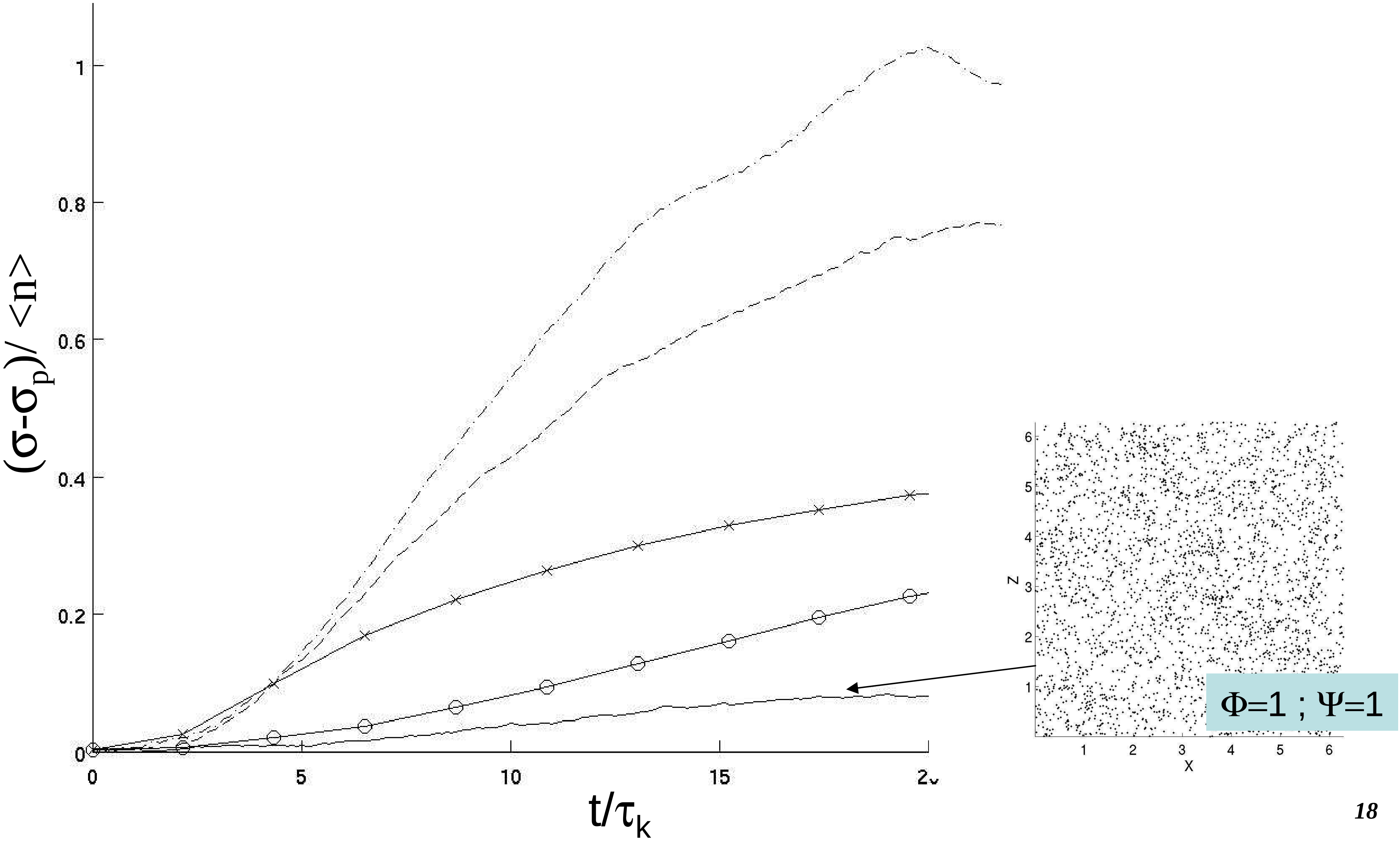


$L_{BOX}/\eta \sim 16$

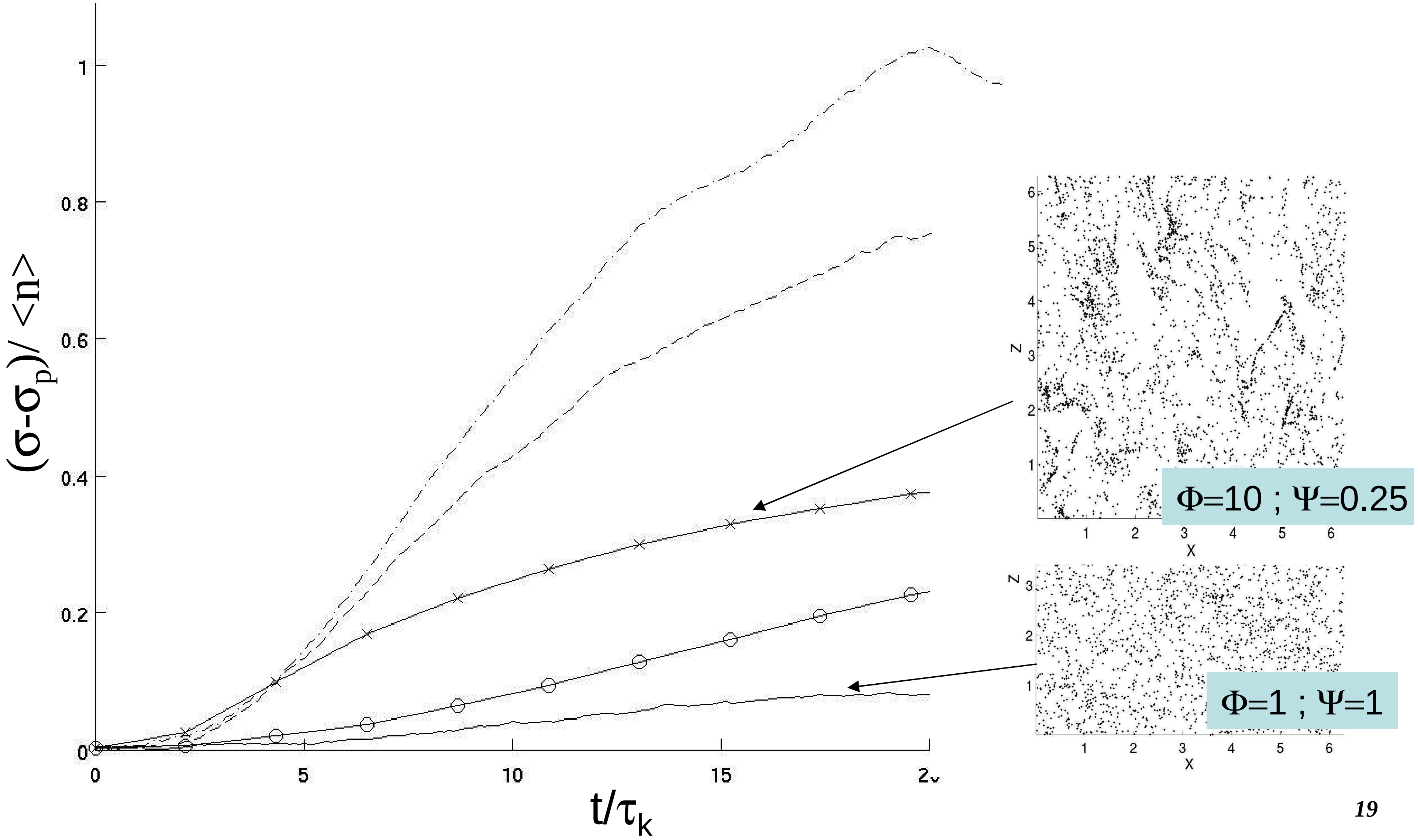




Initial transient of accumulation



