In the flow

Particles and fields in fluid systems

Enrico Calzavarini

Soutenance en vue de l'obtention de l'Habilitation à Diriger des Recherches

JURY

Rapporteurs :
ERIC CLIMENT, PR. Imperial College - CNRS, UK
CRISTIAN MARCHIOLI, PR. Università di Udine, IT
ANNE SERGENT, PR. Sorbonne Université

Examinateur :
FRANÇOIS G. SCHMITT, DR. CNRS - Université de Lille

Garant: GILMAR MOMPEAN, PR. Émérite, Université de Lille

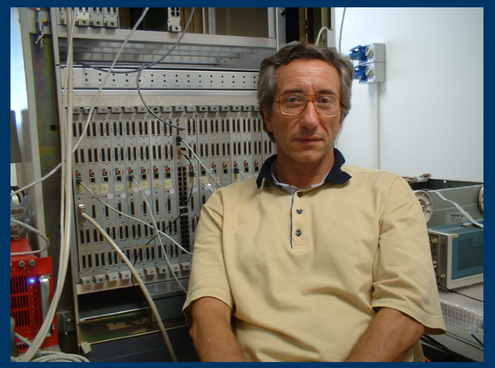
16 October 2026, Lille

Outline

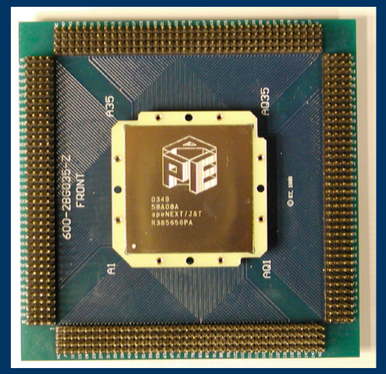
1. My path (a little bit of history)
2. MCF in Lille (2010 -today)
3. The work ahead (some ideas)

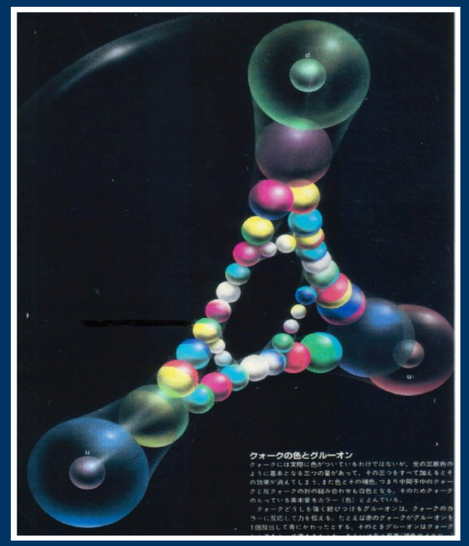
A little bit of history

2002 - 2005 PhD Close to the machine



Raffaele (Lele) Tripiccione (1956-2021)



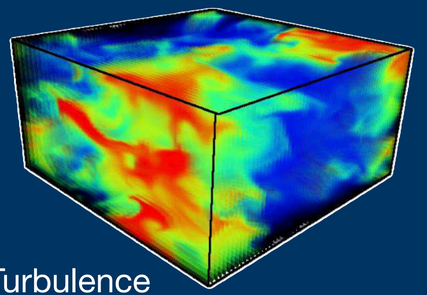


Lattice QCD

Gravitational Waves



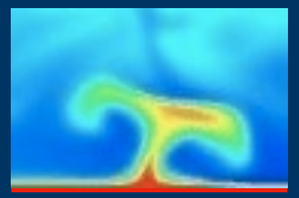
Matched filters for **coalescing binaries detection** on massively parallel computers, E. Calzavarini et al., Comp. Phys. Comm. 2003



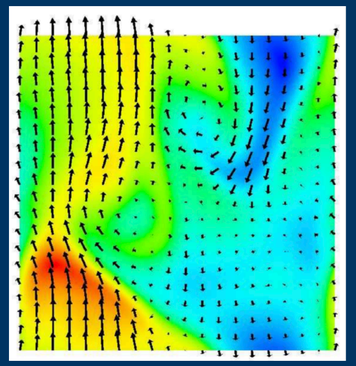
Turbulence

The age of universality

Kolmogorov *vs.* Bolgiano-Obhukov scaling



Homogeneous isotropic turbulence *vs.* Homogeneous Rayleigh-Bérnard



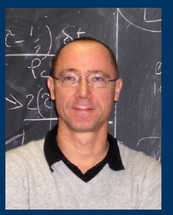
Dissipative anomaly *vs.* Ultimate regime of Heat-transfer



F. Toschi



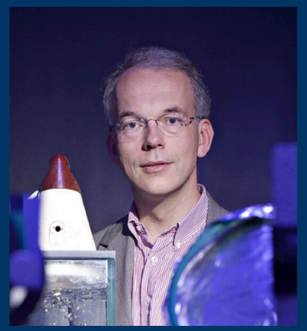
R. Benzi



L. Biferale

A little bit of history

2005 - 2008 University of Twente (NL) , Physics of Fluids group



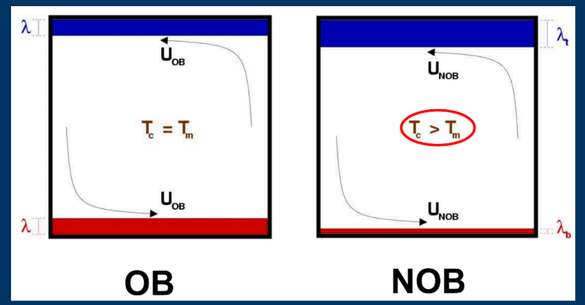
Detlef Lohse

Physics of Fluids

The age of complications

The non-Oberbeck-Boussinesq (NOB) Pandora box





Water

Glycerol

Ethane liquid

Ethane gas



Siegfried Grossmann



Guenter Ahlers

Encounter with bubbles



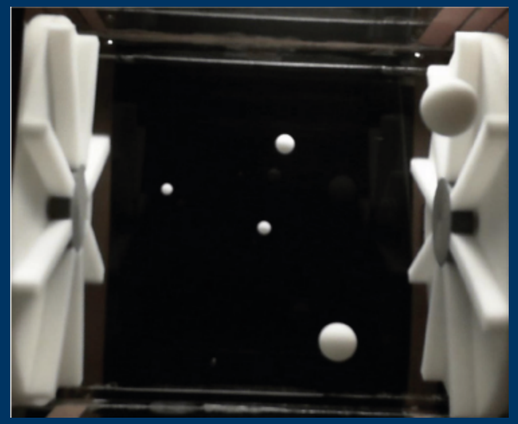
A little bit of history

2008 - 2010 Ecole Normale Supérieure de Lyon

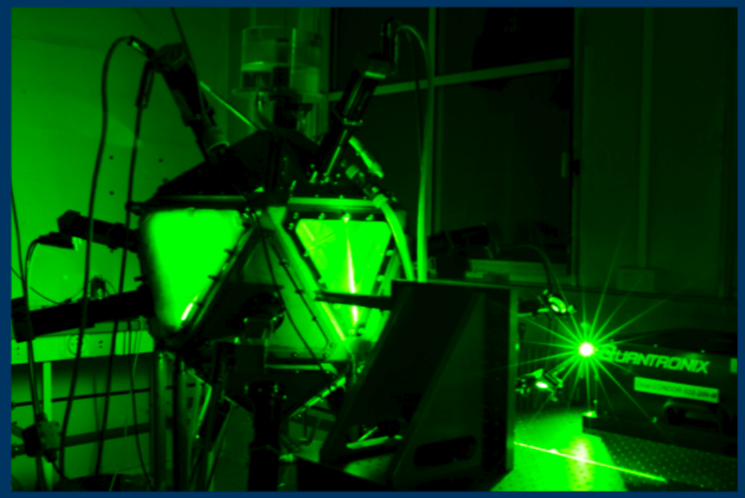


Jean-François Pinton

ENS DE LYON



Von Karman Flow (a.k.a. the french washing machine)



