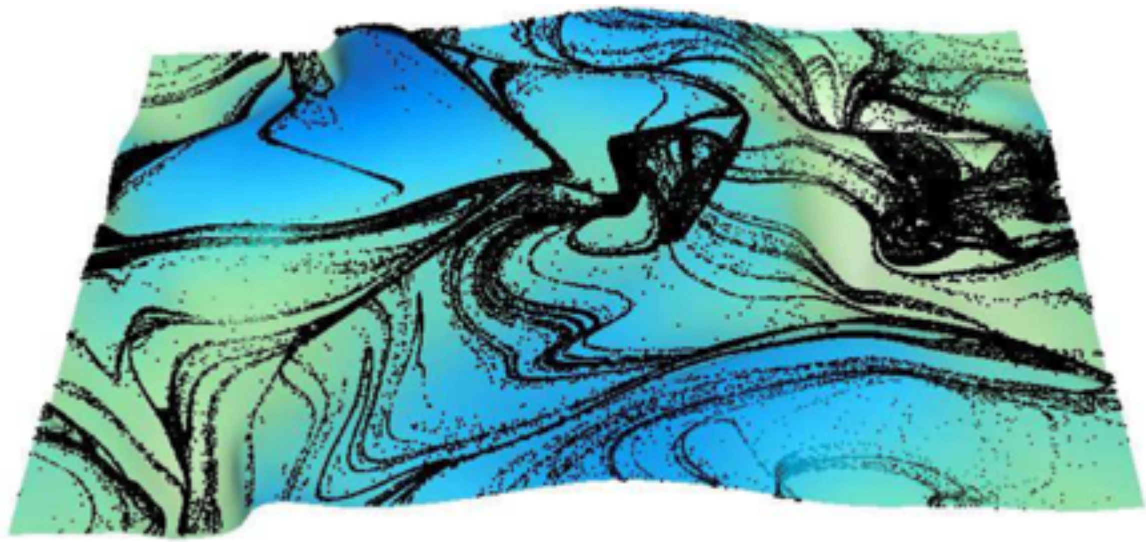
Layering of Microorganisms by Buoyancy

Filippo De Lillo



"Large-scale confinement and small-scale clustering of floating particles in stratified turbulence"
A Sozza, F D, S Musacchio and G Boffetta
arXiv:1509.03540 [physics.flu-dyn](2015)

Flowing Matter – COST Action MP1305

Lagrangian transport: from complex flows to complex fluids
Lecce, March 7-10, 2016

Layering of Microorganisms by Buoyancy

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Large-scale confinement and small-scale clustering of floating particles in stratified turbulence
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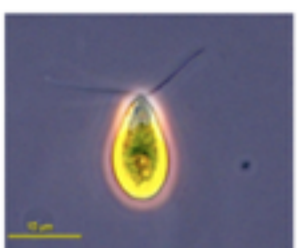
Motivations

Phytoplankton is composed by **one-celled organisms** able to perform **phototaxis**
It is at the basis of the oceanic food web
It is the source of about 50% of the oxygen "produced" on the earth
It is fundamental for carbon cycle

Phytoplankton actually **can often move** actively
Many phytoplankters are able to swim
Some control their buoyancy
Doing so allows them to stay in the "photic" layer…
Phytoplankton is "patchy" at several scales which affects:

- exploitation of nutrients
- predation
- mating (when reproducing sexually)
- access to light (mutual shading…)

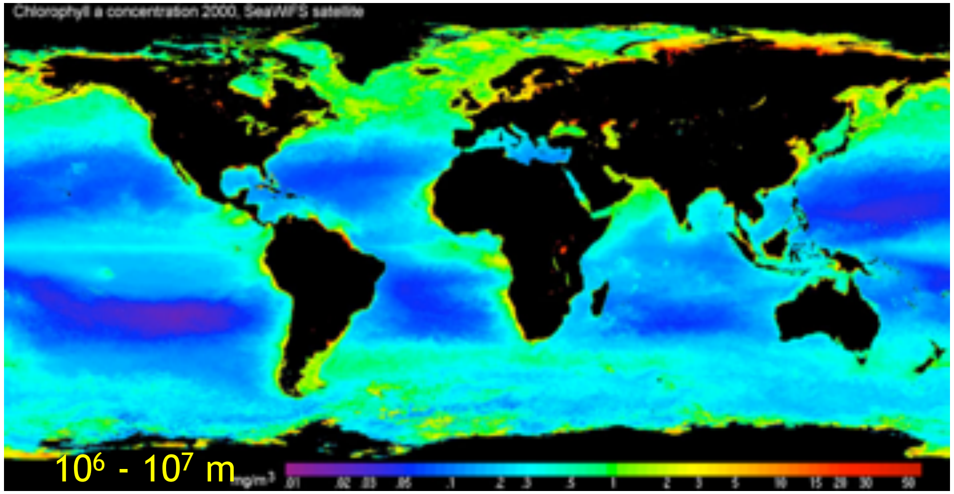
Phytoplankton



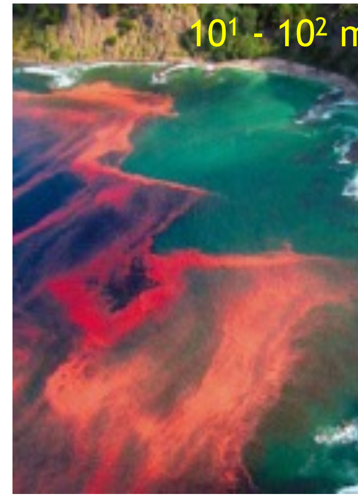
Zooplankton

Phytoplankton “patchiness”

Phytoplankton form inhomogeneous distributions over many scales

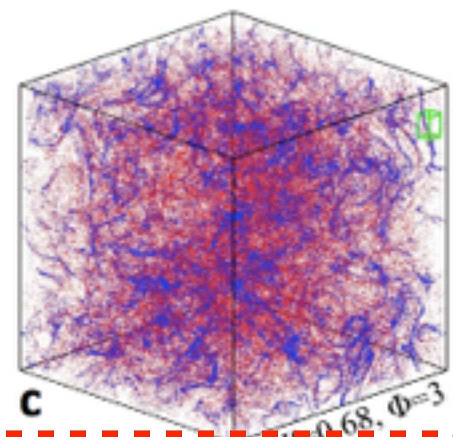


Global distribution of chlorophilla



Red tide bloom of *Noctiluna scintillans*

Thin layers of *Heterosigma akashiwo* near Shannon Point (WA)

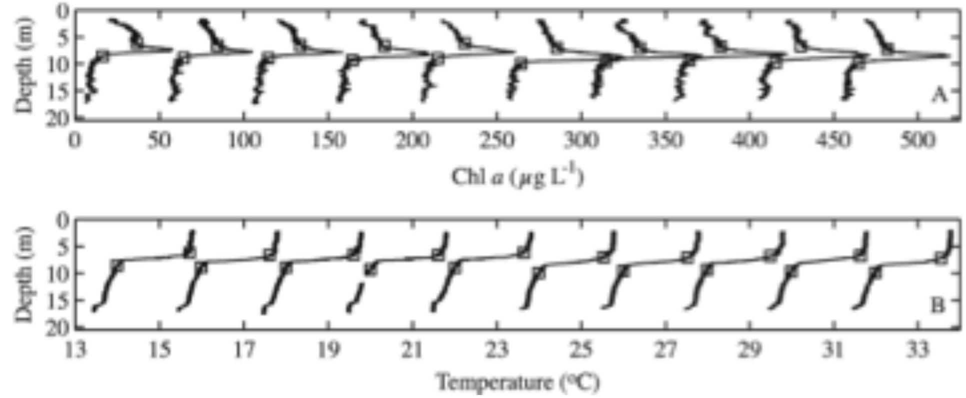


W.M. Durham, *et al*., Nature Comm. **4**, 2148 (2013)

Different mechanisms (echological, biological, physical) for different scales

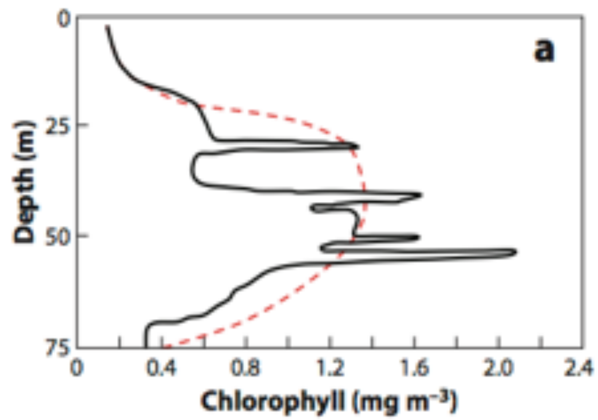
Thin phytoplankton layers

- high concentration (up to 100 x background).
- vertical thickness cm to few m
- horizontal size up to km
- persistence up to days
- typical in coastal oceans.