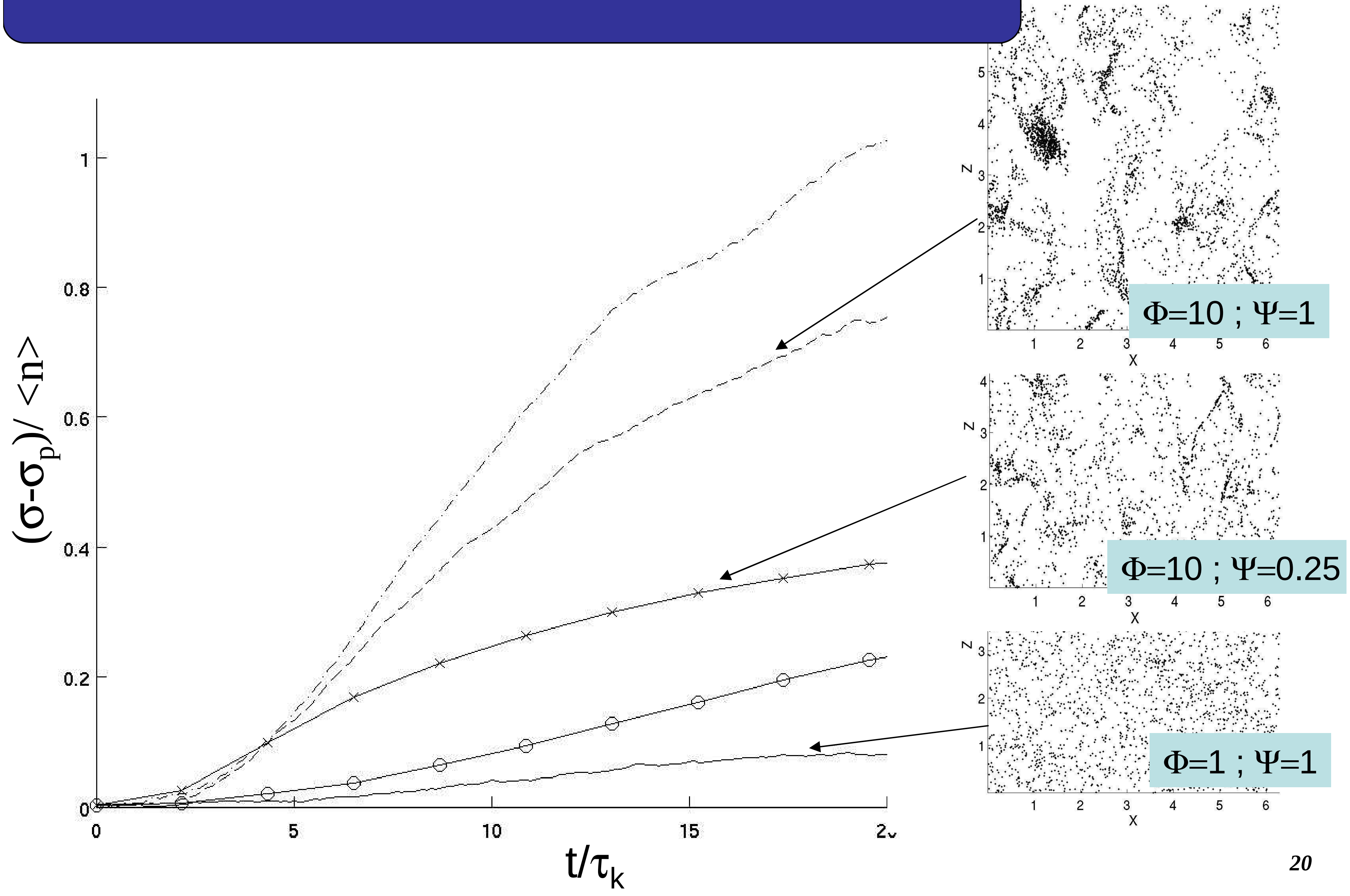
Initial transient of accumulation



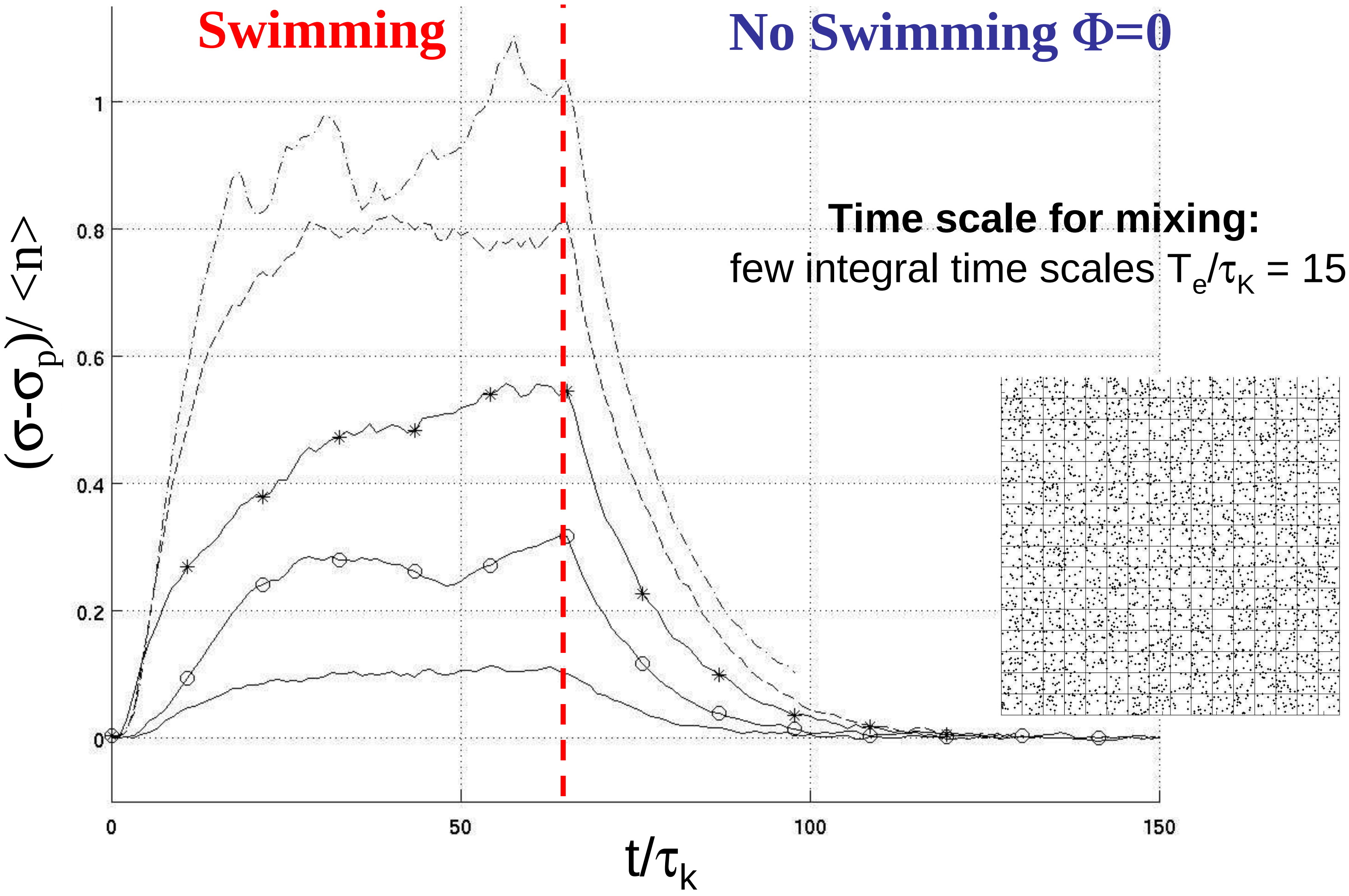
Φ=10 ; Ψ=0.25

Φ=1 ; Ψ=1

Initial transient of accumulation



