Role of Hydrodynamics in Bioconvection

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∂'Alembert - Sorbonne Université - Paris - France

BGUM - Oxford - July 2025

comic adapted from xkcd.com

Thermal-Convection

Passive fluid: external energy supply

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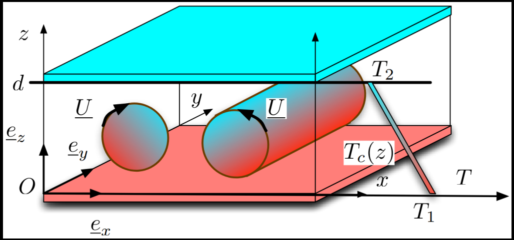

Buoyancy-Driven ($T \propto \rho$)

i.e.: *Rayleigh-Bénard*

Boussinesq 1903, Thuval 2020

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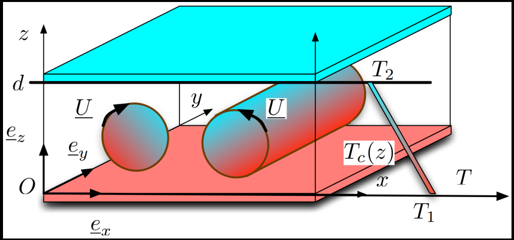

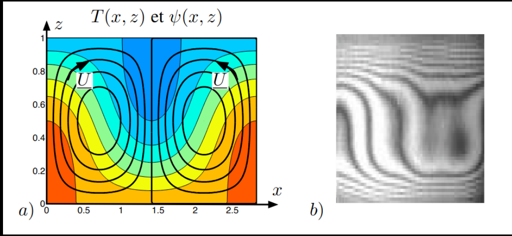

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Thermal-Convection

Passive fluid: external energy supply

All the spaghetti was eaten

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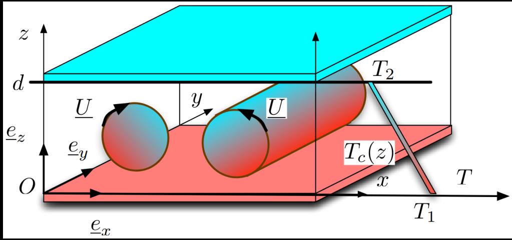

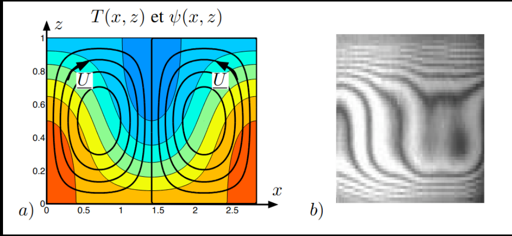

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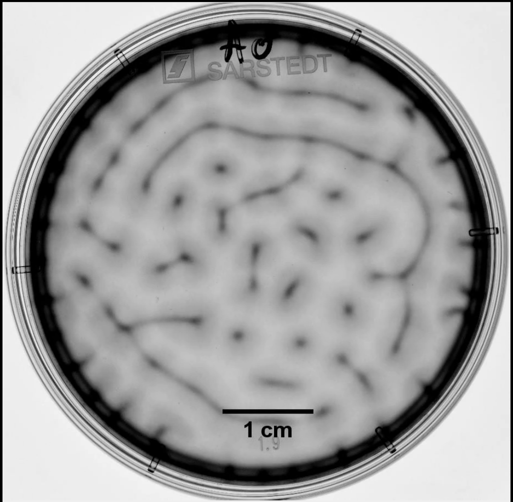
Bio-convection

Active fluid: a colony of *Chlamydomonas Reinhardtii* (CR)



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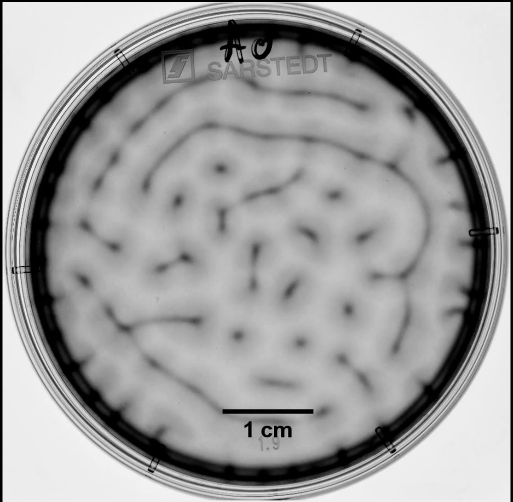

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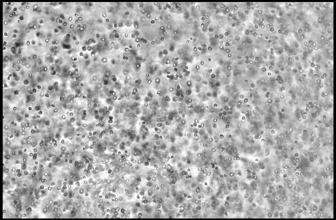

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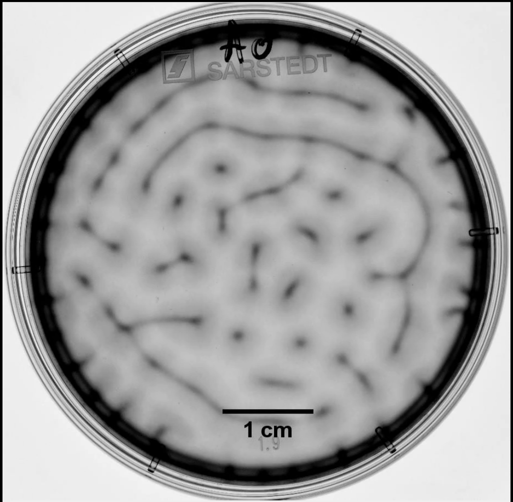

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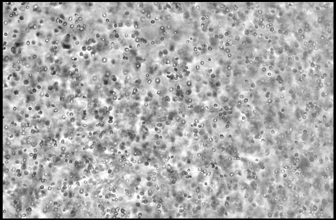

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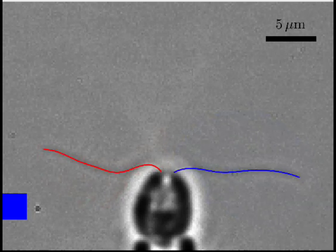
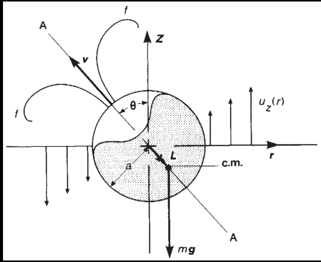


Leptos *et al.* 2013, real time.

Bio-convection, triggering mechanisms*

(*) Present state-of-the-art

1. CR reorients towards gravity (*gravitaxis, bottom-heavy*)



Kessler 1985

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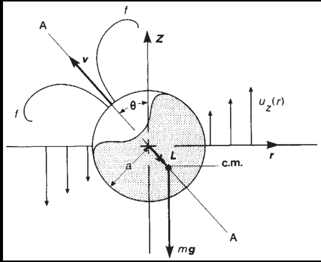

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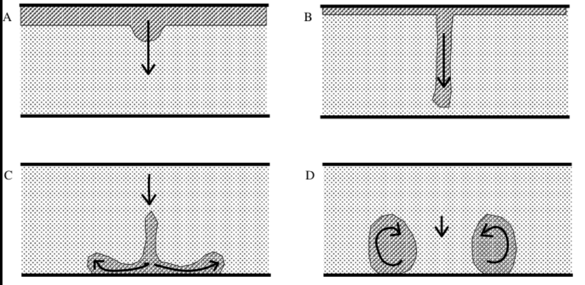

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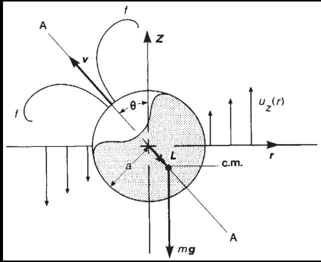

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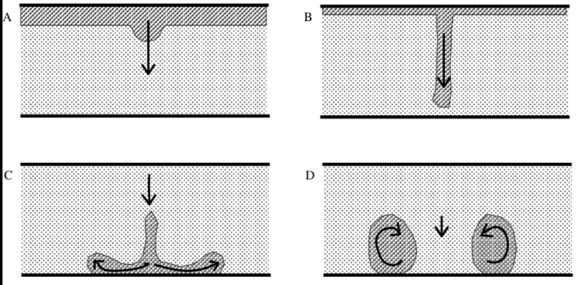

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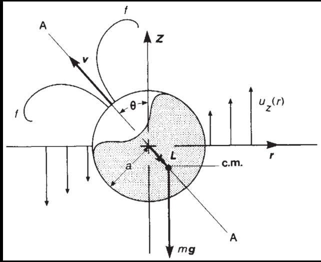
4. **Plumes** impact the bottom, recirculation and rise of convection pattern.