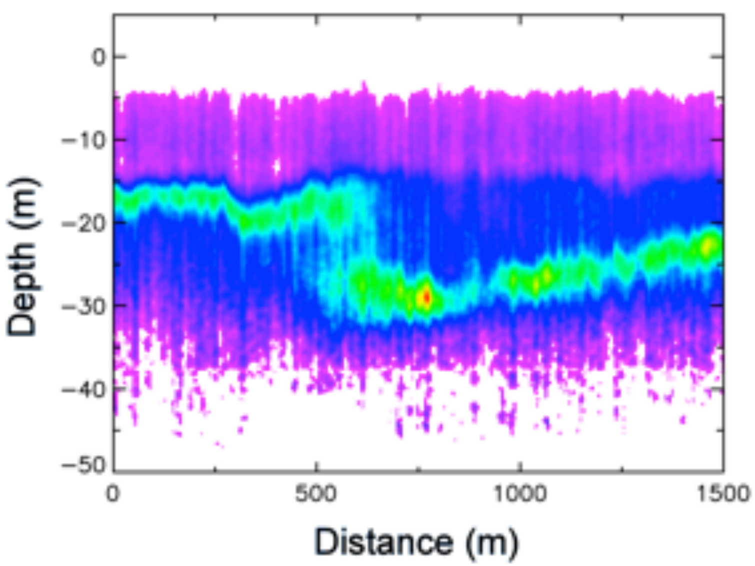
J.V. Steinbuck et al, *Limnol. Oceanogr.* **54** (2009)

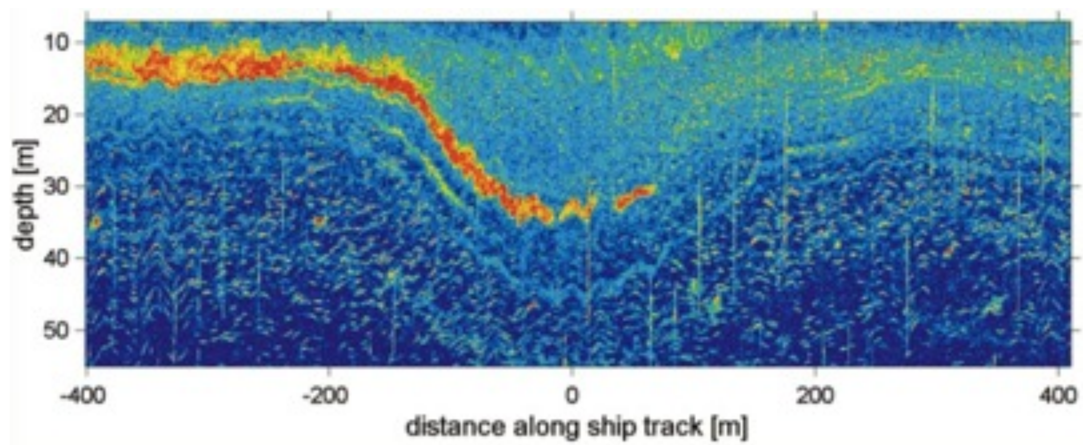
Often correlated
with strong gradient in density
or vertical shear.



Thin layers observed in 1967 off San Diego, California.

Can be used to track the pycnocline

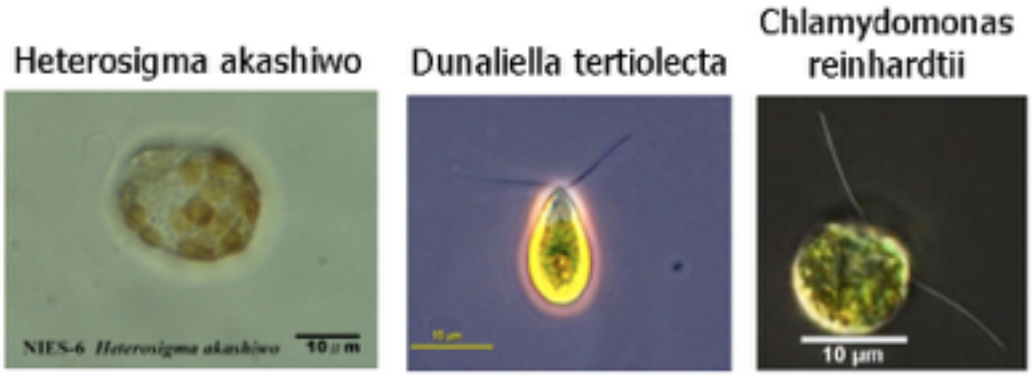




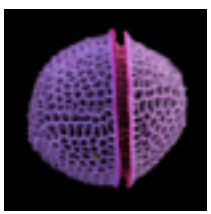
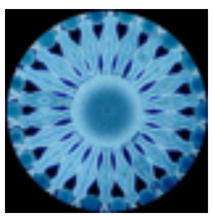
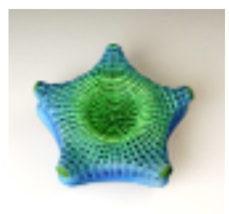
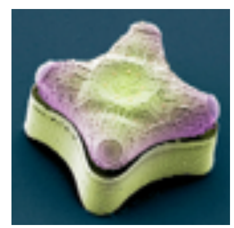
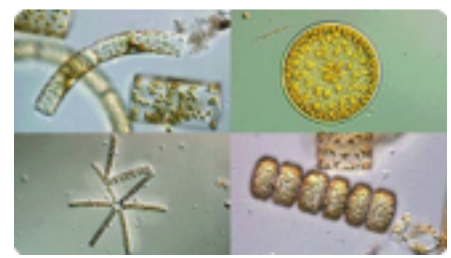
Lidar vertical section of the pycnocline *Churnside et al (2009)*

Very diverse species form layers

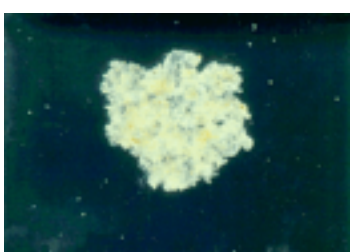
Swimming: flagellate algae, dinoflagellates, etc.



Non-swimming phytoplankters: diatoms

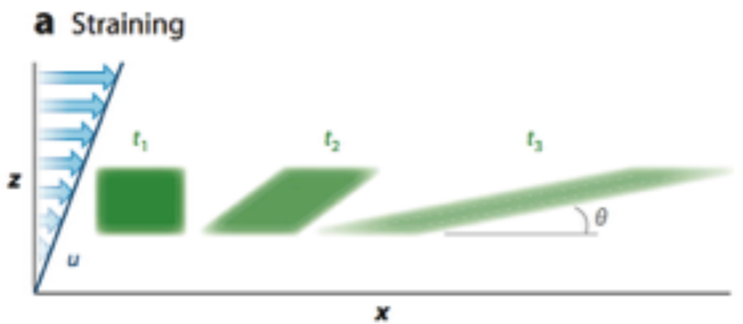
Marine snow: aggregates of diatoms, fecal pellets, bacteria….