LEM (Lagrangian exploration module)

Inertial particles in turbulence

Simulations ↔ Experiments



E. Lévêque



R. Volk



M. Bourgoin

A little bit of history

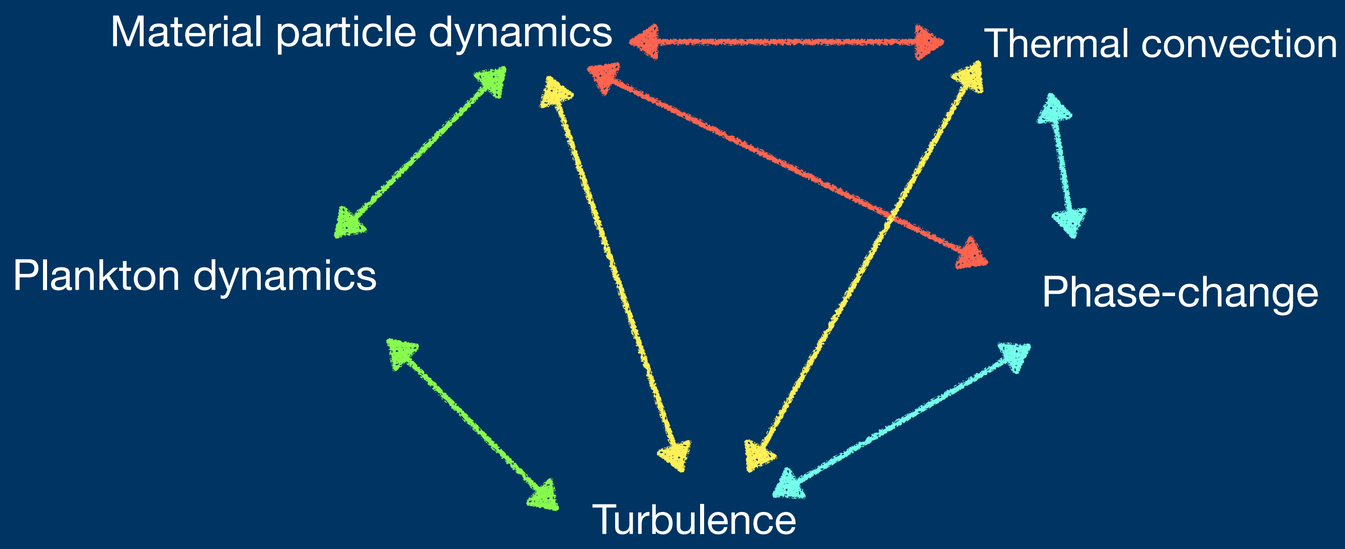
2010 - now Université de Lille - Polytech'Lille

LABORATOIRE de MECANIQUE de LILLE — E.C. LILLE E.N.S.A.M. U.S.T.L.

LML → 2018 UML

Unité Mécanique Lille UML J. Boussinesq

The age of **couplings**



1. My path (a little bit of history)
2. MCF in Lille (2010 -today)
3. The work ahead (some ideas)

Very little would have been possible without …

PhD

Kalyan Shrestha 2015



With: Gilmar Mompean

Hamidreza Ardeshiri 2016



With: Francois Schmitt

Babak Rabbanipour 2018



With: Silvia Hirata, Najib Ouarzazi

Himani Garg 2019



With: Stefano Berti, Gilmar Mompean

Wenwei Wu 2021



With: Francois Schmitt, Lipo Wang

Vinicius Tergolina 2022



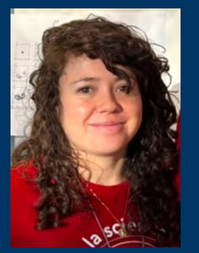
With: Stefano Berti, Gilmar Mompean

Saad Raza 2025



With: Silvia Hirata

Luz Andrea Silva-Torres



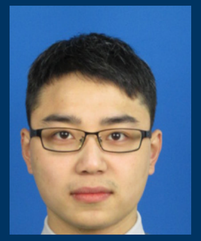
With: Stefano Berti

Ousman Daouda Ali



With: Silvia Hirata, Amir Bahrani, Tom Lacassagne

Linfeng Jiang 2022



Ziqi Wang 2022



Yihong Du



With: Chao Sun (Tsinghua Univ., China)

Vojtěch Patočka (Pdoc)



With: Nicola Tosi (DLR, Berlin)

Visiting PhD students Samuele Tommasi 2026

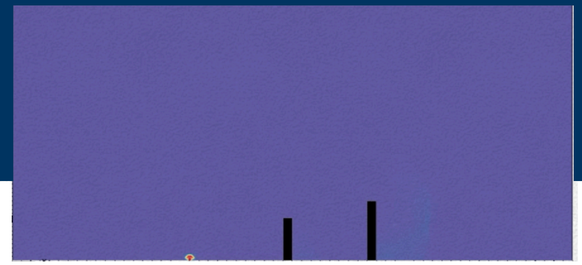
Intern Students (M2) Takwa Abdallah 2026, Adrien Defamie 2026, Javad Sherafatpour 2024 , Sara Ben Sadek 2023, Yanis Malem 2023, Longxiang Huang 2022, Raj Jayeshkumar Gandhi 2021,Yueting Jiang 2020, Kaci Alloua 2014

Intern Students (M1) Yan Zhang 2025, Dorian Hazard 2025, Ilies Haouche 2022, Akshay Anand & Mohand Padmanabha 2018, El-Mehdi Gouda, Mouhcine Tahri 2017, Yue Sun & Yu Zhan 2015, Tsirisitraka Ricky Raza, Vanduc Nguyen 2016

Intern Students (Engineering School Y1,Y2, Y3) Giovanna Veras Borges Mota 2026, Jhonata do Nascimento Santos 2025, Elias Oliveira 2025, Kevin Nicolas & Lucas Decelle 2024, Florent Delmotte 2023

Intern Students (L1-3) Daphné Bouilliez, Marine Gilbert, Jeanne Lepêtre 2019 , Drucké Thomas, Opdebeeck Elian, Phan Charlène, 2018 , Richard Israel Lagree, Basile Cuypers, 2017 , Boujdaria Omar, Buchet Daphnée, Zhongjie Zha 2016, Shashank Gupta, Arpit Gupta 2013 , Prinsul Niranjan 2012, Adnan Akhtar 2011