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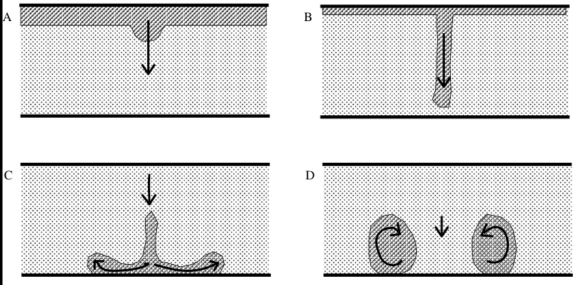

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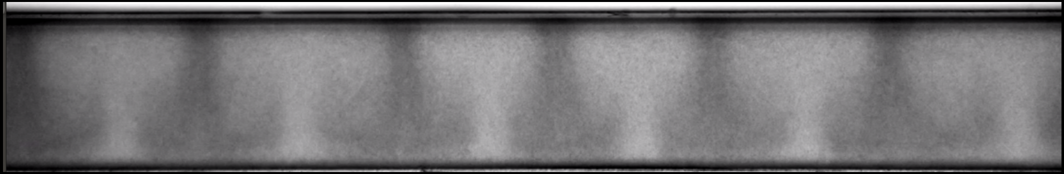
Experiments Are plumes *really* triggered by the *dense layer*?

Dark spots (cell concentration) first occurring **far** from the dense layer?



Side view. Height $= 1mm$, $\Delta t = 2s$, 10fps. **Experiment by H. de Maleprade.**

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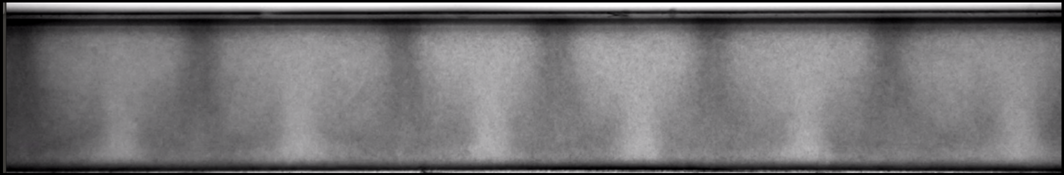

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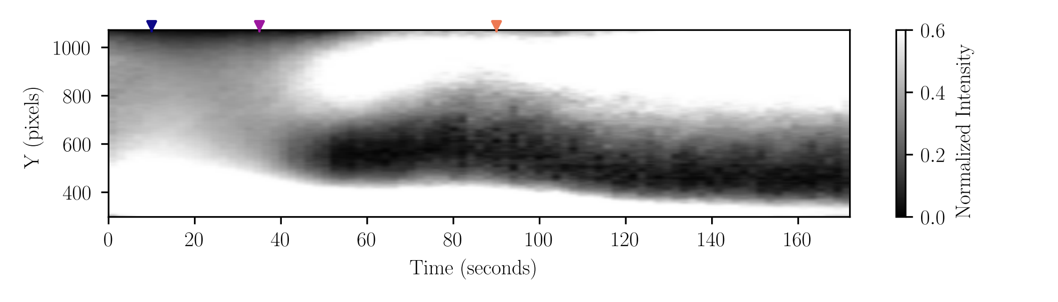

Spanwise-averaged intensity. Simultaneous dense layers forming at top and bulk

Modelling bio-convection: a **microswimmer**-driven flow

Agent-resolved, $Re \ll 1$

- **Fluid-Solid coupling**: $\nabla \cdot \mathbf{u} = 0, \ \nabla^2 \mathbf{u} = \nabla p$

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  - *meshless* methods (e.g. **Stokesian Dynamics**, Ishikawa 2020, ...)

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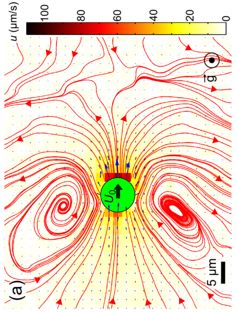
  - *meshed* methods (e.g. **Fluid Particle**, Jibuti Rafai Peyla 2014, ...)

Modelling flagellate microswimmers



Time-averaged flow field around a biflagellate. Drescher *et al.* 2010.

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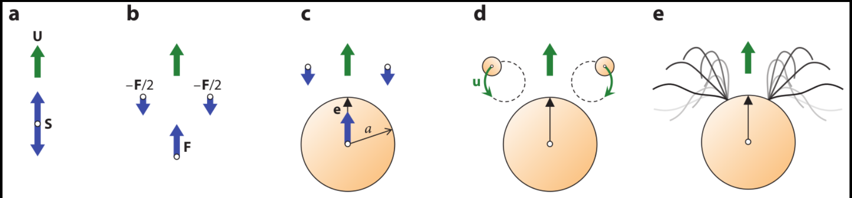
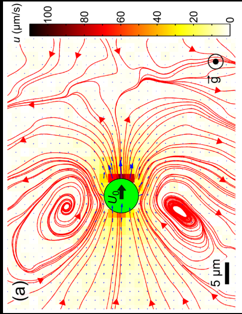


(a) Lushi & Peskin 2012, (b) Drescher *et al.* 2010, (c) Jibuti *et al.* 2014, (d) Wan *et al.* 2019, Friedrich & Julicher 2012. From Ishikawa 2024.



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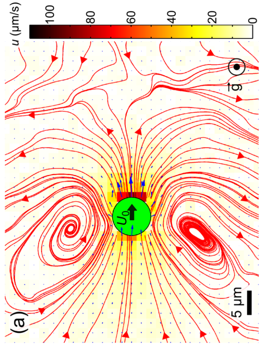
Introducing the tHree model



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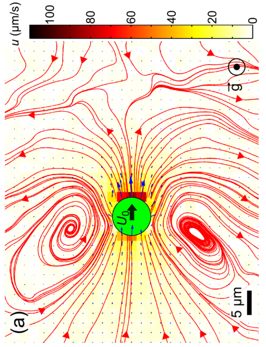

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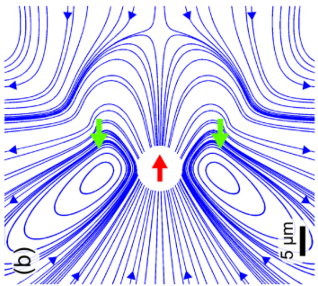
Three *point-forces*



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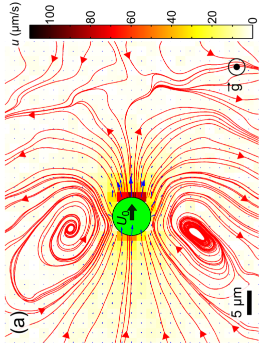

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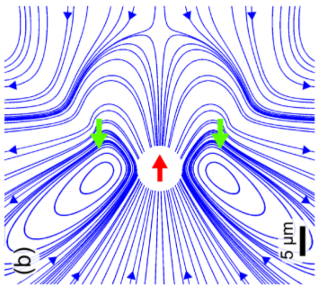

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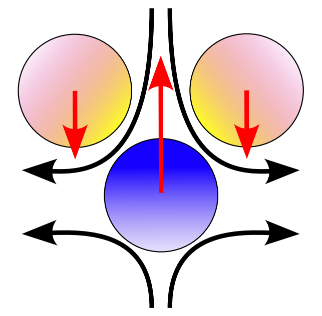
3 *forces* + 3 *bodies*



tHree model of a biflagellate puller.