Back to mixing



Time scale for mixing:
few integral time scales T_e/τ_K = 15

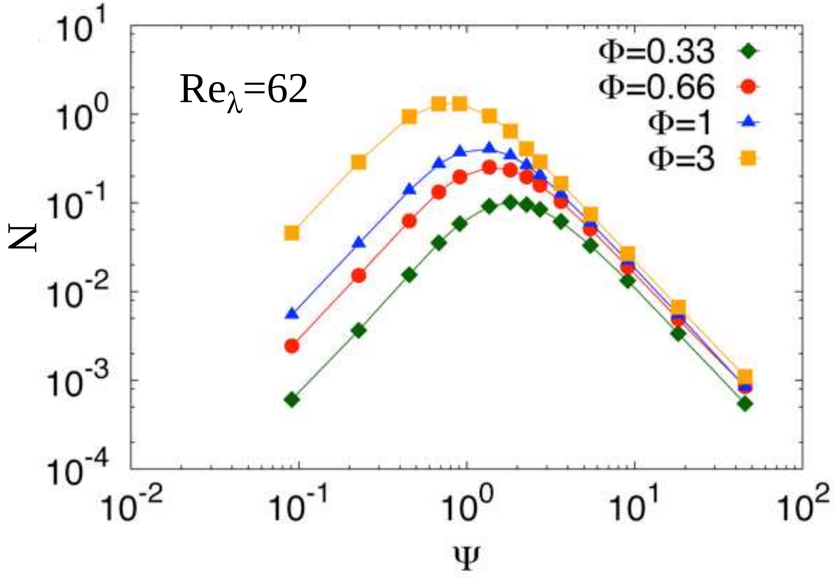
Kolmogorov Scaling