Developing a CFD code



Started as industrial project: deconfinement of LNG cold gasses CH_4



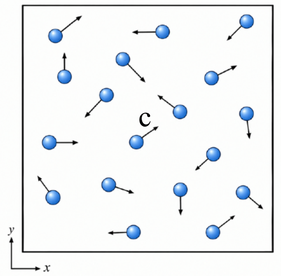
Kalyan

Choice of Boltzmann equation methods

$$\frac{\partial f}{\partial t} + \mathbf{c} \cdot \nabla_{\mathbf{x}} f + \frac{\mathbf{F}}{m} \cdot \nabla_{\mathbf{c}} f = \Omega(f)$$

$$f(\mathbf{x}, \mathbf{c}, t)$$

gas dynamics



$$\rho(\mathbf{x}, t) = m \int f(\mathbf{x}, \mathbf{c}, t)\, d\mathbf{c}$$

$$\rho \mathbf{u} = m \int \mathbf{c}\, f\, d\mathbf{c}$$

fluid dynamics



OPEN CODE

https://github.com/ecalzavarini/ch4-project

Hamid



Lagrangian tracking for point-like particles

Babak



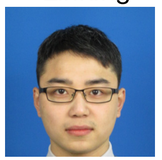
Enthalpy method for **Phase change**

Ziqi



Conjugate heat transfer

Linfeng



IBM method got finite-size particles

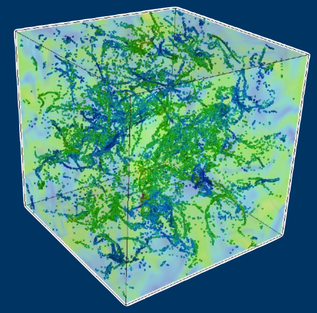
Ousman



Particle-fluid **two-way** couplings

Part 1

Material particles transported by turbulent flows

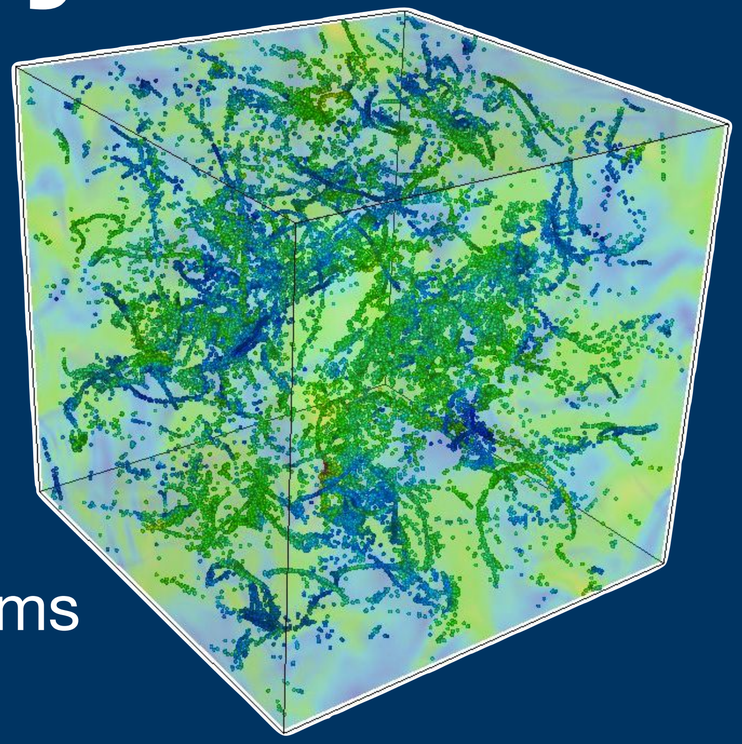


Part 2

Phase-change phenomena interacting with fluid flows



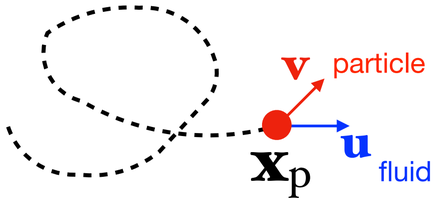
Part 1
Particles transported by turbulent flows

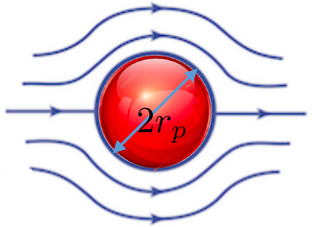


Accelerations, rotations settling and … microorganisms

A particle does not go with the flow

$$\mathbf{v}(t) \neq \mathbf{u}(t)$$





$$Re_p = \frac{||\mathbf{u}-\mathbf{v}||(2r_p)}{\nu} \ll 1$$

Hydrodynamic forces on a particle?

Small inertial particles (point-particles)

Stokes (1851)

Boussinesq (1885), Basset (1888), Oseen (1927) -> BBO eq.

Tchen (1947), Corrsin-Lumley(1956)

Maxey-Riley (1983), Gatignol (1983) -> MRG eq. *extension to non-uniform creeping flows*

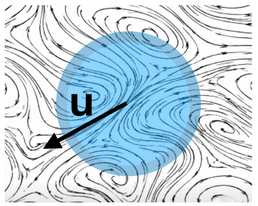
$$\frac{d\mathbf{x_p}}{dt} = \mathbf{v}(t)$$

$$m_p \frac{d\mathbf{v}}{dt} = 6\pi\mu r_p(\mathbf{u}-\mathbf{v}) + m_f \frac{D\mathbf{u}}{Dt} + \frac{m_f}{2}\frac{d(\mathbf{u}-\mathbf{v})}{dt} + 6r_p^2\sqrt{\pi\rho_f\mu}\int_0^t \frac{d(\mathbf{u}-\mathbf{v})}{d\tau}\frac{d\tau}{\sqrt{t-\tau}} + (m_p - m_f)\mathbf{g}$$

drag | fluid acceleration | added mass | history | buoyancy

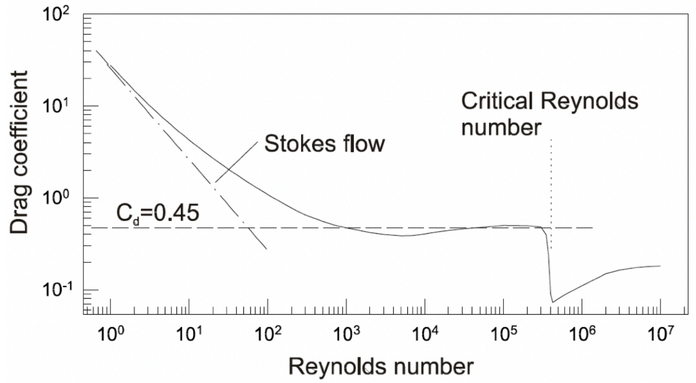
A particle does not go with the flow

Corrections to the small inertia limit



- Finite-size effect (Faxén laws 1922)

- Finite-Reynolds effect: drag correlations (e.g. Shiller-Naumann 1933)



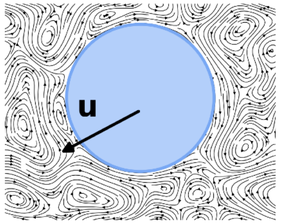
- Lift force (Saffman 1965, Auton JFM 1987)

And for even bigger particles?

Rigid body motion + Navier-Stokes + no-slip b.c.