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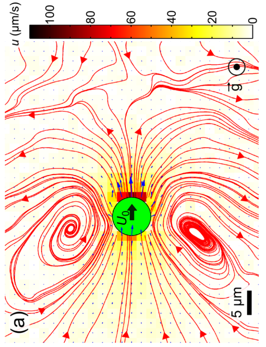

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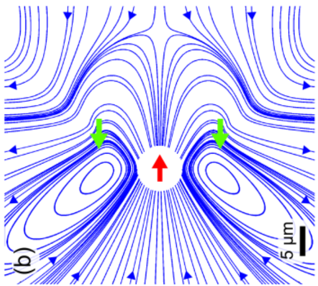

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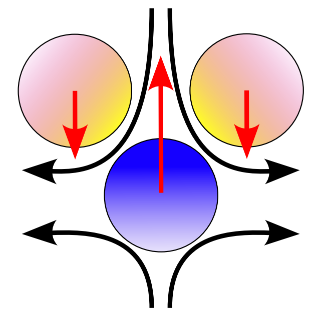

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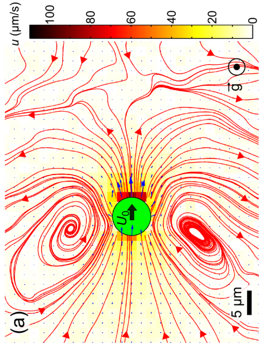

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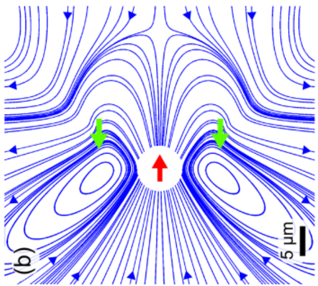

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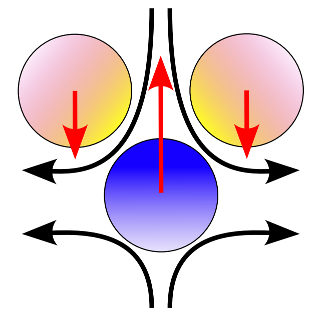

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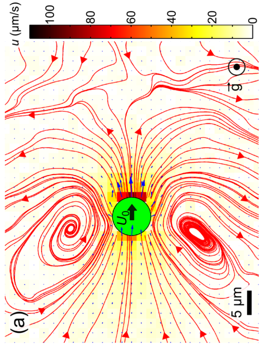
- Same physical **model**, **compatible** with **multiple** resolution **methods/scales**



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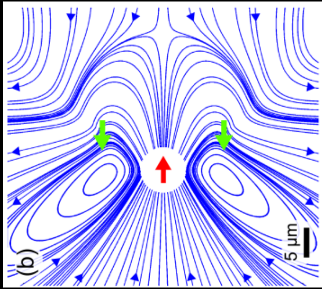

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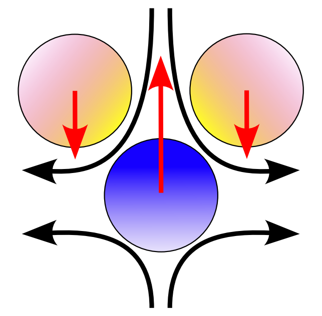


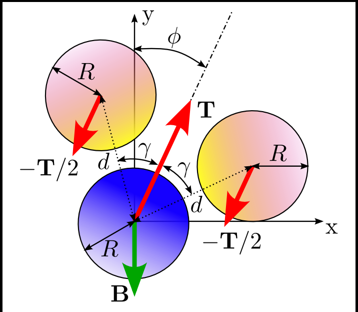
tHree model of a biflagellate puller.

Why still another model?

- Same physical **model**, **compatible** with **multiple** resolution **methods/scales**
- Access to **complex physics** (confinement, light, non-linearities...)

Characterising tHree model. Single, force free swimmer's velocity U

A. Palotai 2025 internship.



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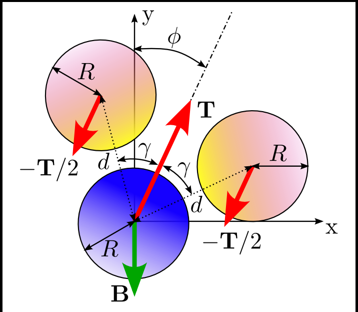

Analytical solution

$$U = \frac{F}{6\pi\mu R}\left(1 - \frac{3R\sin^2(\alpha)}{2d} - \frac{3R\cos^2(\alpha)}{4d} + \frac{R^3\sin^2(\alpha)}{2d^3} - \frac{R^3\cos^2(\alpha)}{4d^3}\right)$$

following Kim & Karilla 1991

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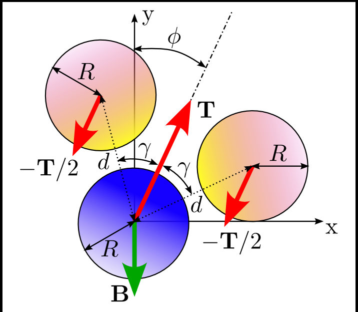

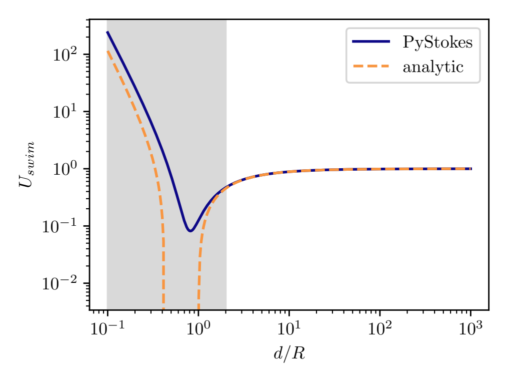

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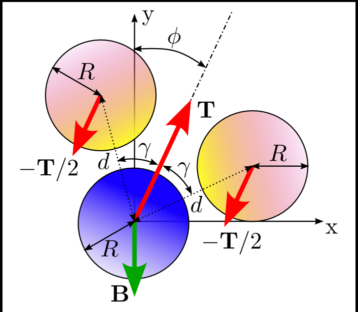

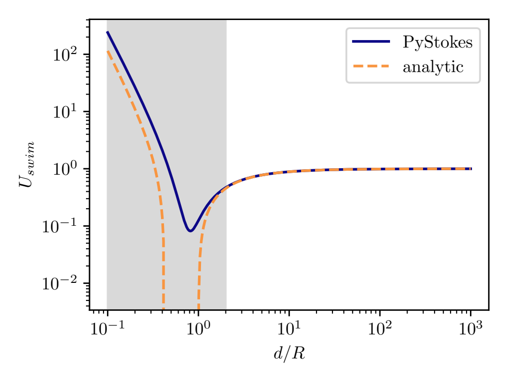

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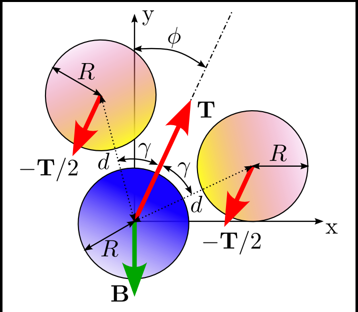

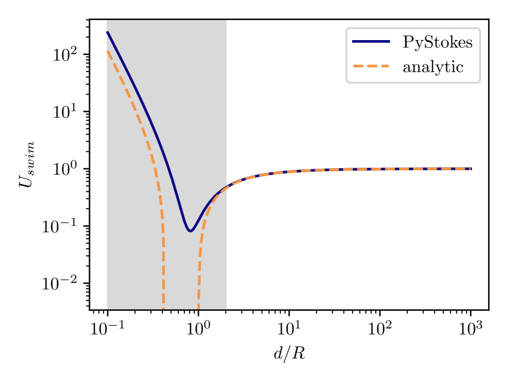

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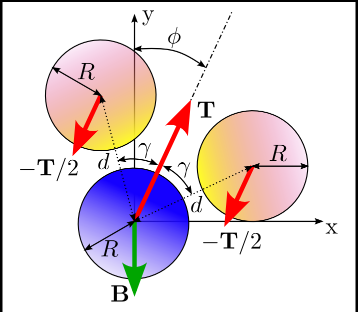