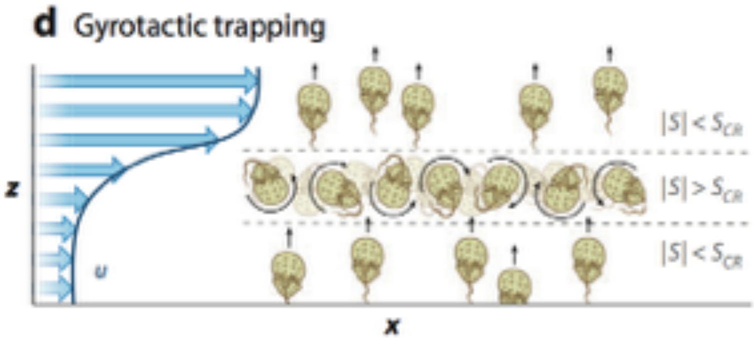
Mechanisms for layer formation

W.M. Durham, R. Stocker, *Annu. Rev. Marine Sci.* **4**, 177 (2012)

…just some examples



Birch DA, *et al*., Deep-Sea Res. **55,** 277 (2008)



Algae would swim upwards but are trapped because of strong rotation

W.M. Durham, *et al*. Science **323**, 1067 (2009)

Santamaria, *et al*., Phys. Fluids **26**, 111901 (2014)

Alldredge et al., Mar. Ecol. Prog. Ser. 233, 1 (2002)

Birch, Young, Franks, *Limnol. Oceanogr.* **54** (2009)

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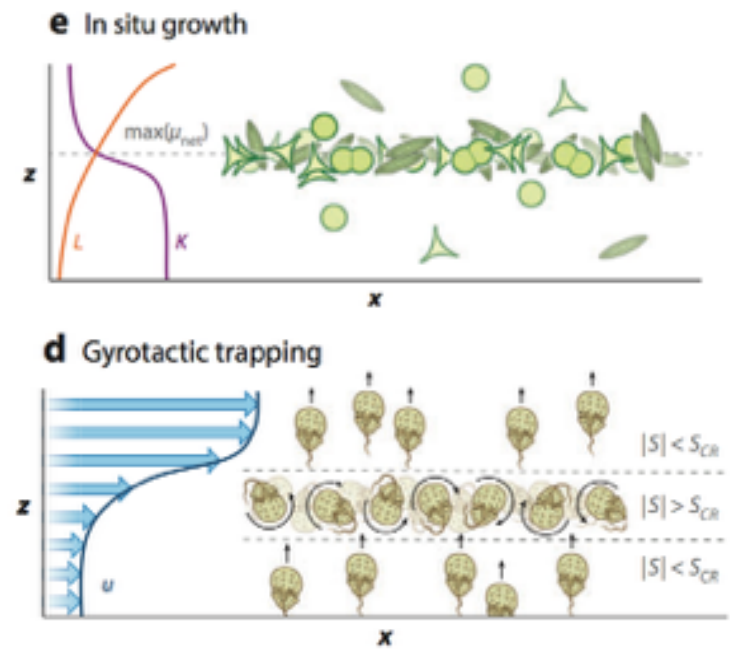
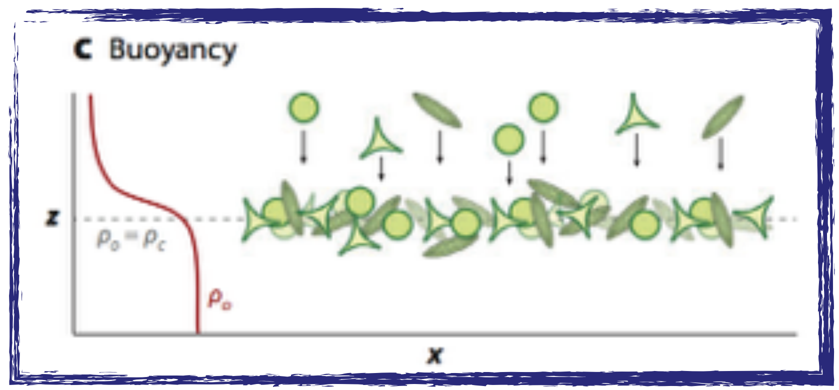
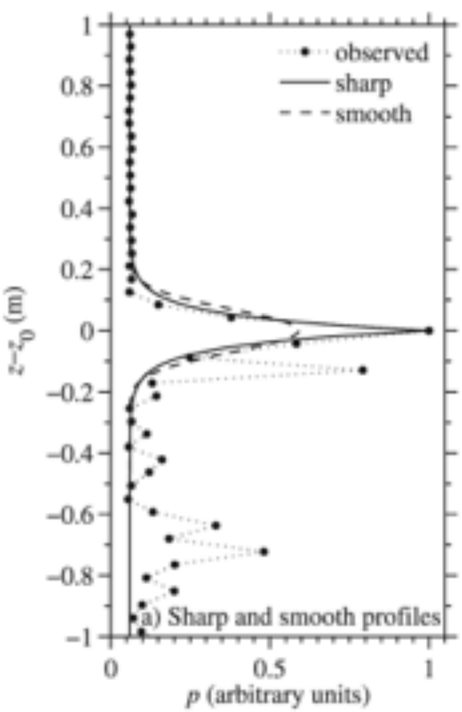


Several processes with different origin
-biological (*in-situ* growth)
-physical-biological (**gyrotactic trapping**)
-physical (**buoyancy**). ← **in this talk**

How to tell them apart?
species involved <—> mechanism
mechanism <—> expected distribution
[Birch, Young, Franks, *Limnol. Oceanogr.* **54** (2009)]



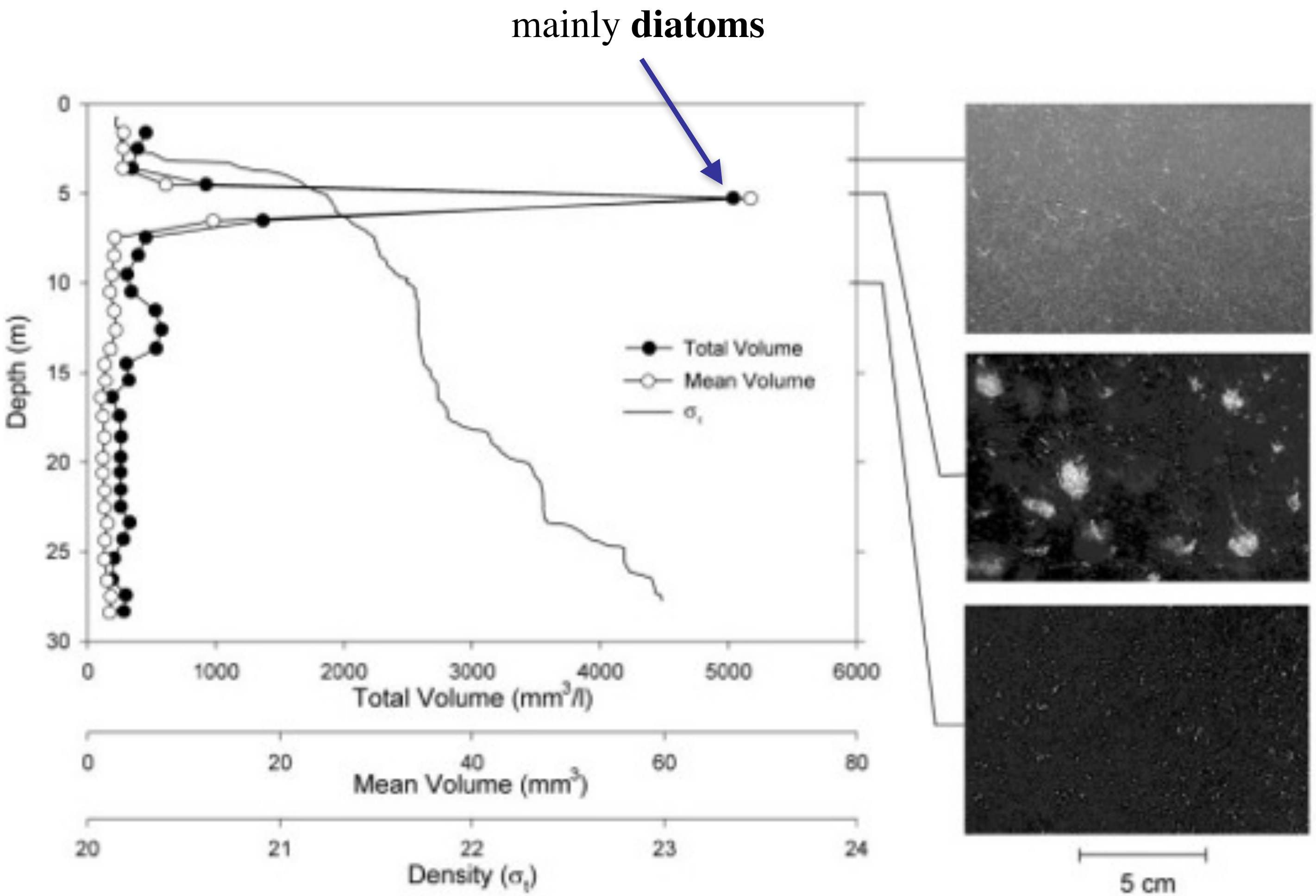


$$p_{\text{sink}}(z) = P\sqrt{\frac{\gamma}{2\pi\kappa}}\exp\left(-\frac{\gamma(z-z_0)^2}{2\kappa}\right)$$