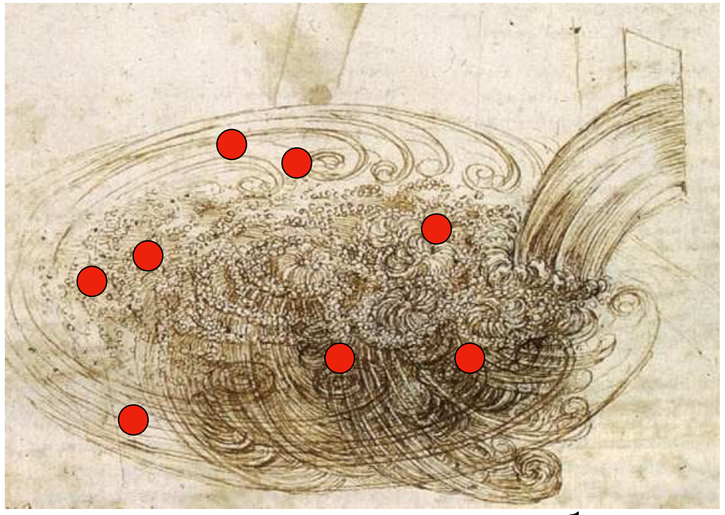
$$m_p \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \mathbf{F} \qquad \mathbf{F} = \oint_{S_p} \boldsymbol{\sigma} \cdot \mathbf{n} \, dS$$

$$\frac{\mathrm{d}\boldsymbol{\mathcal{I}}\boldsymbol{\Omega}}{\mathrm{d}t} = \mathbf{T} \qquad \mathbf{T} = \oint_{S_p} (\mathbf{x} - \mathbf{r}) \times (\boldsymbol{\sigma} \cdot \mathbf{n}) \, dS$$



Inertial particles in turbulence

Why is it challenging?



$$\partial_t \mathbf{u} + (\mathbf{u}\cdot\boldsymbol{\nabla})\mathbf{u} = -\boldsymbol{\nabla} p + \frac{1}{Re}\boldsymbol{\Delta}\mathbf{u}$$

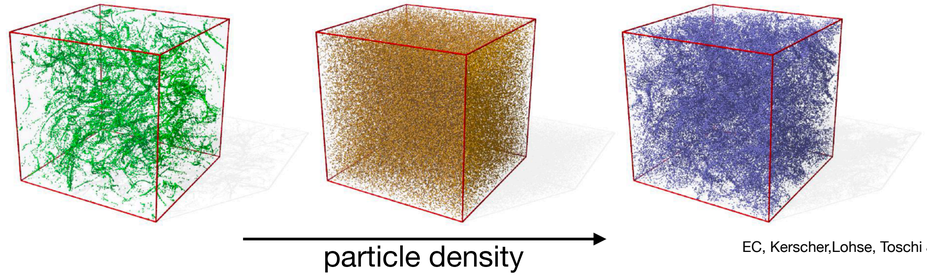
$$Re \to \infty$$

Nonlinear, Chaotic, Intermittent, Multiscale, Energy-cascading flow

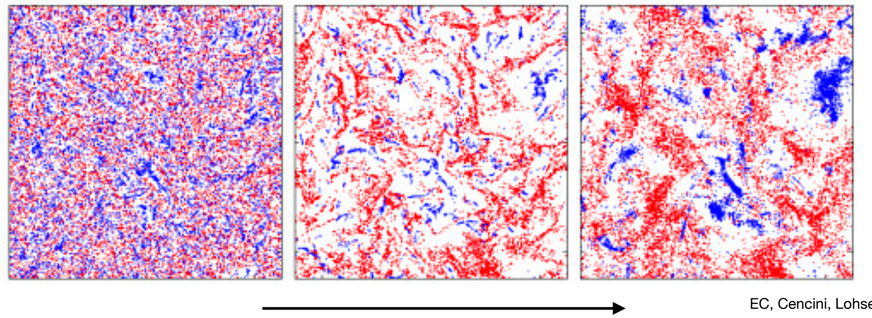
How to study it?

- Statistical approach
- Experimental measures
- Validate models using computer simulations

Complex phenomenology



EC, Kerscher,Lohse, Toschi JFM 2008



EC, Cencini, Lohse, Toschi PRL 2008

Clustering, segregation, modified collision rates

modulation of settling speeds

global drag reduction/enhancement,…

Accelerations of particles in turbulence

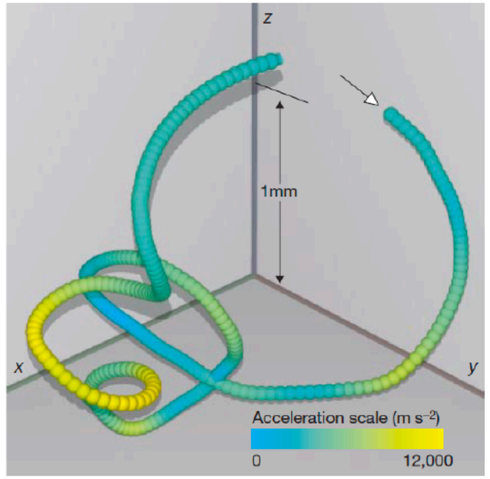
statistics

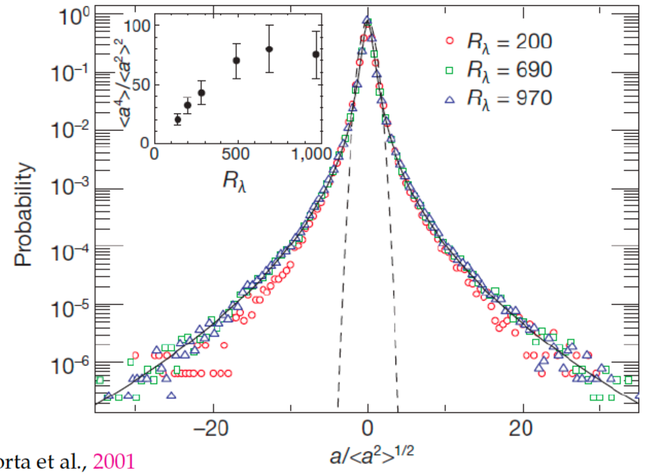
$pdf(\mathbf{a}_p) \qquad \langle \mathbf{a}_p^n \rangle$