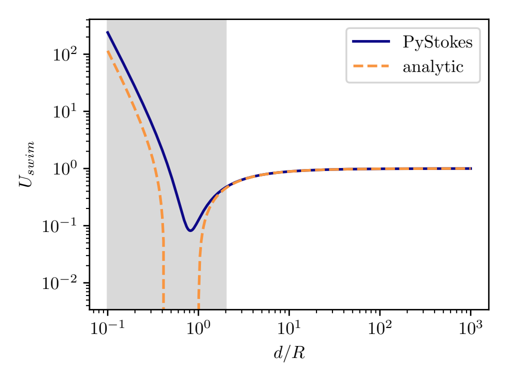

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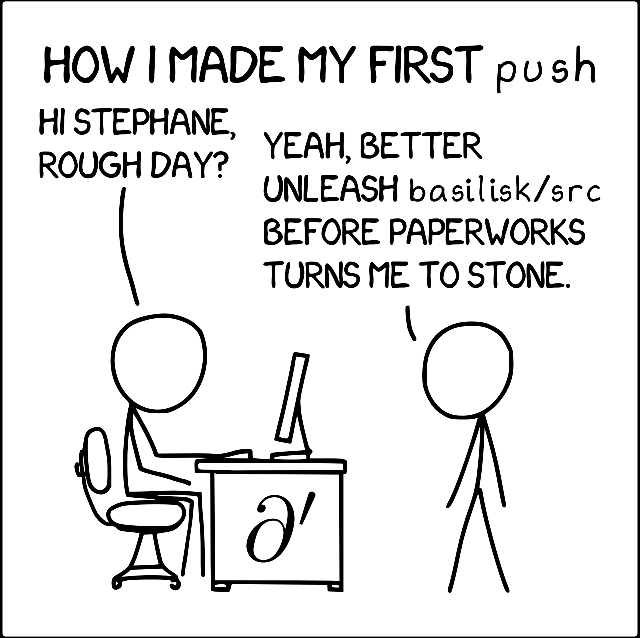
- Particle collapsing $=$ 0 thrust $=$ 0 *efficiency*



Based from real events. March 2025. Inspired by xkcd.com

Microhydrodynamics with Basilisk

A number of validation available on `sandbox/fpicella/README/...`

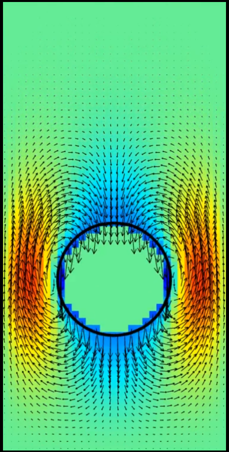
```
#include "grid/quadtree.h"
#include "ghigo/src/myembed.h"
#include "ghigo/src/mycentered.h"
  // -> myviscosity-embed.h -> mypoisson.h
#include "fpicella/src/driver-myembed-particles.h"
 // adapted from sandbox/Antoonvh/tracer-particles.h
int main () {stokes = true;}
```

Velocity BC on embed: `ghigo/src/mypoisson.h`

projection step: from $\mathbf{u}^*$ ($\nabla \cdot \mathbf{u}^* \neq 0$, no BC on embed...)

$$\nabla \cdot (\alpha \nabla p) = \frac{\nabla \cdot \mathbf{u}^* + \mathbf{u}_{embed} \cdot \mathbf{n}}{\Delta t} \quad (1)$$

$$\mathbf{u} \leftarrow \mathbf{u}^* - \Delta t \alpha \nabla p \quad (2)$$

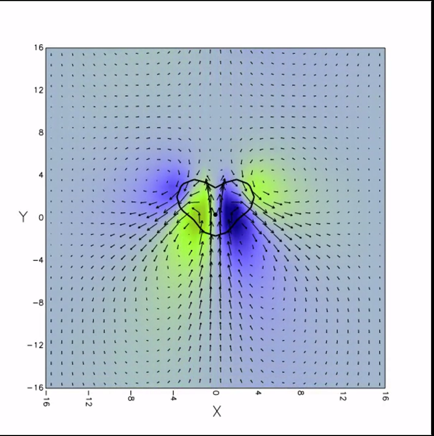


A sedimenting cylinder.
Validation: Dvinsky Popel 1987.

A general-purpose framework for the tHree model

tHree in **Basilisk**

finite volume, adaptive mesh...

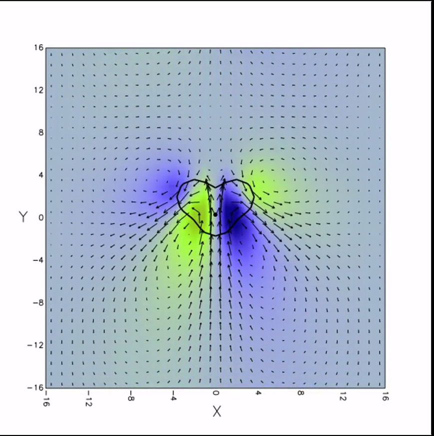


basilisk.fr/sandbox/fpicella

A general-purpose framework for the tHree model

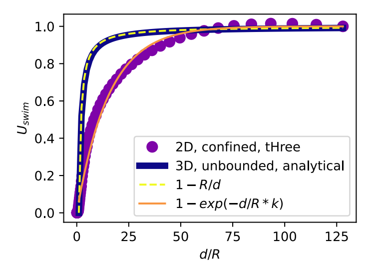
tHree in **Basilisk**

finite volume, adaptive mesh...



basilisk.fr/sandbox/fpicella

- quasi-steady Stokes solver
  `basilisk.fr/src/navier-stokes/centered.h`
- Forces: *smooth kernel* (Cortez 2001)
- Body: high-viscosity blobs (Tanaka & Araki 2000)
- Multiple-particle tracking
  `basilisk.fr/sandbox/Antoonvh/tracer-particles.h`



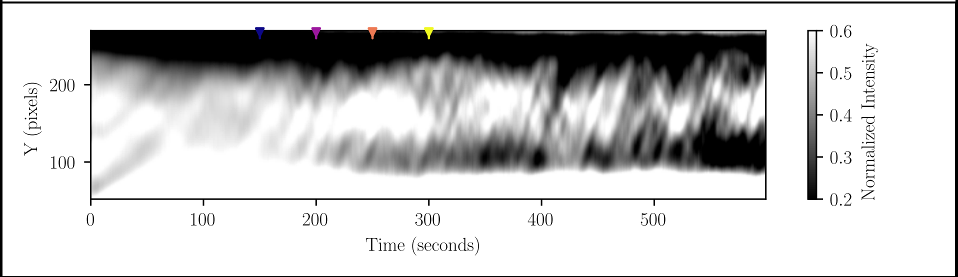
tHree swimming velocity.
2D Basilisk vs 3D analytic prediction.

Simulating bio-convection: **tHree model**

microswimmer-driven instabilities. Cell height $64 \cdot R$, cell width $512 \cdot R$, 512 tHree microswimmers.