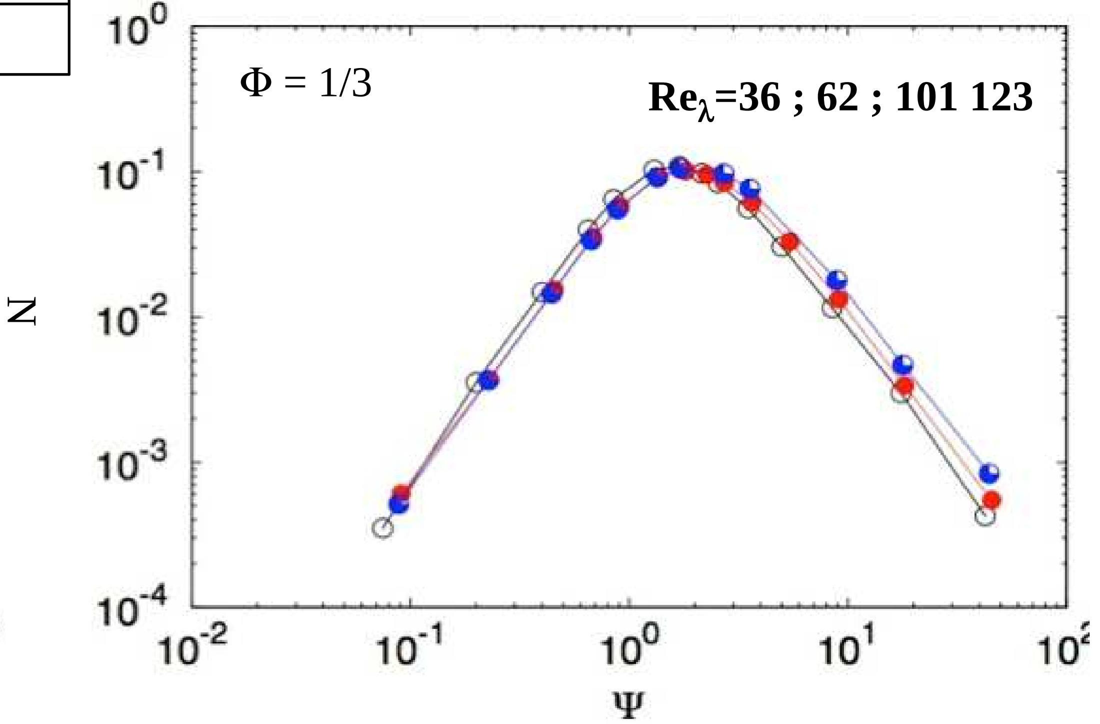
Re$_\lambda$	***M***	**Number of cells**	λ/η_K
36	64^3	300,000	11.7
62	128^3	300,000	15.7
101	256^3	2,400,000	19.5
123	512^3	3,200,000	21.7