$\langle \mathbf{a}_p(t) \cdot \mathbf{a}_p(t+\tau) \rangle$

Fluid tracer

$\mathbf{a}_f(Re)$





La Porta et al., 2001

Particle

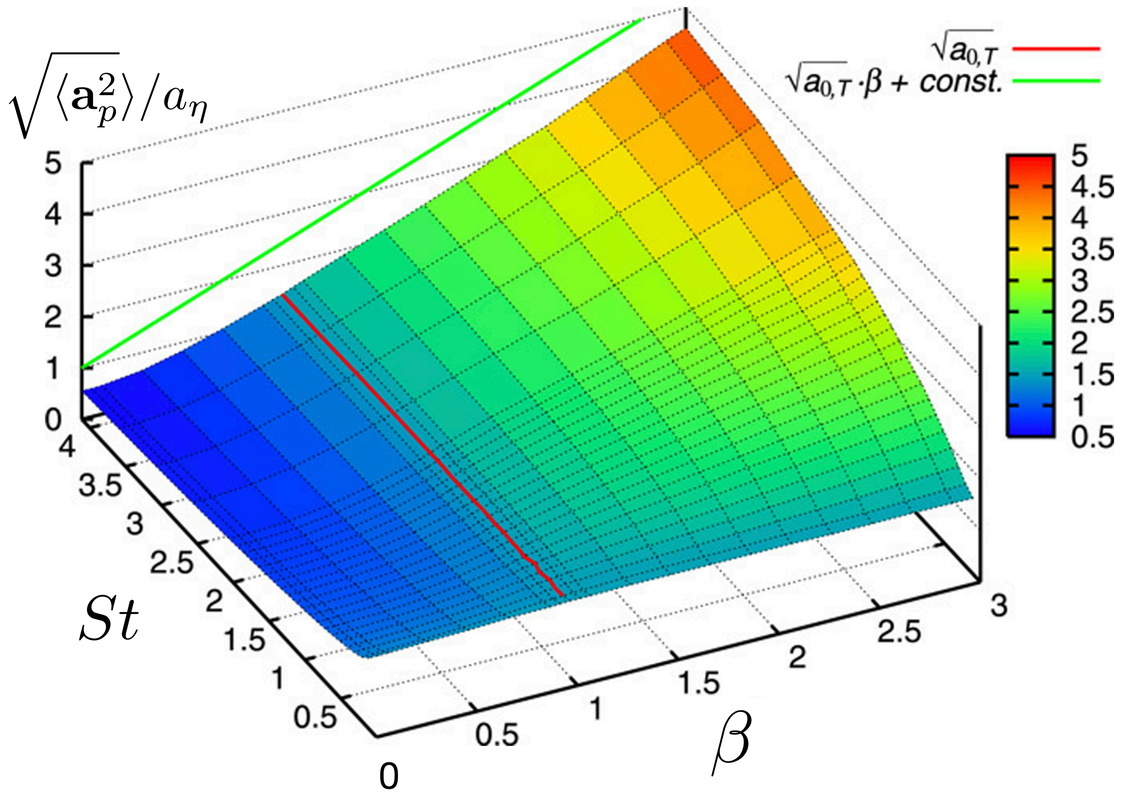
$$\mathbf{a}_p(Re, \beta, St, Fr, \alpha, \ldots)$$

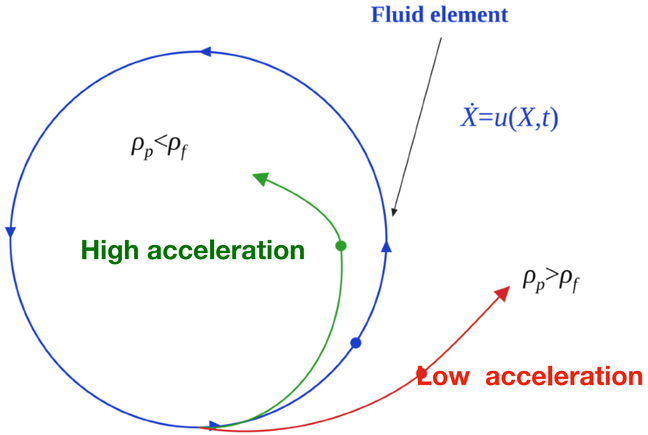
density — size — buoyancy — shape

$$\beta = \frac{3}{1 + 2\rho_p/\rho_f} \qquad St = \frac{\tau_p}{\tau_f} = \frac{r_p^2}{3\nu\beta\tau_f} \qquad Fr = \frac{a_f}{(\beta - 1)g} \qquad \alpha = \frac{l}{d}$$

Accelerations of particles in turbulence

Mass density effect $\mathbf{a}_p(Re, \beta, St, Fr, \alpha, \ldots)$





Temporal filter of fast timescales $t < \tau_p$ → ejection from vortices

Added mass acceleration → injection into vortices

Volk, EC, Verhille, Lohse, Mordant, Pinton, Toschi, Physica D (2008)

Accelerations of particles in turbulence

Size effect $\mathbf{a}_p(Re, \beta, St, Fr, \alpha, \ldots)$

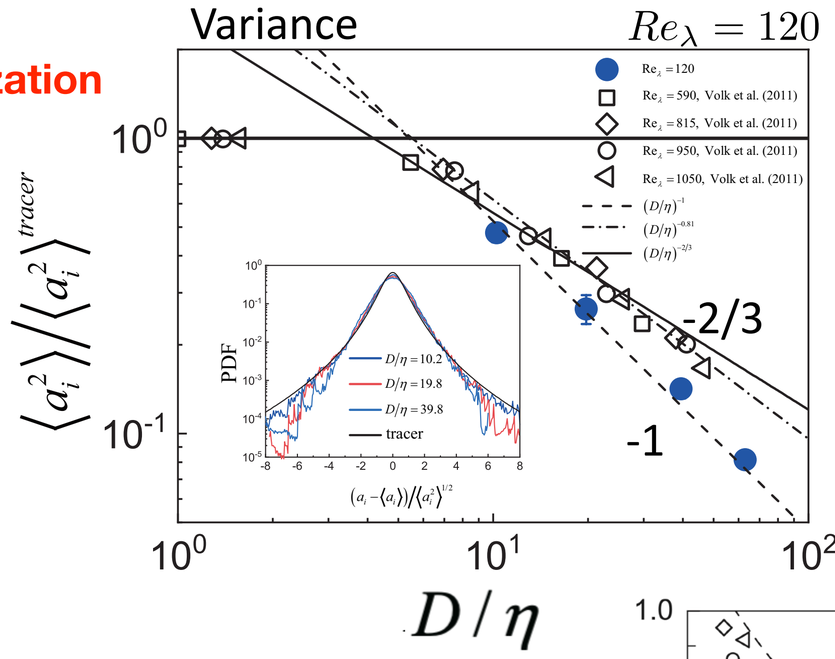
Spatial filter of small structures → **Gaussianization**