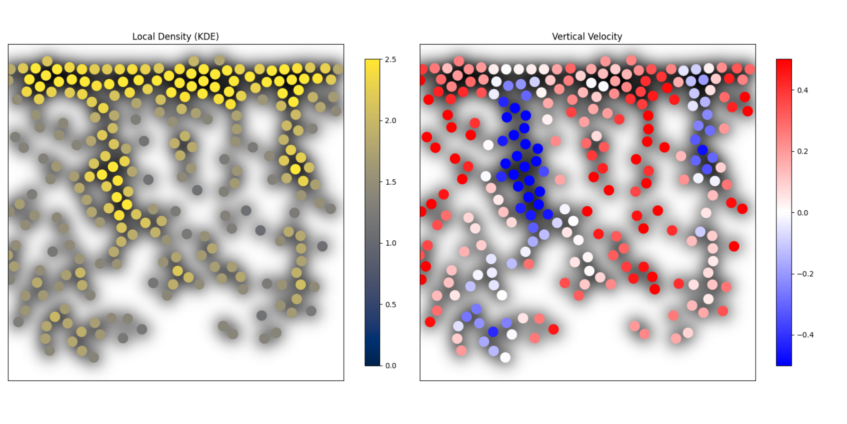
Simulating bio-convection: **tHree model**

microswimmer-driven instabilities. Cell height $64 \cdot R$, cell width $512 \cdot R$, 512 tHree microswimmers.



Spanwise-averaged intensity. Dense layers forming simultaneously at top and bulk. (statistics ok?)

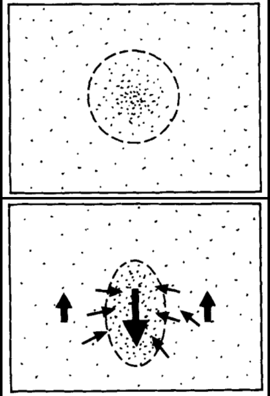
Local concentration fluctuation **triggers plumes** (?)



Before the onset of *plumes*, **local high cell concentration**:

---

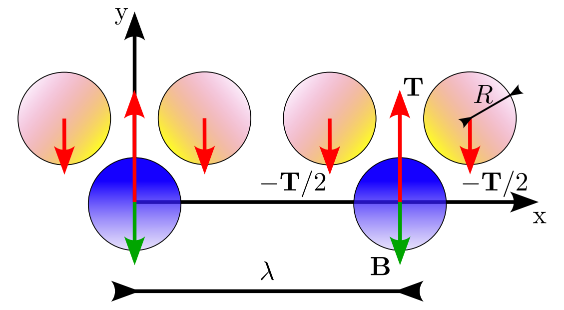
1. observed **far from free-surface** (role of microhydrodynamics!)
2. → **negative velocity**



Kessler 1985

Binary interactions

Loss of *hydrodynamic efficiency*



- $\phi = 0$, aligned, variable distance λ.
- $\mathbf{T} = [0, 4, 0]$, $\rho = \mu = 1$
- zero buoyancy $\mathbf{B} = \mathbf{0}$
- identical blob sizes
  $R = 1.$, $d = 1.$, $\beta = 1.$

Binary interactions

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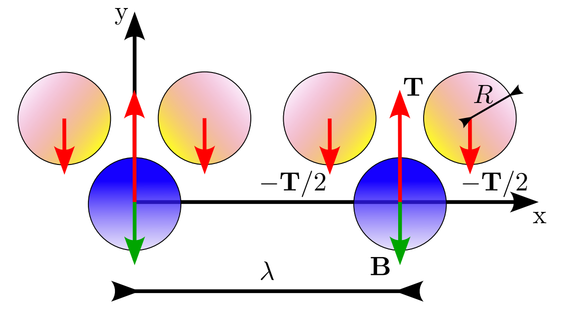

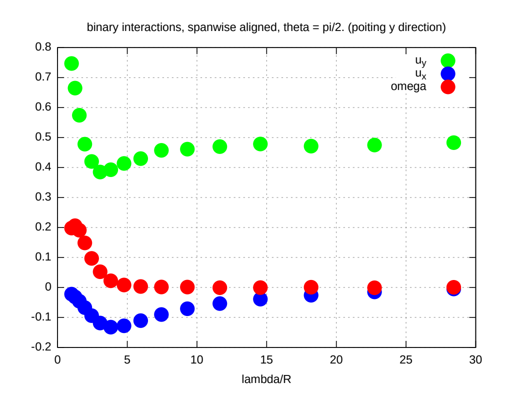

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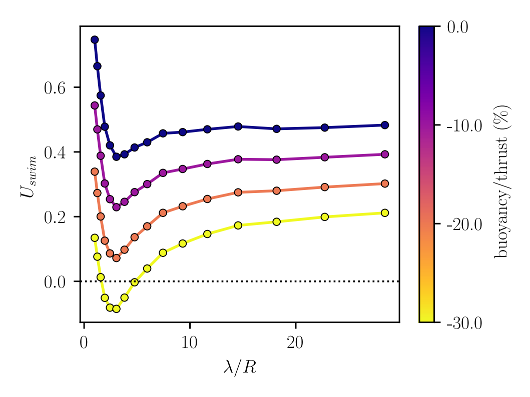
- zero buoyancy $\mathbf{B} = \mathbf{0}$
- identical blob sizes
  $R = 1., d = 1., \beta = 1.$

- below $\lambda/R = 3$, contact (unphysical)
- Repulsion (u_x) @ approach (puller)
- **Efficiency (u_y) drops @ approach**

Binary interactions + negative buoyancy

Identical to previous slide, but with **B** < 0

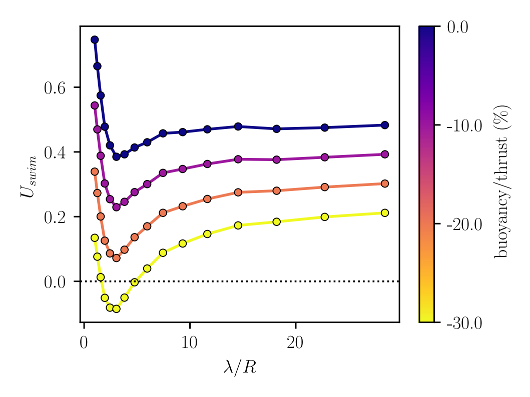


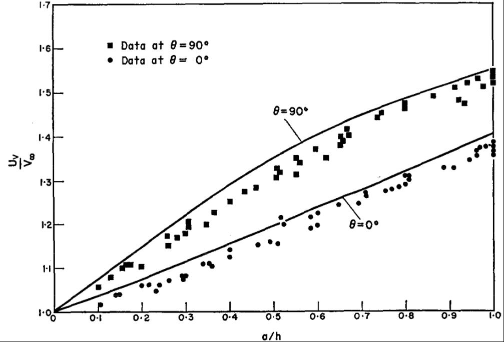
Confinement + added gravity

- decrease swimming **velocity**...
- ... up to **negative @ approach!**

Binary interactions + negative buoyancy

Identical to previous slide, but with **B** < 0





Goldman, Cox & Brenner, 1966

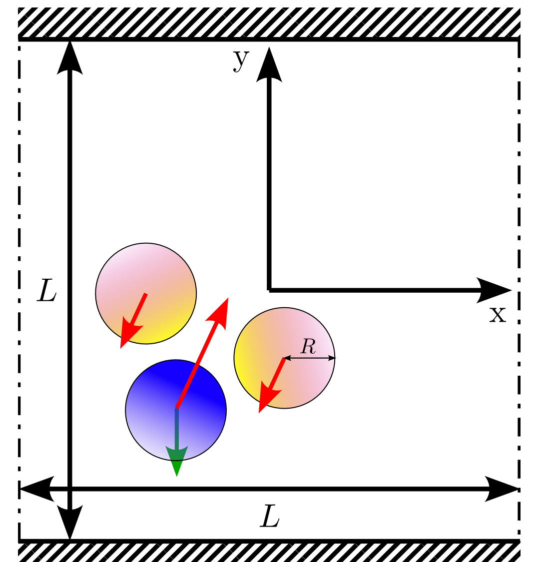
Confinement + added gravity

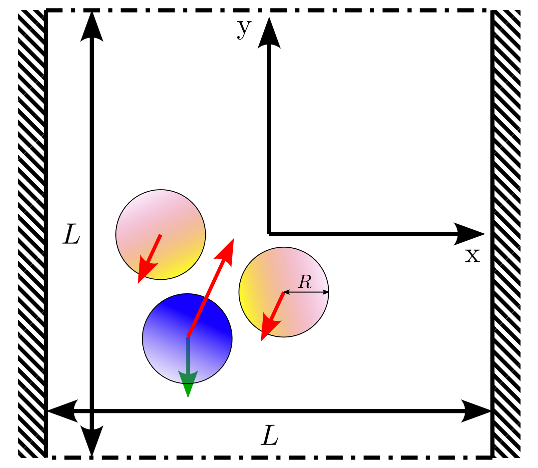
- decrease swimming **velocity**...
- ... up to **negative @ approach!**

- Purely sedimenting particles
- $a/h = \frac{1}{\lambda/R}$
- As particle approaches (right), increse in sedimentation speed!