Gaussian distribution for buoyancy driven layers

$$\gamma = \frac{R^2 N^2}{18\nu}$$

Buoyancy + stratification: layers of non-swimmers



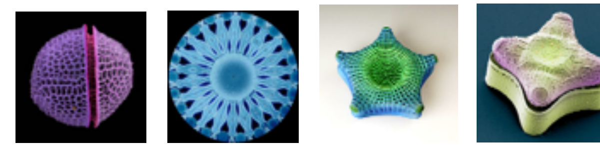
Alice L. Alldredge et al.,
Occurrence and mechanisms
of formation of a dramatic thin
layer of marine snow.
Mar. Ecol. Prog. Ser. 233, 1 (2002)

Marine snow can form from aggregates of diatoms
Mucus formed in an upper layer with lower salinity
can make the formation neutrally buoyant at greater depth

Buoyancy + stratification: layers of non-swimmers

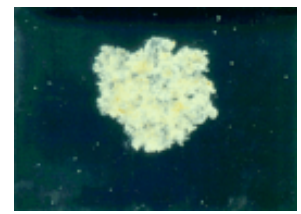
A Sozza, F D, S Musacchio and G Boffetta
arXiv:1509.03540 [physics.flu-dyn](2015)

Diatoms



~10μm

Marine snow



up to ~ 0.5÷1cm

Stratified turbulence

- Boussinesq equations: small density fluctuations
- Incompressible velocity field: $\nabla \cdot \mathbf{u} = 0$
- Linear stratification: $\rho(\mathbf{x},t) = \rho_0 - \gamma z + \gamma\theta(\mathbf{x},t)$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\frac{1}{\rho_0}\nabla p + \nu\nabla^2\mathbf{u} - N^2\theta\hat{\mathbf{z}} + \mathbf{f}$$

$$\frac{\partial \theta}{\partial t} + \mathbf{u}\cdot\nabla\theta = \mathbf{u}\cdot\hat{\mathbf{z}} + \kappa\nabla^2\theta$$

$N = (\gamma g/\rho_0)^{1/2}$ Brunt-Väisälä frequency

Floating cells

Velocity **v** of a small particle transported by the velocity field **u**(**x**,t)
(M.R. Maxey, J.J. Riley, *Phys. Fluids* **26**, 883 (1983))

$$\frac{d\mathbf{v}}{dt} = \beta\frac{d\mathbf{u}}{dt} - \frac{\mathbf{v}-\mathbf{u}}{\tau_p} + (1-\beta)\mathbf{g}$$

$\tau_p = a^2/(3\nu\beta)$
Stokes time

$0 \leq \beta = 3\rho/(\rho + 2\rho_p) \leq 3$

HEAVY ⟷ LIGHT

($\beta = 1$ ⇨ neutral)

Model for small floaters

$$\frac{d\mathbf{v}}{dt} = \beta\frac{d\mathbf{u}}{dt} - \frac{\mathbf{v}-\mathbf{u}}{\tau_p} + (1-\beta)\mathbf{g}$$

MR Maxey, and JJ Riley, Phys. Fluids **26**, 883 (1983)

- Species or aggregates that are **almost neutrally buoyant:** $\beta \sim 1$
- Introduce the covelocity **w=v-u** and neglect the density terms $(1-\beta)$ when not multiplied by **g** (Boussinesq approximation)

$$\frac{d\mathbf{w}}{dt} = -\frac{\mathbf{w}}{\tau_p} + (1-\beta)\mathbf{g}$$

- to the first order in the Stokes time: $\mathbf{w} = -\frac{2}{3}\tau_p N^2(z-\theta)\hat{\mathbf{z}}$

$$\frac{d\mathbf{x}}{dt} = \mathbf{u}(\mathbf{x},t) - \frac{1}{\tau}(z-\theta(\mathbf{x},t))\hat{\mathbf{z}}$$

relaxation time

$$\tau = 3/(2\tau_p N^2)$$

relaxation parameter

$$R = \frac{\tau}{\tau_\eta}$$

- Elastic relaxation towards the **isopycnal surface** $h(x,y,t)$ defined by $z-\theta(\mathbf{x},t)=0$, h=z, or $h(x,y)-\theta(x,y,h)=0$

- the Stokes time no longer appears explicitly

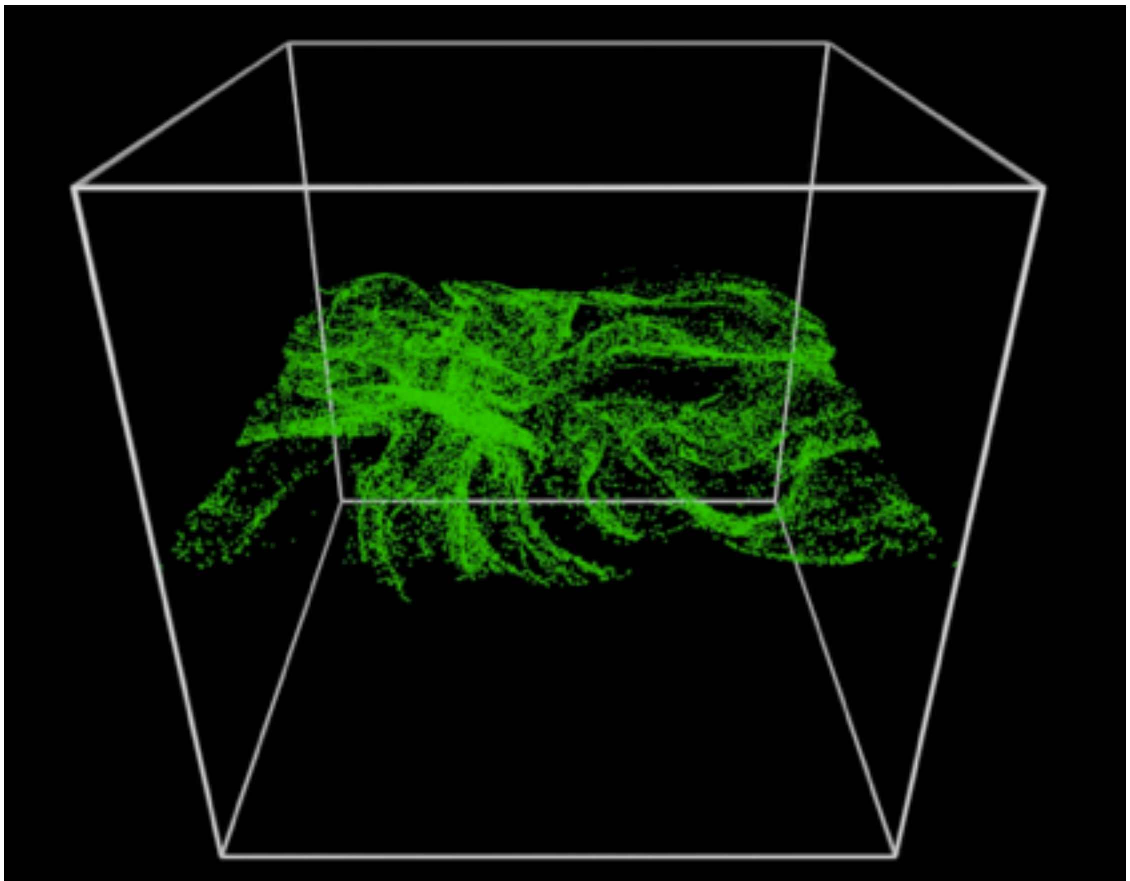
In the absence of density fluctuations, $\theta = 0$, particles simply relax to the plane z=0 (see M. De Pietro et al, Phys. *Rev. E* **91**, 053002 (2015) and Perlekar, Benzi, Nelson and Toschi PRL105,144501 (2010))

Numerical simulations

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\frac{1}{\rho_0}\nabla p + \nu\nabla^2\mathbf{u} - N^2\theta\hat{\mathbf{z}} + \mathbf{f}$$

$$\frac{\partial \theta}{\partial t} + \mathbf{u}\cdot\nabla\theta = \mathbf{u}\cdot\hat{\mathbf{z}} + \kappa\nabla^2\theta$$

$$\frac{d\mathbf{x}}{dt} = \mathbf{u} - \frac{1}{\tau}(z-\theta)\hat{\mathbf{z}}$$