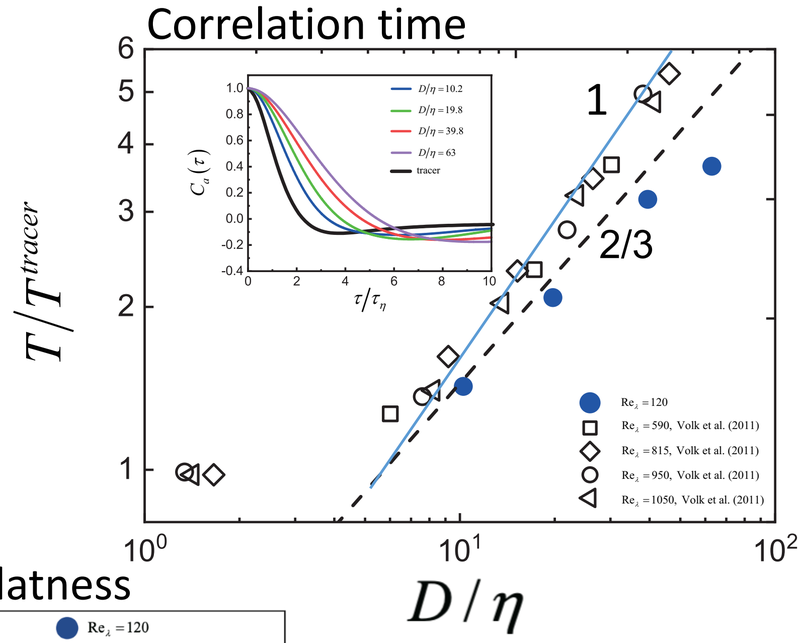
Coarse-grained scalings

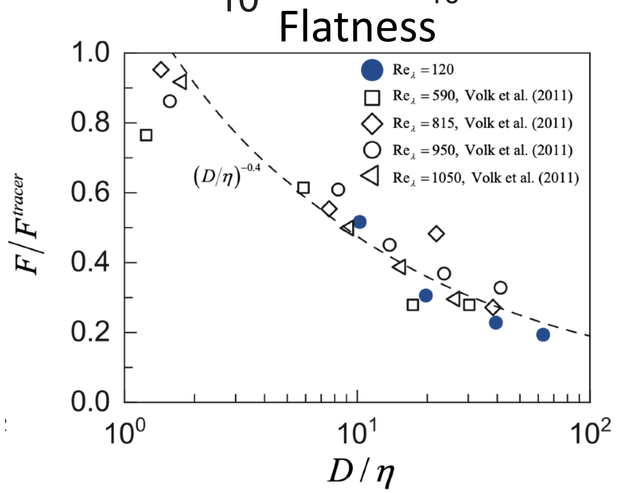
$$\langle a_p^2 \rangle \sim \left(\frac{\delta_D p}{D}\right)^2 \sim \left(\frac{(\delta_D u)^2}{D}\right)^2 \sim D^{-\frac{2}{3}}$$

$$\tau_a(D) \sim \frac{D}{\delta_D u} \sim D^{2/3}$$

$$\mathcal{F}_a(D) \sim D^{\zeta_8 - 2\zeta_4 < 0}$$







EC, Volk, Bourgoin, Leveque, Pinton, Toschi, JFM (2009)

Y. Fan, C.Wang, L.Jiang, C.Sun EC, EPL (2024)

Accelerations of particles in turbulence

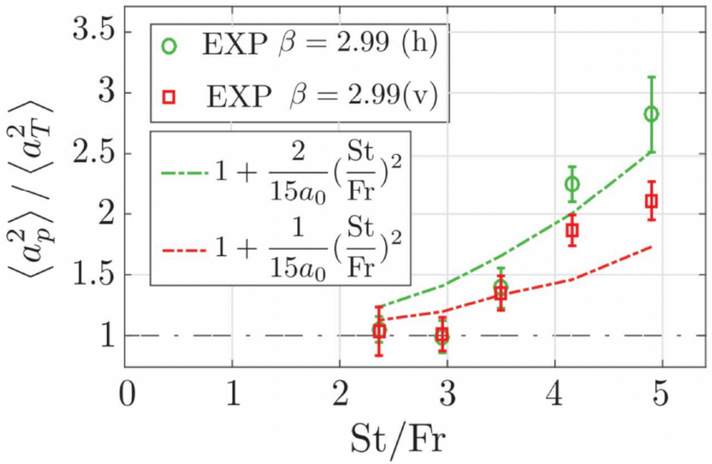
Buoyancy effect $\mathbf{a}_p(Re, \beta, St, Fr, \alpha, \ldots)$

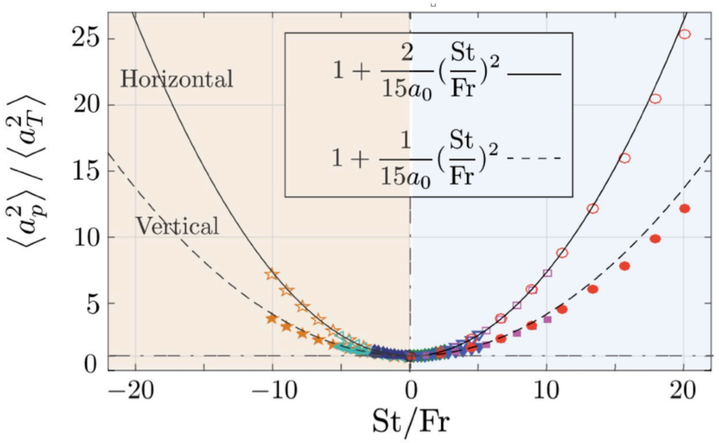
Experiments of tiny bubbles

$$\boldsymbol{a} \simeq D_t \boldsymbol{u} + \frac{\mathrm{St}}{\mathrm{Fr}} \partial_z \boldsymbol{u}$$

$$\frac{\langle a_{p,x}^2 \rangle}{\langle a_f^2 \rangle} \simeq 1 + \frac{2}{15 a_0} \left(\frac{St}{Fr} \right)^2$$

$$\frac{\langle a_{p,z}^2 \rangle}{\langle a_f^2 \rangle} \simeq 1 + \frac{1}{15 a_0} \left(\frac{St}{Fr} \right)^2$$





Experiment Twente Water Tunnel



Varghese Mathai



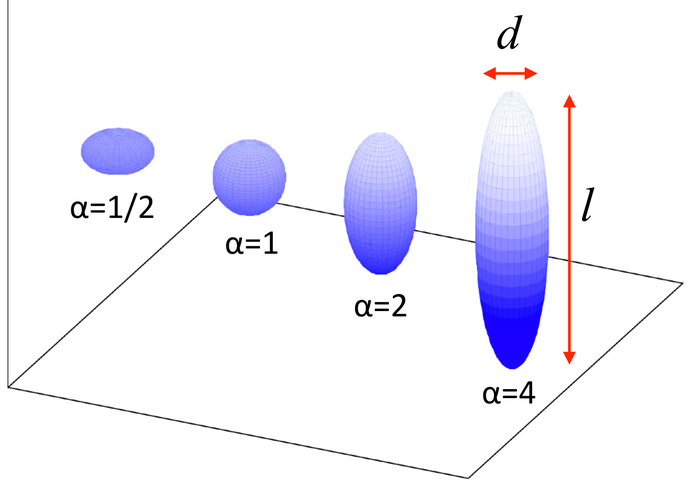
V. Mathai, EC, J. Brons, C. Sun, D. Lohse, PRL (2016)