Plumes without a free-surface

Single Swimmer

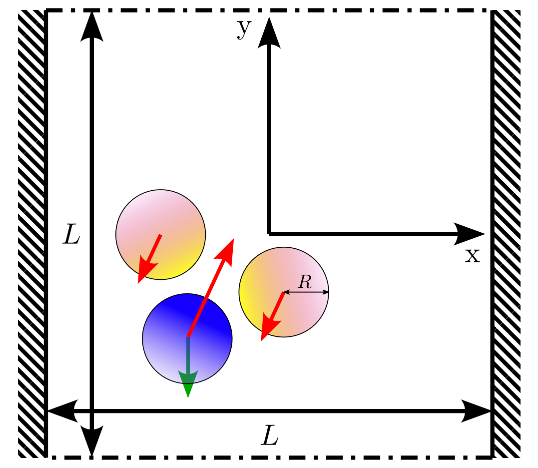




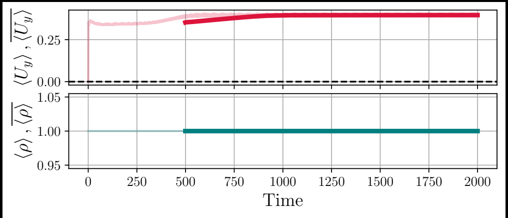
"infinitely tall vertical pipe"

Plumes without a free-surface

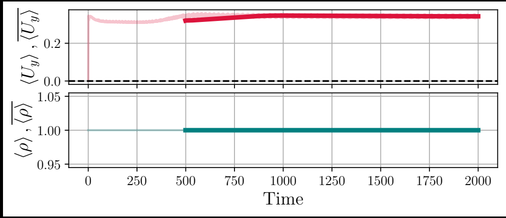
Single Swimmer



"infinitely tall vertical pipe"



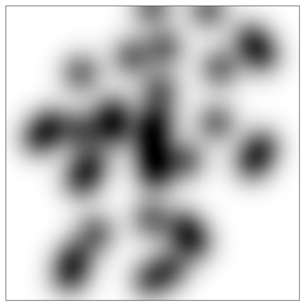
$|\mathbf{B}| = |\mathbf{T}| \cdot 0.0\%$

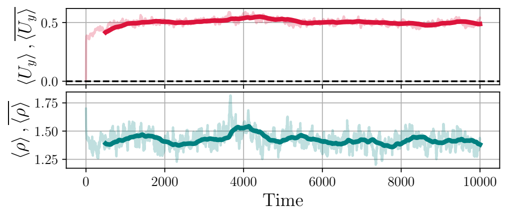


$|\mathbf{B}| = |\mathbf{T}| \cdot 2.5\%$

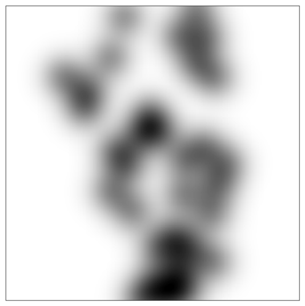
Plumes without free-surfaces.

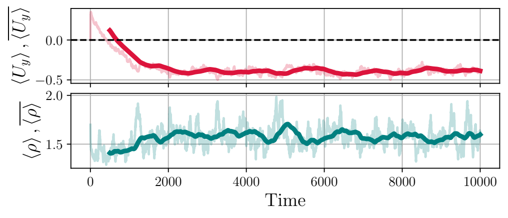
$|\mathbf{B}| = |\mathbf{T}| \cdot 0.0\%$ (no-buoyancy)





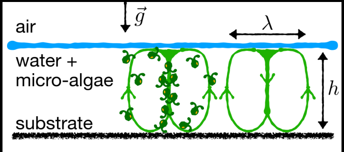
$|\mathbf{B}| = |\mathbf{T}| \cdot 2.5\%$ (negative-buoyancy)

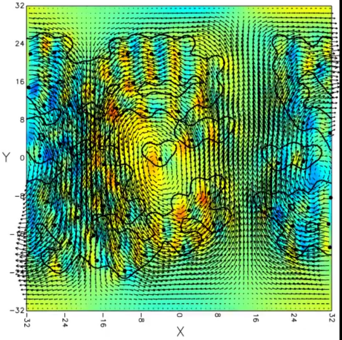




Triggering Bio-convection

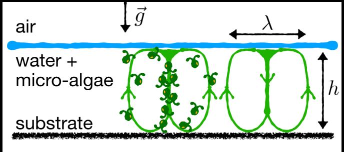
take-home messages

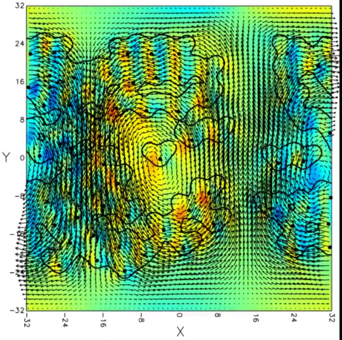




sandbox/fpicella/microswimmer_tHree_forces/plumes_x_periodic.c

1. **Hydrodynamic interaction → concentration fluctuation**





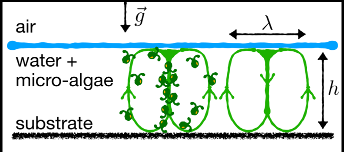
`sandbox/fpicella/microswimmer_tHree_forces/plumes_x_periodic.c`

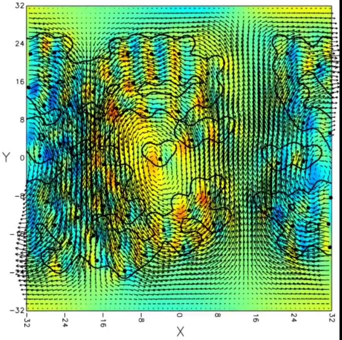
Triggering Bio-convection

take-home messages

1. **Hydrodynamic interaction → concentration fluctuation**

2. **Concentration increase → hydro. efficiency decrese**





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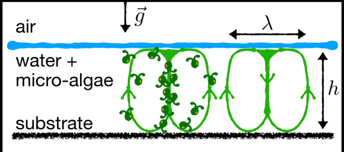
Triggering Bio-convection

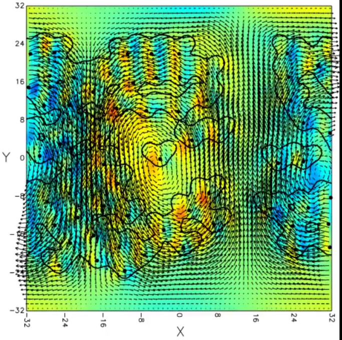
take-home messages

1. **Hydrodynamic interaction →**
   concentration fluctuation

2. **Concentration increase →**
   hydro. efficiency decrese

3. → **sedimentation** kicks-in





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1. **Hydrodynamic interaction → concentration fluctuation**

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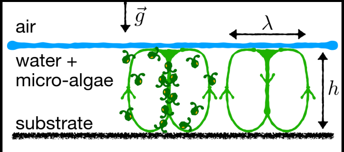
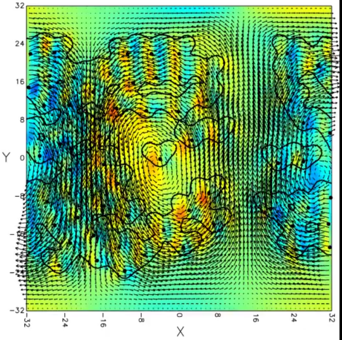
Persp. Numerics + Experiments

- 2D/3D effects?