$$\Psi = B/\tau_K = B\,/\text{Kolmogorov time}$$

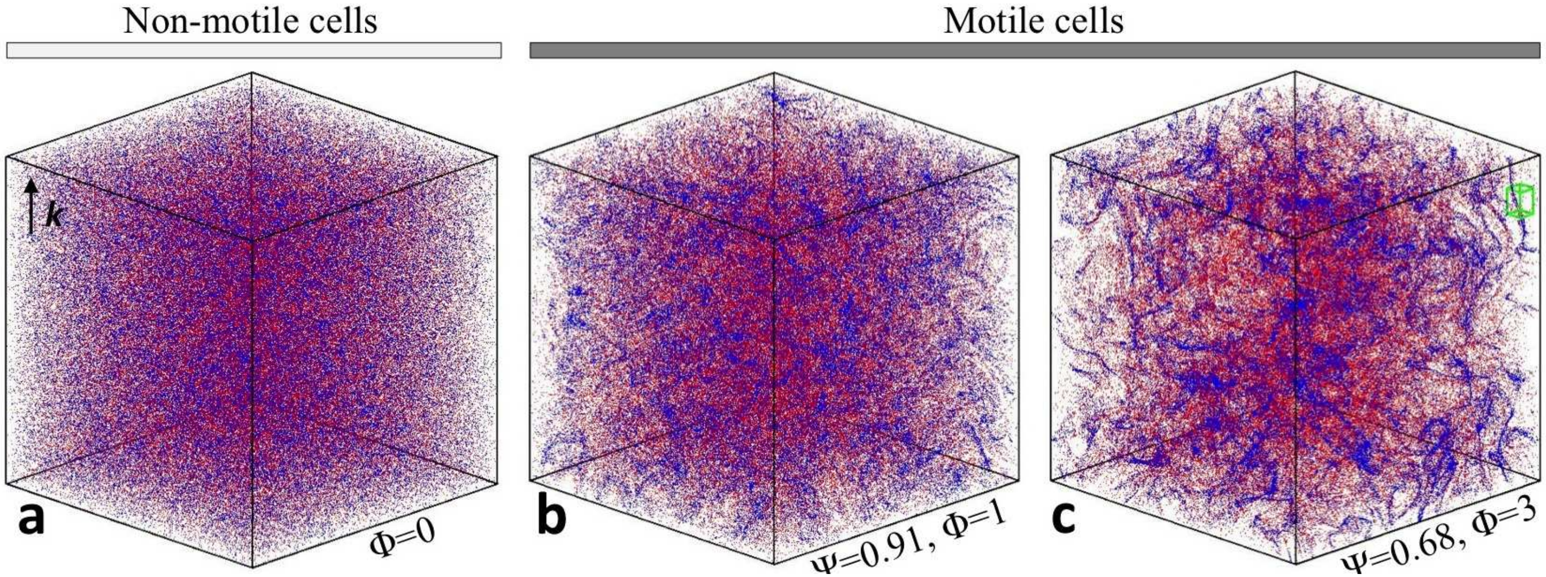
$$\Phi = \frac{V_{Swim}}{v_K} = \frac{\text{Swimming velocity}}{\text{Kolmogorov velocity}}$$