Accelerations of particles in turbulence

Shape effect

$$\mathbf{a}_p(Re, \beta, St, Fr, \alpha, \ldots)$$

axisymmetric spheroids



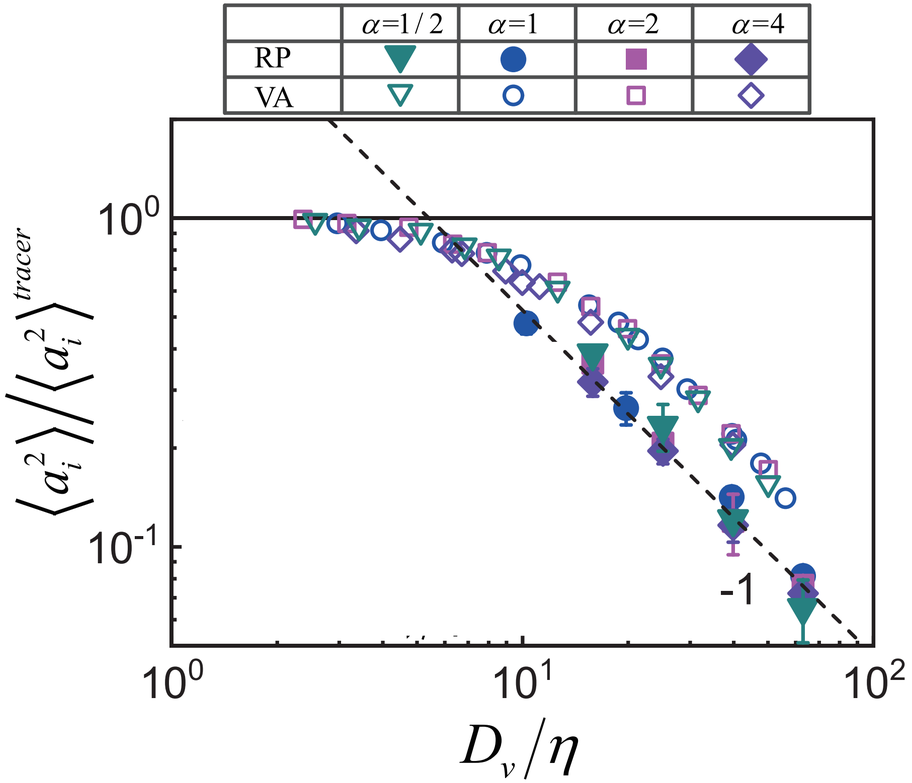
aspect ratio

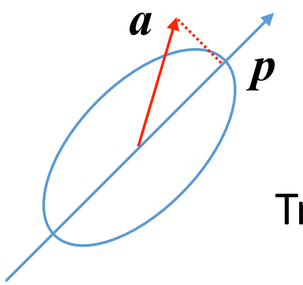
$$\alpha = \frac{l}{d}$$

Volume equivalent diameter

$$D_v = (d^2 l)^{1/3} = d\alpha^{1/3}$$

Acceleration variance



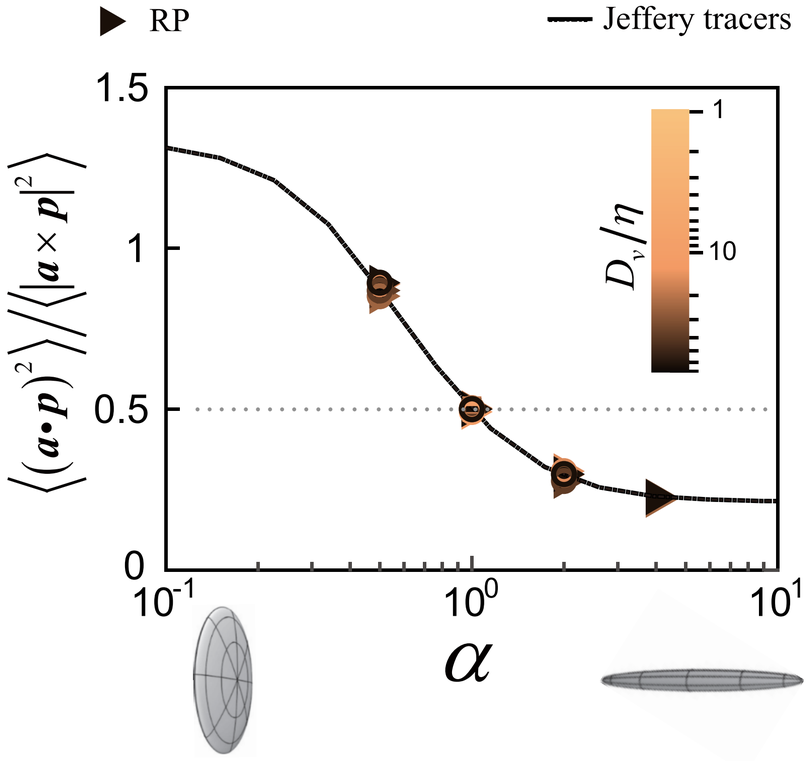


Axial acceleration

$$\boldsymbol{a}^{\parallel} = (\boldsymbol{a} \cdot \mathbf{p})\mathbf{p}$$

Transverse acceleration

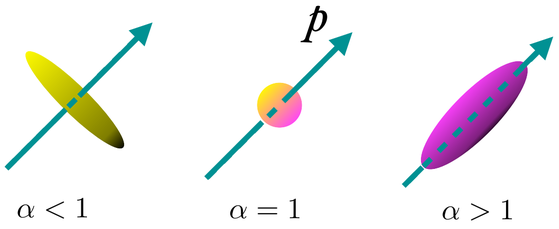
$$\boldsymbol{a}^{\perp} = \boldsymbol{a} \times \mathbf{p}$$