Two dimensionless parameters

$$Fr = \frac{1}{TN} = \frac{\varepsilon^{1/3}L^{-2/3}}{N}$$

$$R = \frac{\tau}{\tau_\eta}$$

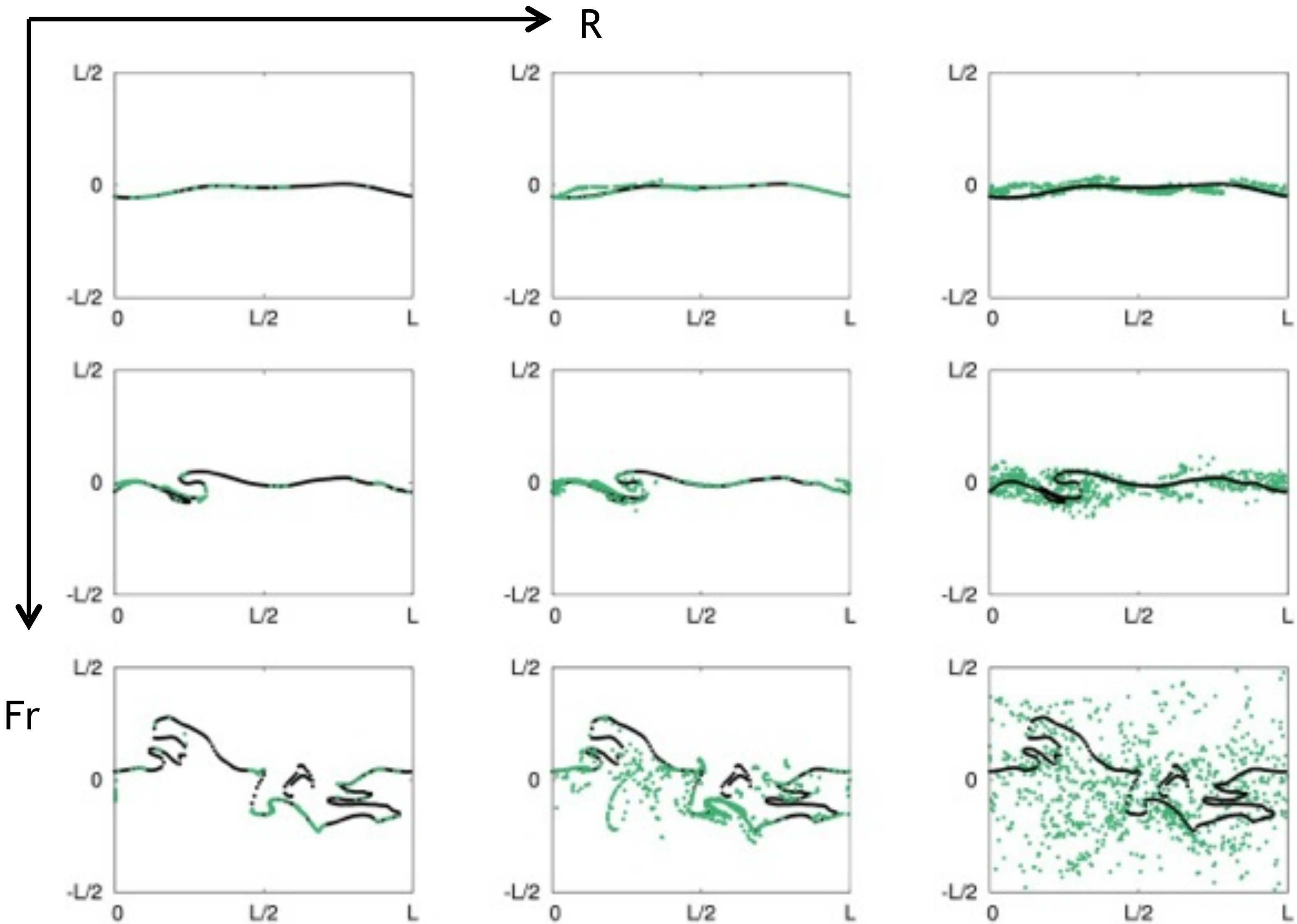
Resolution: 128^3,256^3

Exploration of parameter space

Fr = 0.2, 0.25, 0.3, 0.4, 0.6, 0.8, 1.0
R = 0.3, 0.6, 1.2, 3.0 6.0, 12, 30, 60

Vertical sections

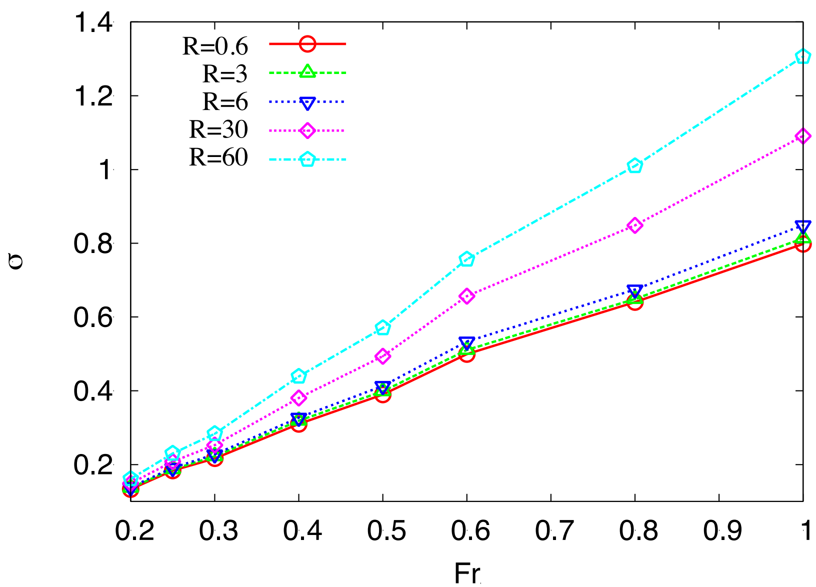
Black lines: the equilibrium surfaces $h(x,y) - \theta(x,y,h) = 0$
Green dots: particles



Vertical confinement

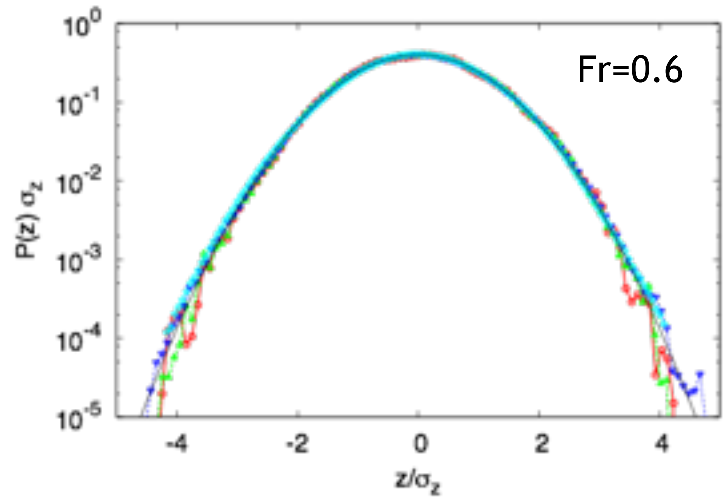
Gaussian (absolute) distribution of floaters
Variance grows (linearly) with Fr and is weakly dependent on R