calmip





Quantifying Patchiness with a Voronoi Tesselation



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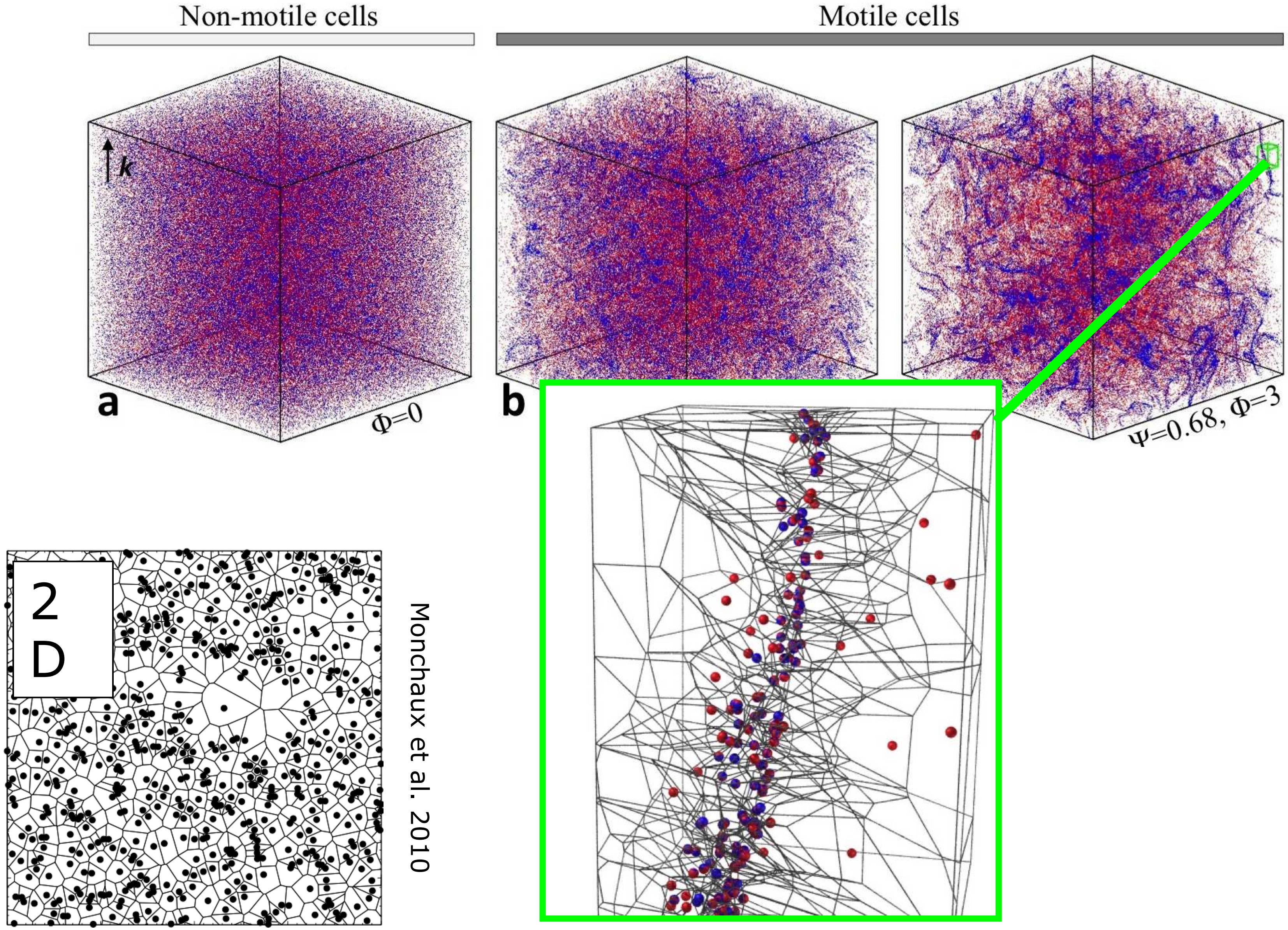