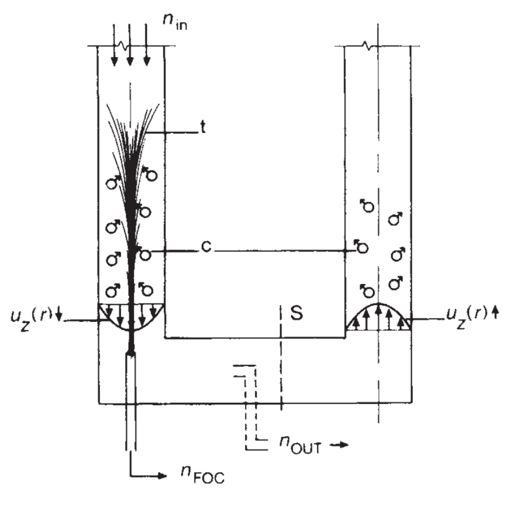


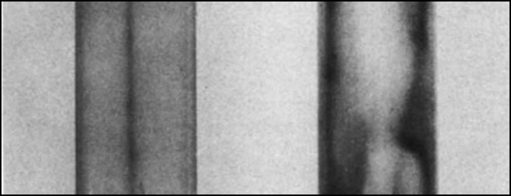


`sandbox/fpicella/microswimmer_tHree_forces/plumes_x_periodic.c`

Single y-periodic plume, experimental proof

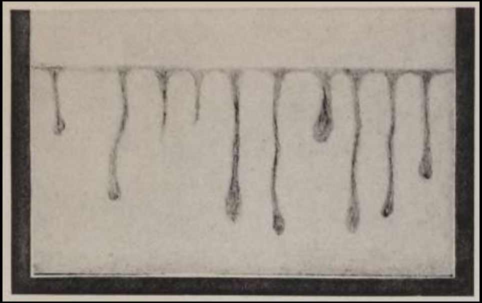
Kessler 1985

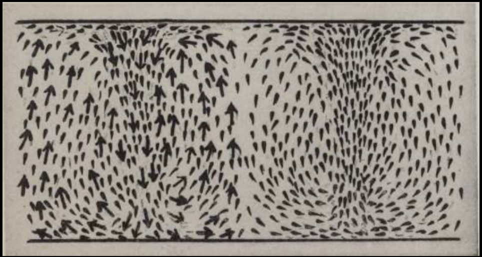




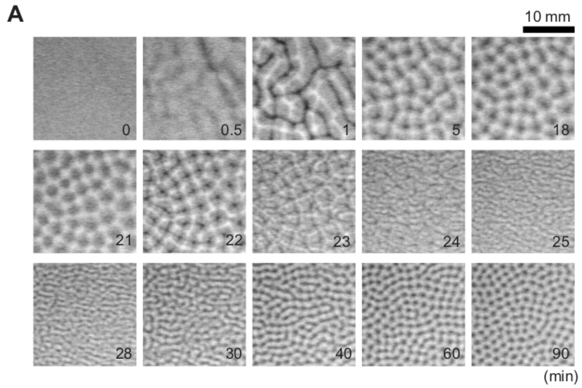
I bet you can not see this with an 'averaged', buoyancy-only model!

Triggering plume $\neq$ sustaining bioconvection





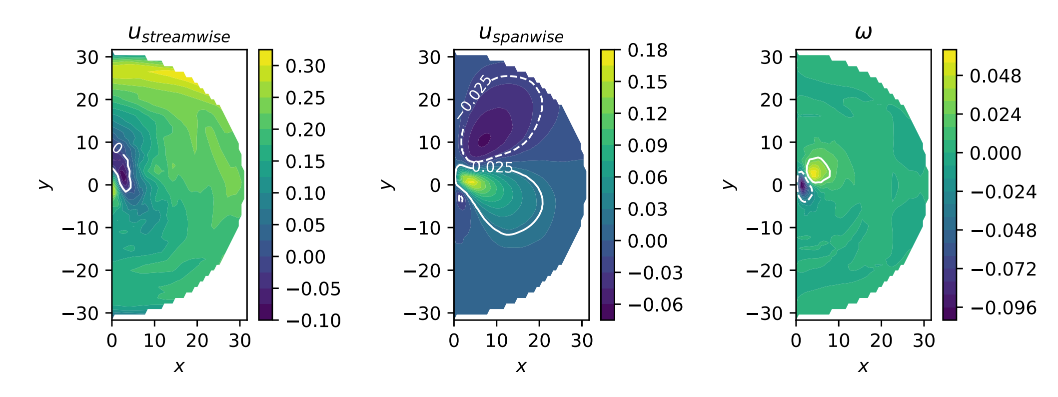
Wager 1911



Long-term bioconvection patterns. Top view.

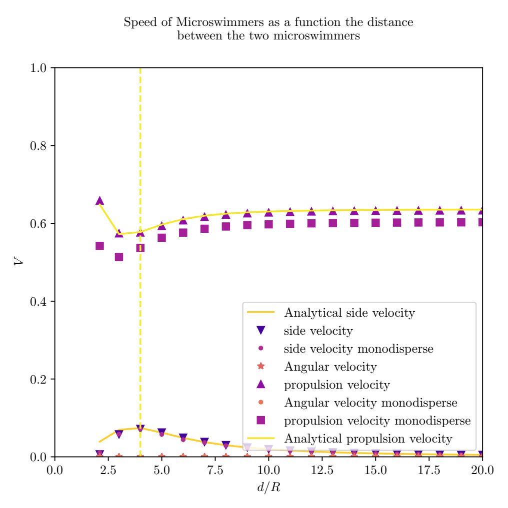
Kage *et al.* 2013

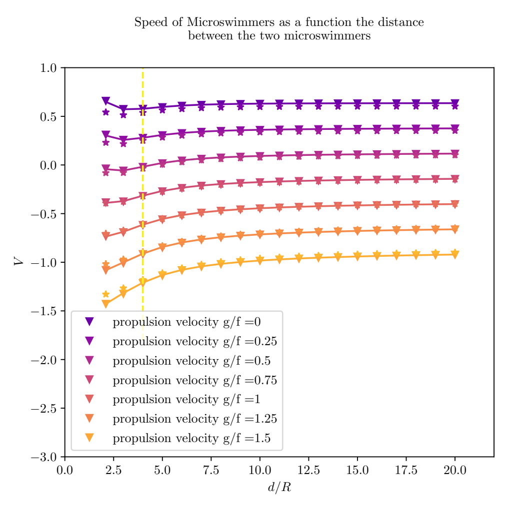
Binary interactions, non aligned



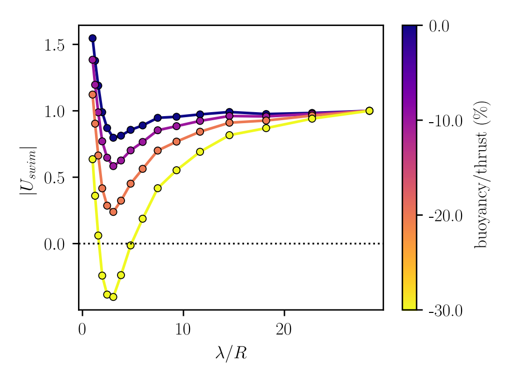
Binary interactions, full 3D

A. Palotai

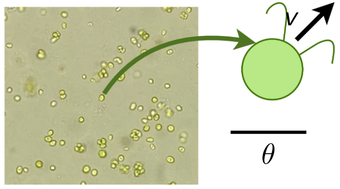




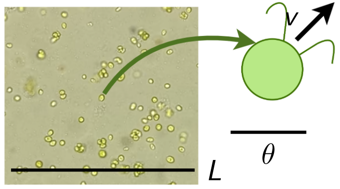
Binary interactions + buoyancy, normalized



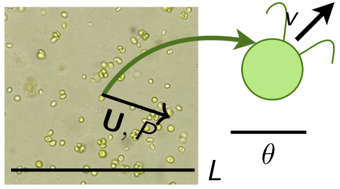
Modelling bio-convection (1): a **buoyancy**-driven flow (?)