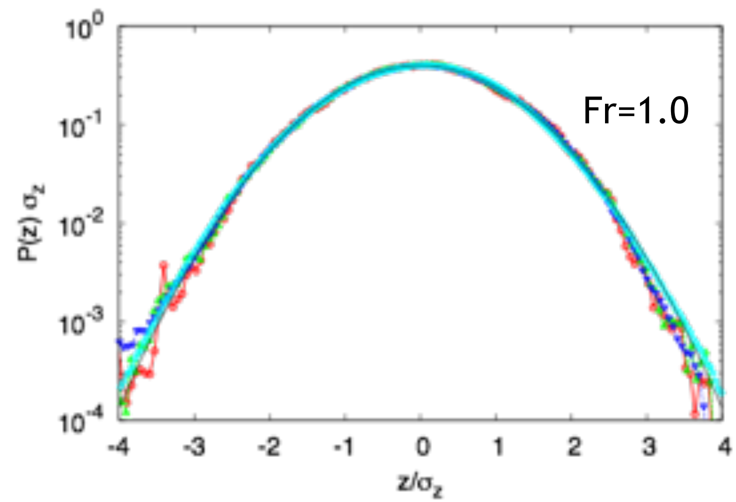
Variance of floater distributions



Consistent with Birch *et al* prediction

Vertical distribution of floaters





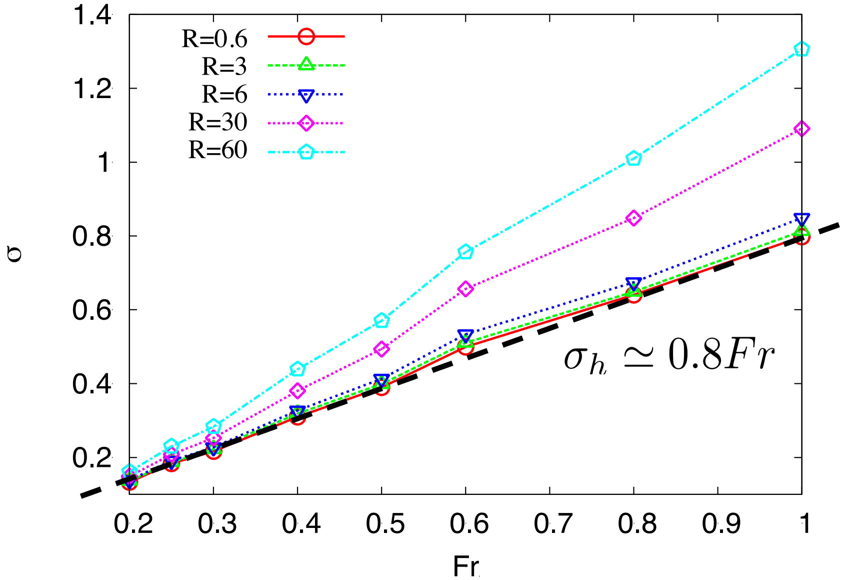
compared with a ***Gaussian***

The vertical size of the thin layer depends weakly on the species

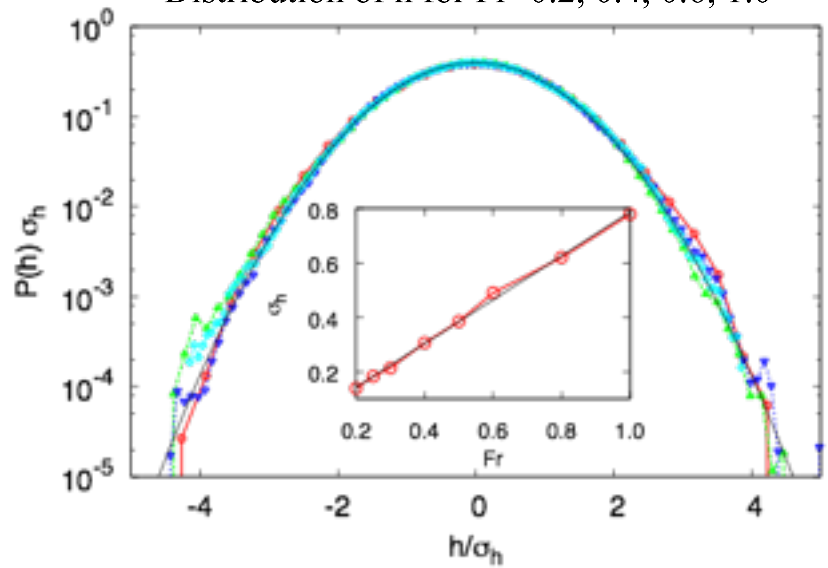
Depth of the isopycnal

For small R, floaters follow very closely the isopycnal surface

Variance of floater distributions



Distribution of h for Fr=0.2, 0.4, 0.6, 1.0



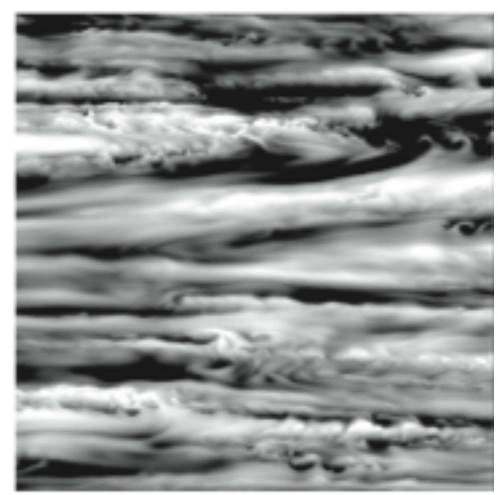
Why Linear?

In stratified turbulence, buoyancy introduces a characteristic vertical scale which is the scale needed for converting kinetic into potential energy

$$L_B \simeq U/N \propto Fr$$

L_B is the correlation scale of vertical velocity which determines the amplitude of iso-density surfaces.

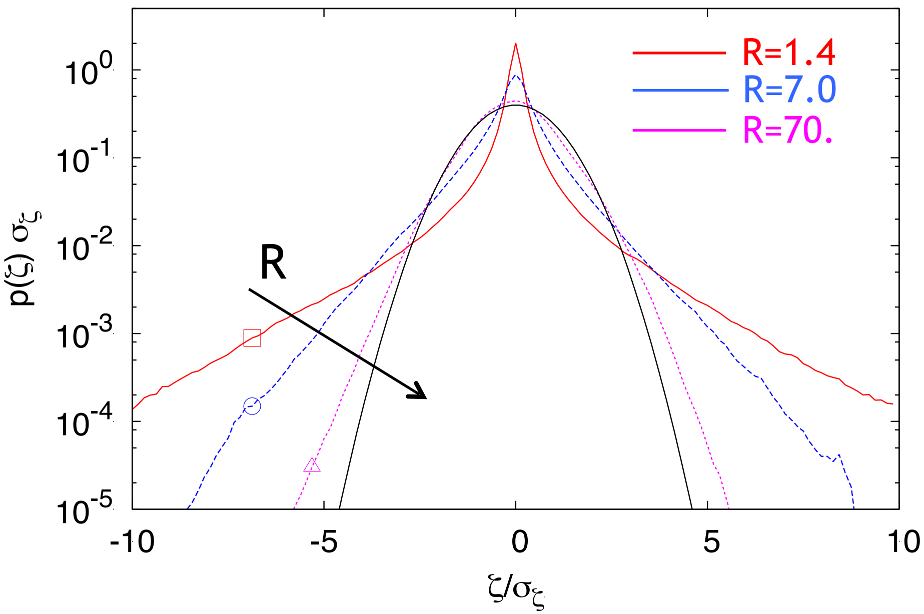
P. Billant, J.M. Chomaz, *Phys Fluids* **13** 1645 (2001)



Simulations of stratified turbulence by
C. Rorai, P.D. Mininni, A. Poquet, *PRE* **89** 043002 (2014)

Distance from the isopycnal

Vertical distance of floaters from the isopycnal surface: $\zeta = z - \theta(\mathbf{x}, t)$



Even if the depth of the particles is Gaussian overall, the **distance from the pycnocline** is not!

$$\frac{d\mathbf{x}}{dt} = \mathbf{u}(\mathbf{x}, t) - \frac{1}{\tau}(z - \theta(\mathbf{x}, t))\hat{\mathbf{z}}$$

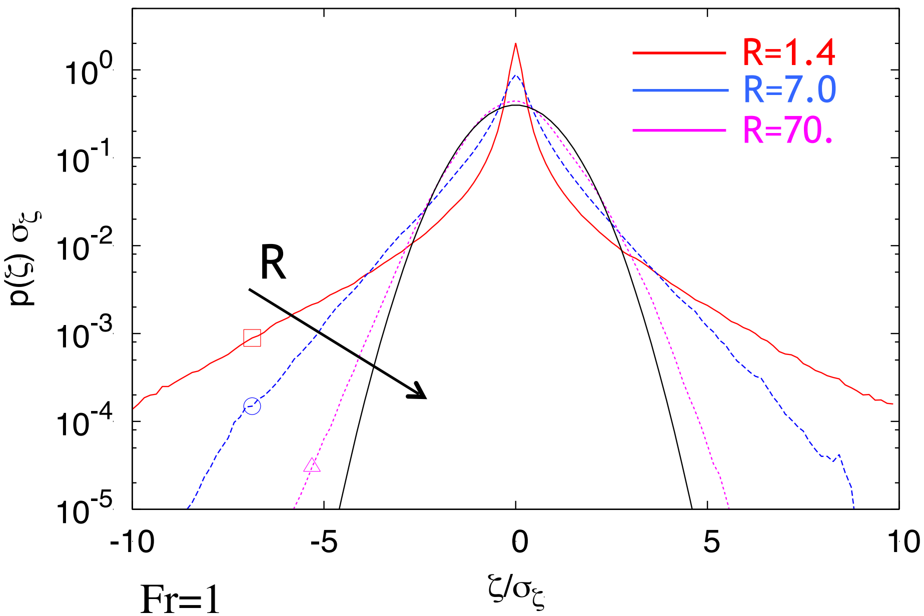
$$\frac{\partial \theta}{\partial t} + \mathbf{u} \cdot \nabla \theta = \mathbf{u} \cdot \hat{\mathbf{z}} + \kappa \nabla^2 \theta$$

$$\frac{d\zeta}{dt} = \frac{dz}{dt} - \frac{\partial \theta}{\partial t} - \frac{d\mathbf{x}}{dt} \cdot \nabla \theta$$

$$\frac{d\zeta}{dt} = -\zeta \left(1 - \frac{\partial \theta}{\partial z}\right) \frac{1}{\tau} + \kappa \nabla^2 \theta$$