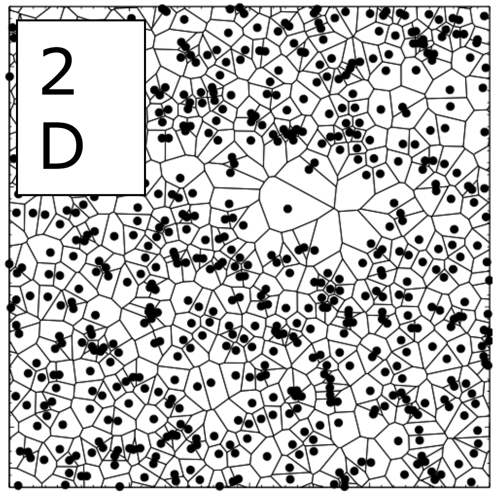
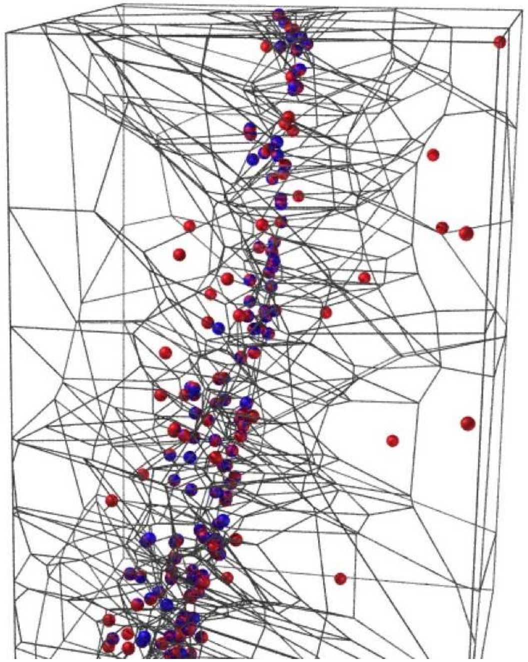


Monchaux et al. 2010

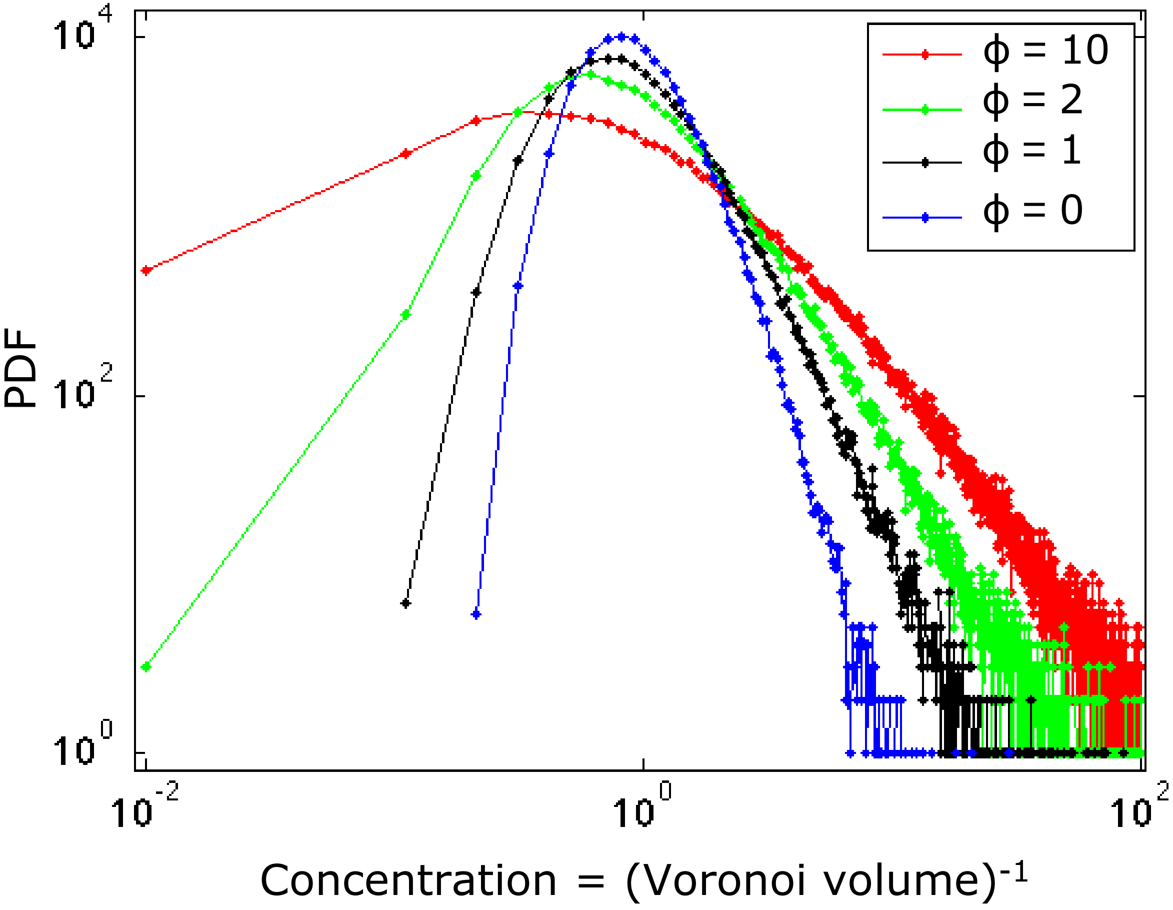
Quantifying Patchiness with a Voronoi Tesselation