Modelling bio-convection (1): a **buoyancy**-driven flow (?)



Modelling bio-convection (1): a **buoyancy**-driven flow (?)



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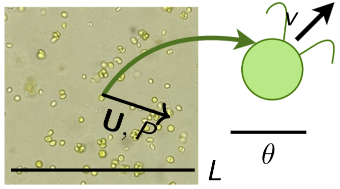


Eulerian, averaged, $L \gg \theta$

$$\frac{D\mathbf{U}}{Dt} = -\mathrm{Sc}\nabla P + \mathrm{Sc}\nabla^2\mathbf{U} \tag{3}$$

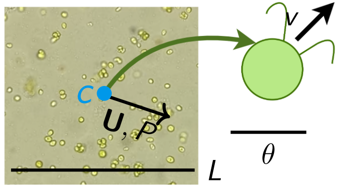
$$\nabla \cdot \mathbf{U} = 0 \tag{4}$$

(5)

(6)

Pedley & Kessler 1990

Modelling bio-convection (1): a **buoyancy**-driven flow (?)



Eulerian, **averaged**, $L \gg \theta$

$$\frac{D\mathbf{U}}{Dt} = -\mathrm{Sc}\nabla P + \mathrm{Sc}\nabla^2\mathbf{U} - \mathrm{Sc}\cdot\mathrm{Ra}\ c\ \hat{\mathbf{g}} \qquad (3)$$

$$\nabla \cdot \mathbf{U} = 0 \qquad (4)$$

(5)

(6)

Pedley & Kessler 1990

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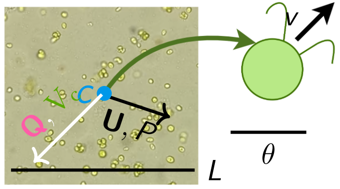

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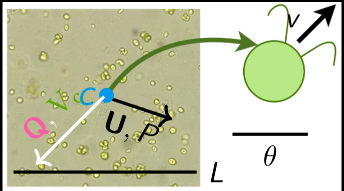
$$\nabla\cdot\mathbf{U} = 0 \tag{4}$$

$$\frac{\partial c}{\partial t} = -\nabla\cdot\left((\mathbf{U} + \mathrm{V_c}\langle\mathbf{Q}\rangle)c - \nabla c\right) \tag{5}$$

(6)

Pedley & Kessler 1990

Modelling bio-convection (1): a **buoyancy**-driven flow (?)



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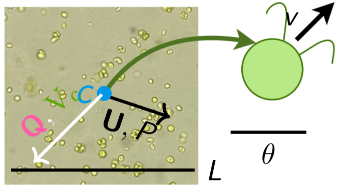
$$\frac{\partial \mathbf{Q}}{\partial t} = \frac{1}{2\mathrm{G}}\left(\hat{\mathbf{g}} - (\hat{\mathbf{g}}\cdot\mathbf{Q})\right) + \frac{\mathbf{\Omega}\times\mathbf{Q}}{2} \quad (6)$$

Pedley & Kessler 1990

Modelling bio-convection (1): a **buoyancy**-driven flow (?)



Eulerian, **averaged**, $L \gg \theta$

$$\frac{D\mathbf{U}}{Dt} = -\mathrm{Sc}\nabla P + \mathrm{Sc}\nabla^2\mathbf{U} - \mathrm{Sc}\cdot\mathrm{Ra}\; c\; \hat{\mathbf{g}} \tag{3}$$

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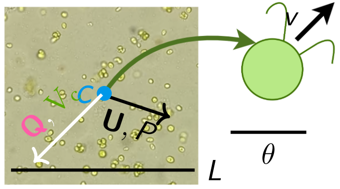
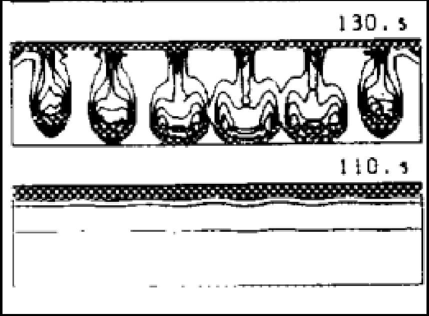
$\mathrm{Ra} \propto$ buoyancy, $\mathrm{Sc} \propto$ diffusion,
$G \propto$ reorientation towards gravity .
$\mathrm{V_c}$, CR *average* swimming **velocity**
$\mathbf{Q}(\mathbf{x}, t)$, CR *average* **orientation**
$c(\mathbf{x}, t)$, CR *average* **concentration**

Pedley & Kessler 1990

Modelling bio-convection (1): a **buoyancy**-driven flow (?)





Harashima *et al.* 1987

Eulerian, averaged, $L \gg \theta$

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$\mathrm{Ra} \propto$ buoyancy, $\mathrm{Sc} \propto$ diffusion,
$G \propto$ reorientation towards gravity .
$\mathrm{V_c}$, CR *average* swimming **velocity**
$\mathbf{Q}(\mathbf{x}, t)$, CR *average* **orientation**
$c(\mathbf{x}, t)$, CR *average* **concentration**

Pedley & Kessler 1990

Simulating bio-convection: averaged, **buoyancy-driven model**

In-house implementation with Spectral Element Method Nek5000

Side view. $\mathrm{Ra}, \mathrm{Sc}, \mathrm{G}, \mathrm{V_c}$ from Ghorai & Hill 1999

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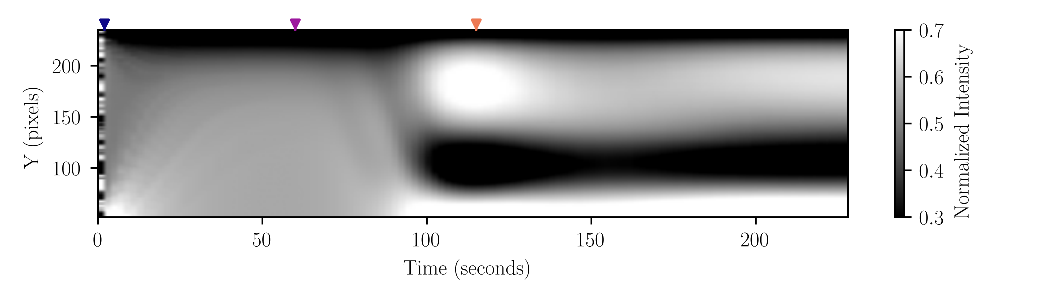
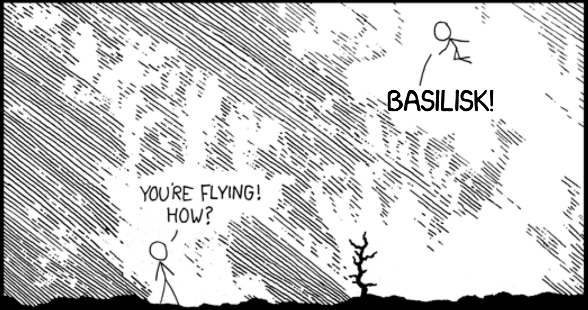
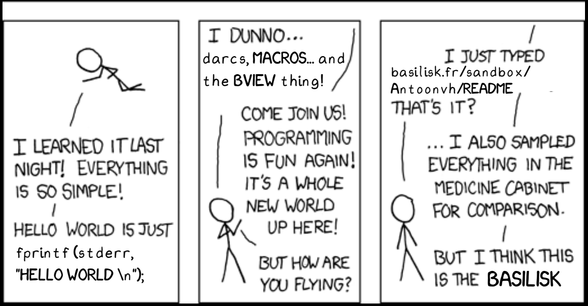


Spanwise-averaged intensity. First top dense layer thinning, then plumes.





inspired by xkcd.com