Distance from the isopycnal

Vertical distance of floaters from the isopycnal surface: $\zeta = z - \theta(\mathbf{x}, t)$

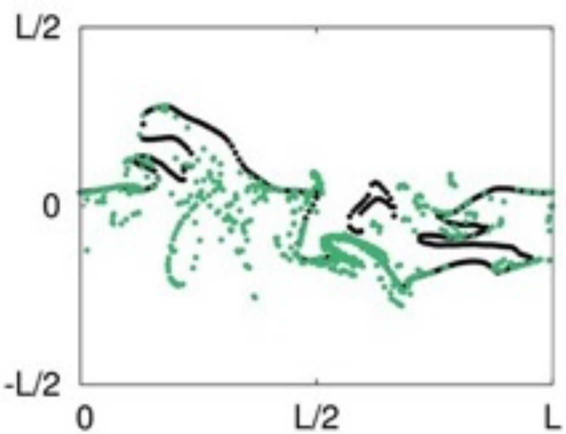


Fr=1

Wile E. Coyote effect

$$\frac{d\zeta}{dt} = -\zeta\left(1 - \frac{\partial\theta}{\partial z}\right)\frac{1}{\tau}$$

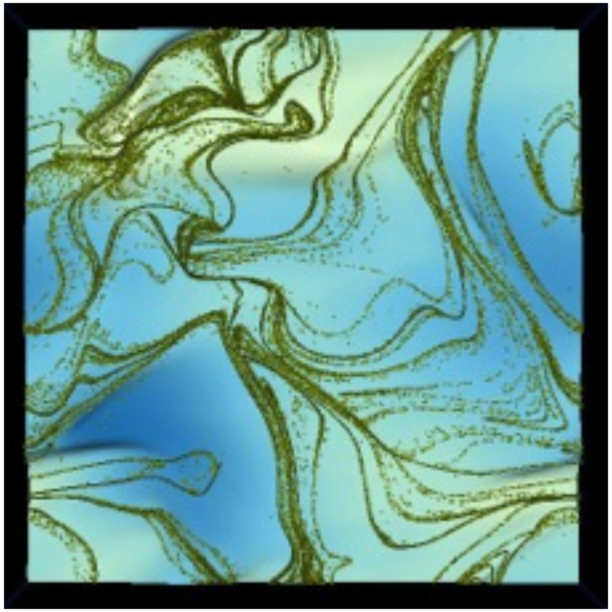
Large fluctuations of ζ are due to the folding of the isopycnal surface.
At a fold the stratification is inverted
$z - \theta$ grows exponentially for a time τ before the particle feels the new surface.



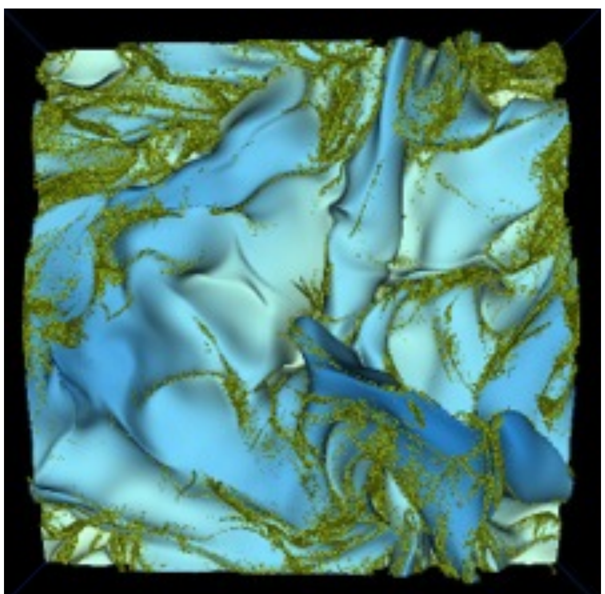
Fractal small scale clustering

$$\mathbf{v} = \mathbf{u} - \frac{1}{\tau}(z-\theta)\hat{\mathbf{z}} \qquad \nabla \cdot \mathbf{v} = -\frac{1}{\tau}\left(1 - \frac{\partial \theta}{\partial z}\right)$$

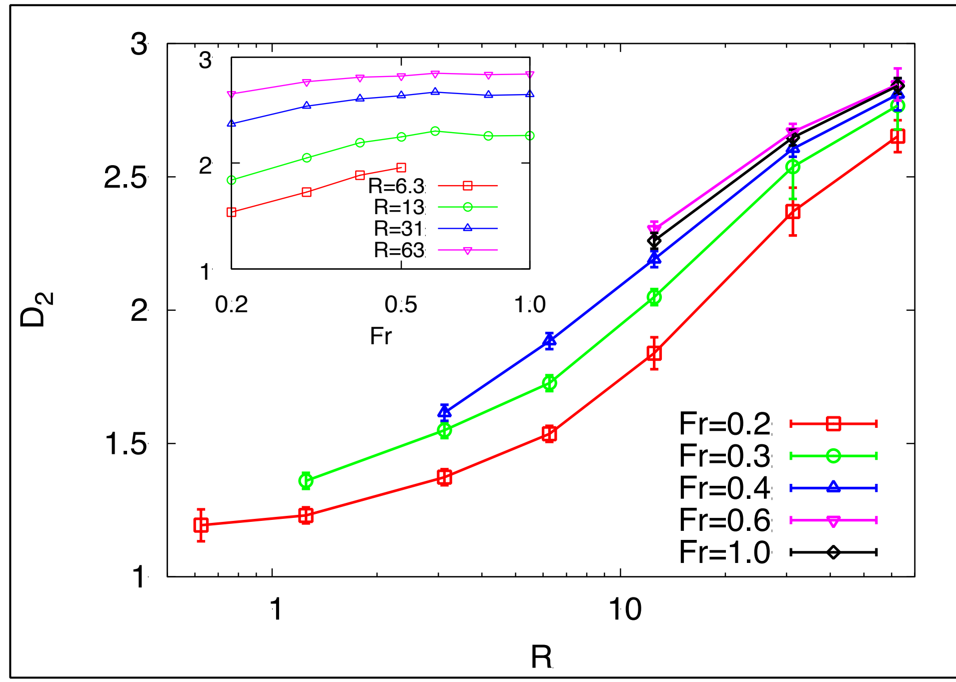
Floaters are transported by a compressible velocity field:
distribution on a fractal set



Fr=0.2
R=0.6



Fr=0.6
R=1.2



$$R = 3/(2\tau_\eta \tau_p N^2)$$

Small scale patchiness:
- mainly controlled by the **particle relaxation time**
- depends **weakly on the stratification**