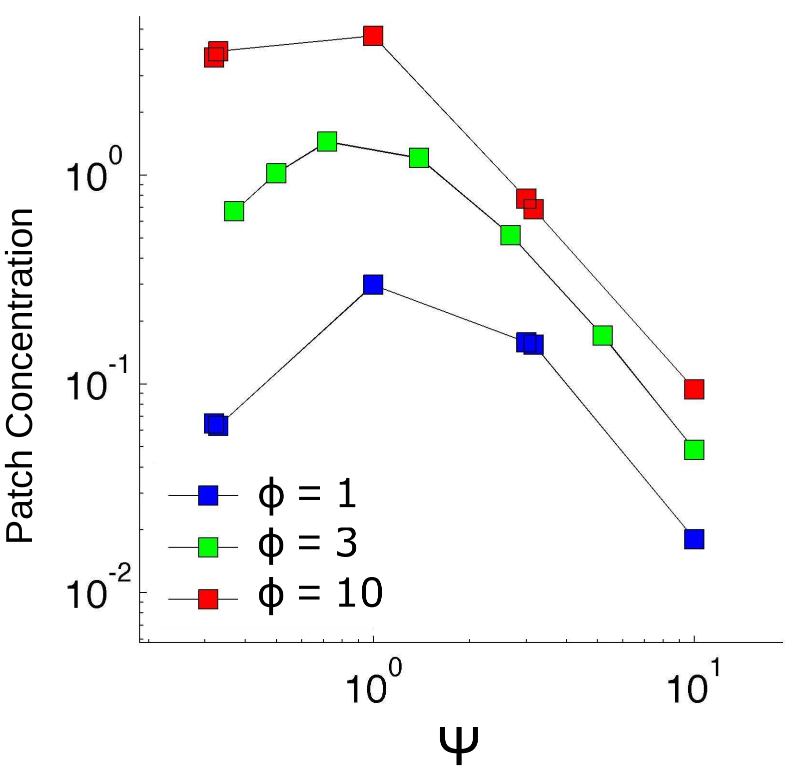
Monchaux et al. 2010

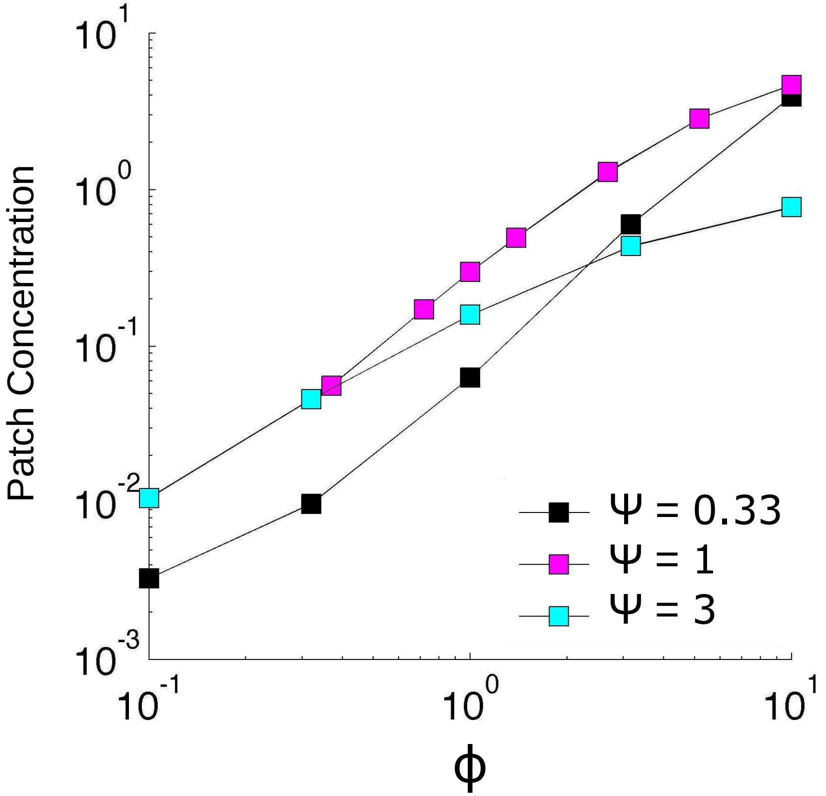


all Ψ = 1



Patchiness as a function of Ψ and φ



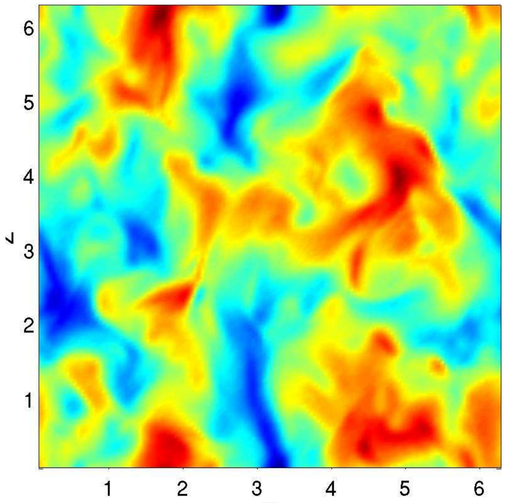


Patchiness most
intense for 'neutral stability'

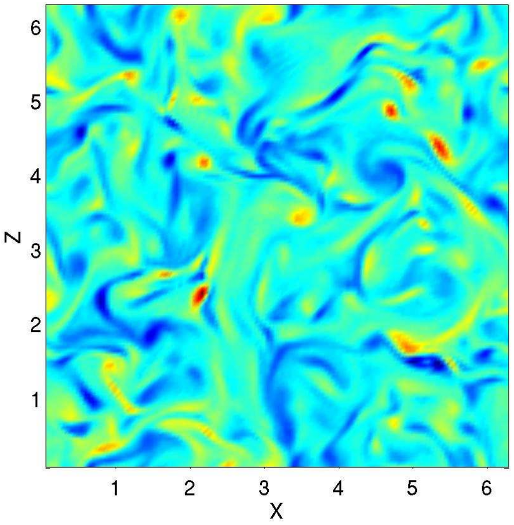
Increased swimming speed
produces more intense patches

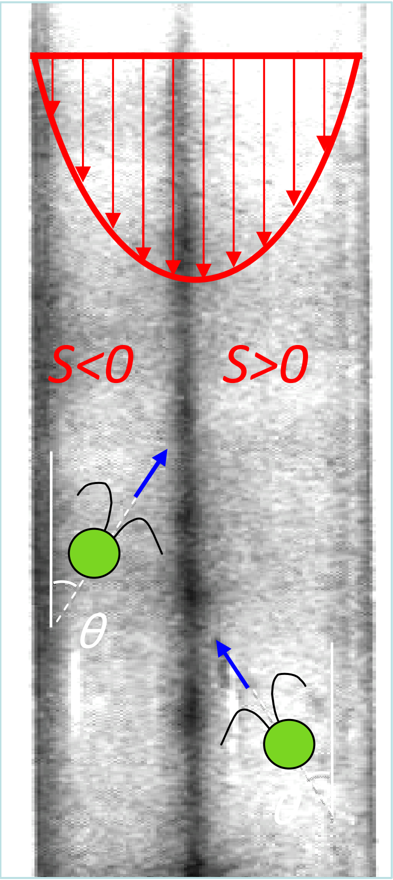
Accumulation mechanism

Vertical velocity w



Horizontal vorticity

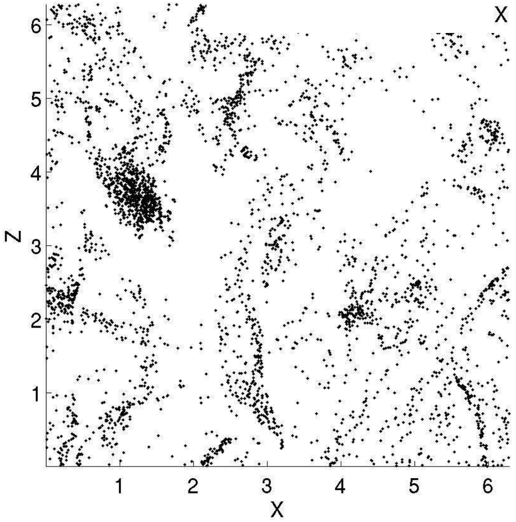


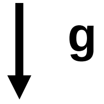


Focusing in downwelling flows

(Kessler, 1985)

Φ=10 ; Ψ=1





Average fluid velocity at cells position

Ψ=1 and Φ=	0	1	2	10	20
$(\sigma-\sigma_p)/\langle n \rangle$	0	0.1	0.5	0.8	1.1
$\langle w \vert_x \rangle / u'$	10^{-4}	-0.08	-0.15	-0.31	-0.24

More details and references

W. Durham, E. Climent, M. Barry, F. De Lillo, G. Boffetta, M. Cencini and R. Stocker
Nature Communications (2013) under revision.
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W.M. Durham, E. Climent and R. Stocker. *Phys. Rev. Letters* – 106, 238102 (2011).
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Acknowledgements and funding

Regional HPC – Calmip (2011-2012).

BQR INPT International Mobility – 2008 – 2009
MIT-France Seed Fund – 2010-2012