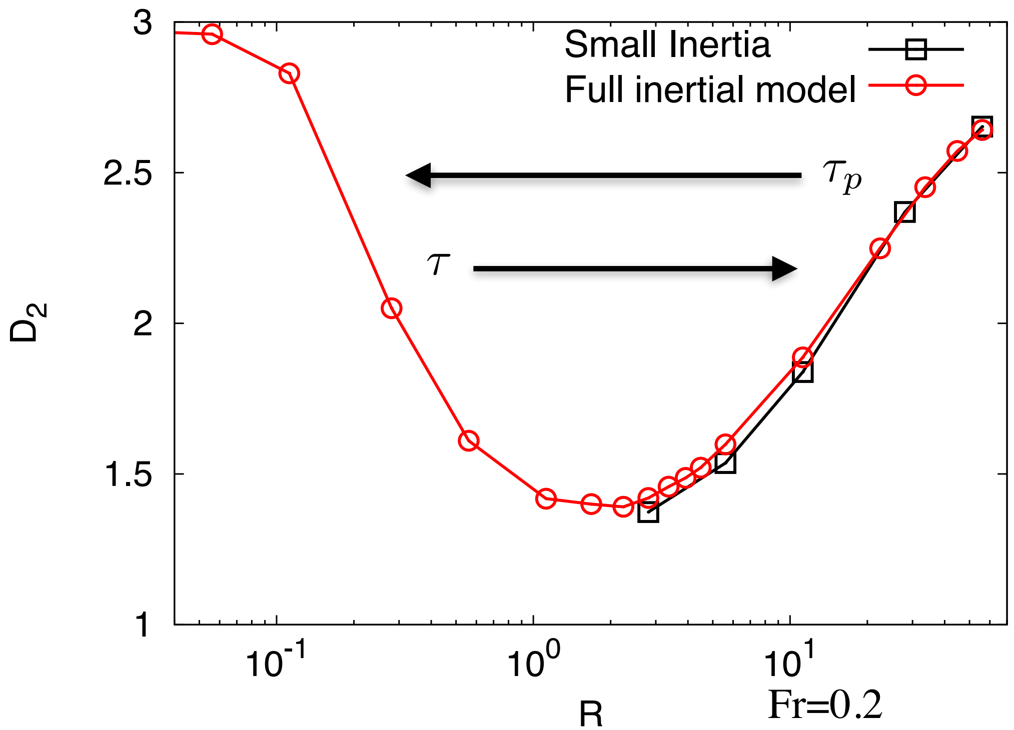
Small scale clustering: small R

The model we considered so far is valid only for small τ_p — large R

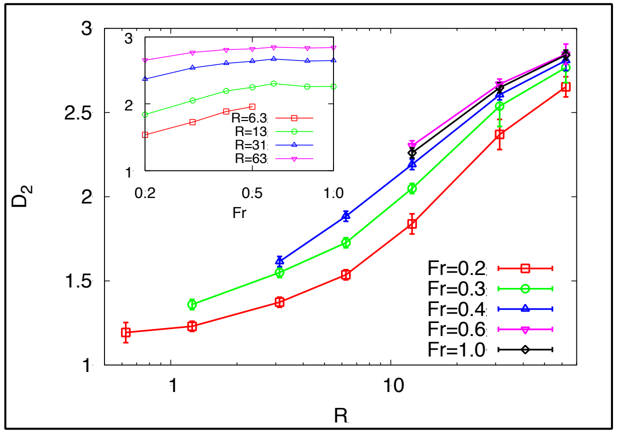
$$\frac{d\mathbf{x}}{dt} = \mathbf{u}(\mathbf{x},t) - \frac{1}{\tau}(z - \theta(\mathbf{x},t))\hat{\mathbf{z}}$$ Small τ_p

$$R > \mathrm{Re}_b \sim \mathrm{Fr}^2\mathrm{Re}$$

$$\frac{d\mathbf{w}}{dt} = -\frac{\mathbf{w}}{\tau_p} + (1-\beta)\mathbf{g}\,,$$ $\mathbf{w}$=$\mathbf{v}$-$\mathbf{u}$ Any τ_p



Fr=0.2



For small Fr the reduced model is accurate down to maximum clustering

An example: aggregates and marine snow

Aggregates of size a ≈ 0.5 cm
in the pycnocline with

$$\eta \sim 3 \times 10^{-3}\mathrm{m}$$

$$\varepsilon \simeq 10^{-8}\, m^2\, s^{-3}$$

$$\tau_\eta \simeq 10\, s$$

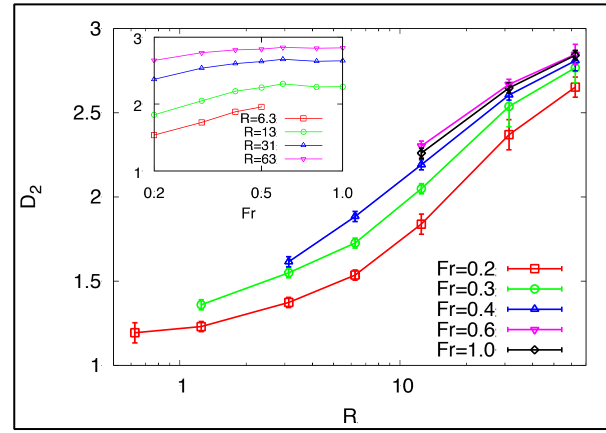
$$\nu \simeq 10^{-6}\, m^2\, s^{-1}$$

$$N \simeq 0.1\, s^{-1}$$

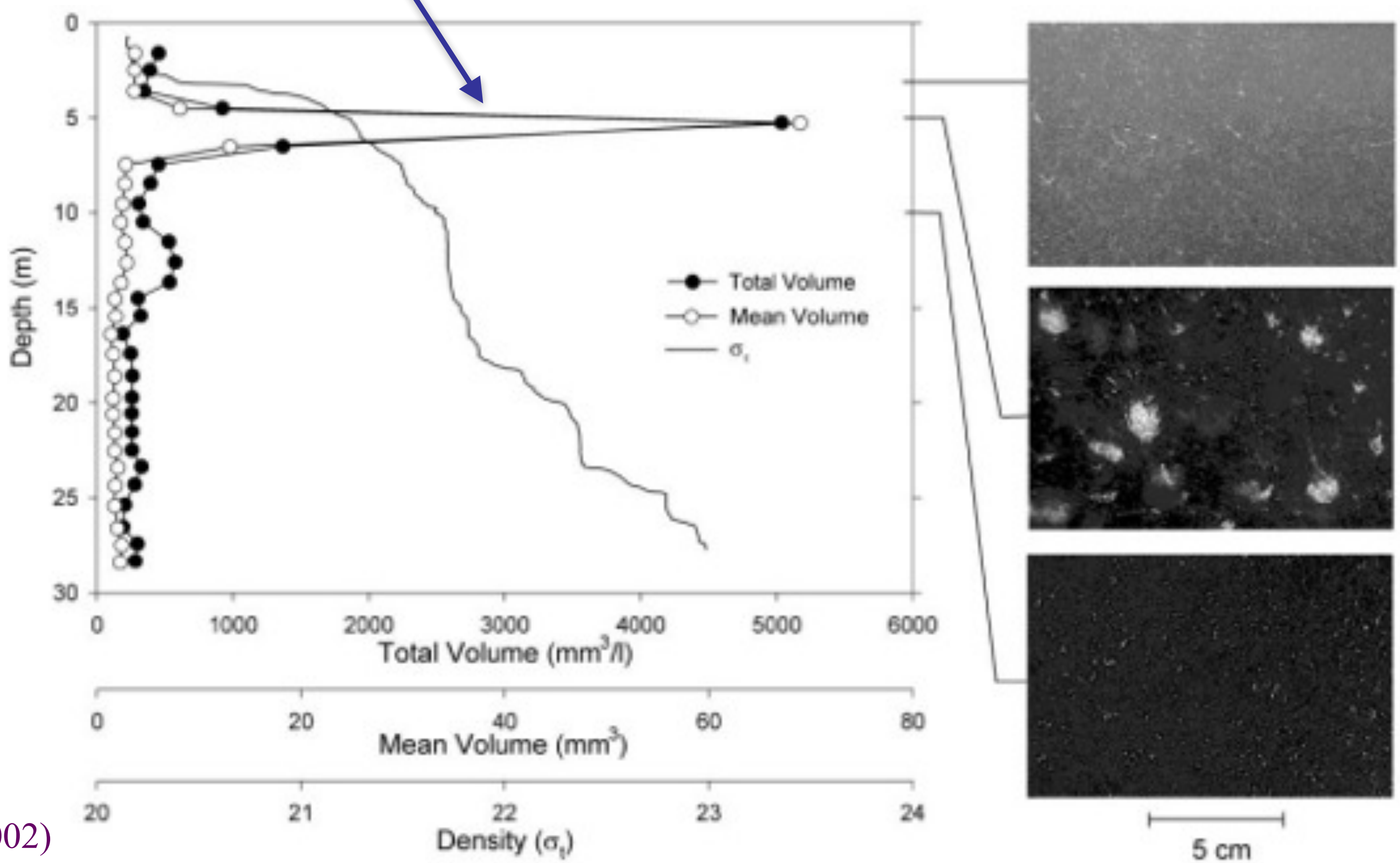
$$\tau \simeq 18\, s \quad R \simeq 1.8$$

$$D_2 \simeq 1.2$$

strong clusterization



mainly **diatoms**



Alice L. Alldredge et al.,
Occurrence and mechanisms
of formation of a dramatic thin
layer of marine snow.
Mar. Ecol. Prog. Ser. 233, 1 (2002)

Conclusions

- Both swimming and non-swimming organisms form thin layers
- For non-swimmers (e.g. diatoms) buoyancy can produce layering
- gaussian distribution of depths

  non-gaussian distances from the pycnocline

  thickness depends mainly on stratification

  intense, fractal clustering **within** the layer; depends mainly on R

Large-scale confinement and small-scale clustering of floating particles in stratified turbulence
A. Sozza *et al.*, arXiv:1509.03540 [physics.flu-dyn](2015)