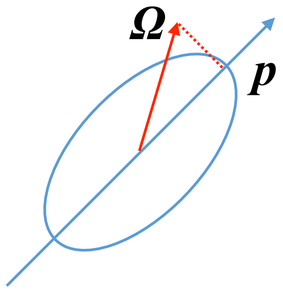


L. Jiang, C. Wang, S. Liu, C. Sun, EC, JFM (2022)

Rotations of particles in turbulence

The tiny particle case



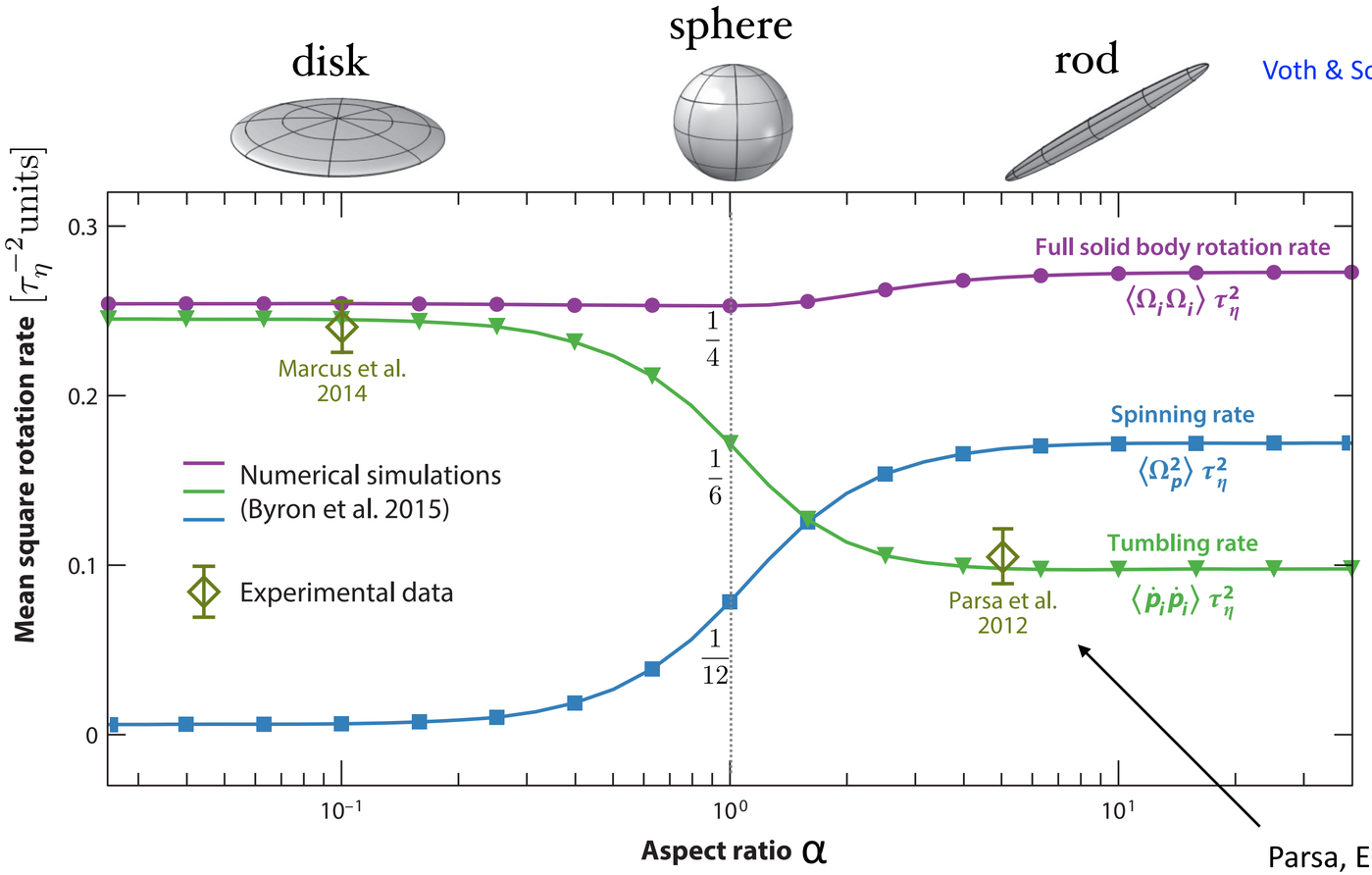


Ω **Angular velocity**

$\dot{\boldsymbol{p}}$ **tumbling rate**

$\Omega_s = (\Omega \cdot \mathbf{p})\mathbf{p}$ **spinning rate**

Jeffery (1922) eq. $\dot{\mathbf{p}} = \boldsymbol{\Omega} \times \mathbf{p}$ $\boldsymbol{\Omega} = \frac{\boldsymbol{\omega}}{2} + \frac{\alpha^2 - 1}{\alpha^2 + 1}\mathbf{p} \times \mathcal{S}\mathbf{p}$



Voth & Soldati, Ann Rev Fluid Mech 2017

Parsa, EC, Voth, Toschi, PRL 2012

Rotations of particles in turbulence

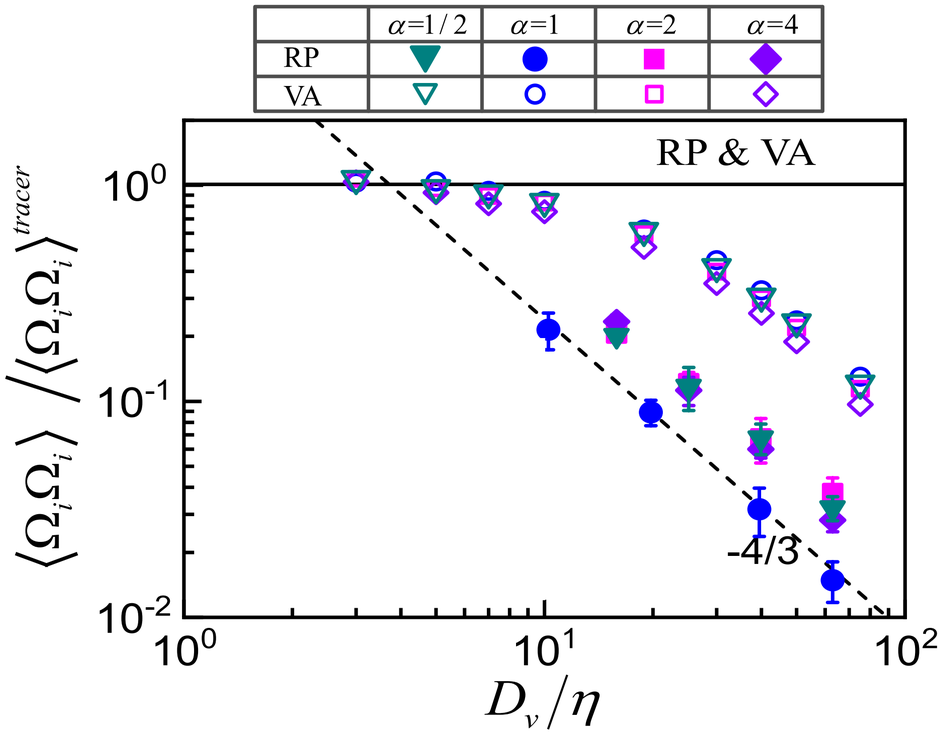
The large particle case

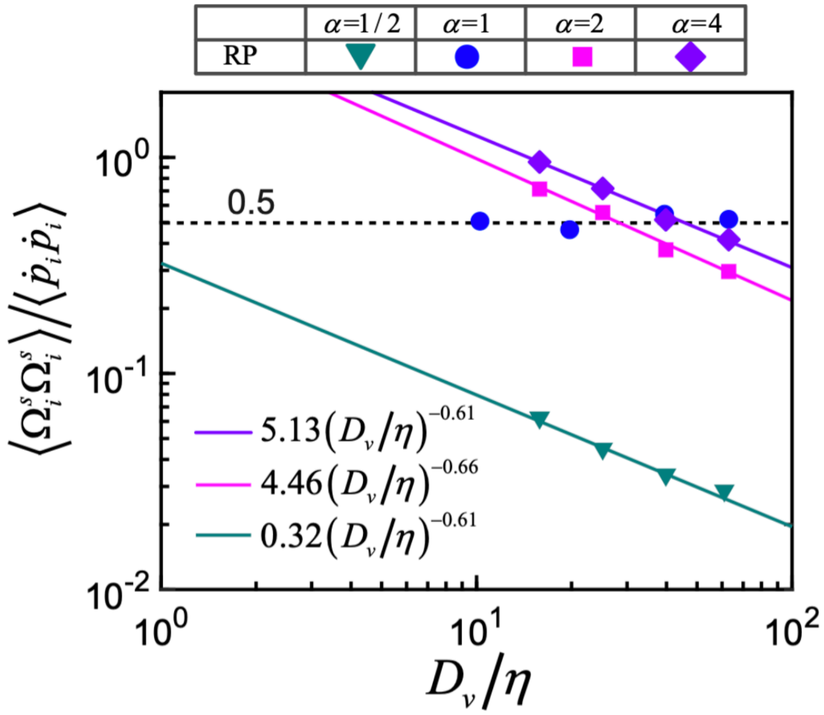
$$\langle \Omega^2 \rangle \sim \frac{1}{\tau_{eddy}(D)^2} \sim \frac{\delta_D u^2}{D^2} \sim D^{-\frac{4}{3}}$$

$$\langle \Omega_i^s \Omega_i^s \rangle \sim d^{-4/3}$$

$$\langle \dot{p}_i \dot{p}_i \rangle \sim l^{-4/3}$$

$$\frac{\langle \Omega_i^s \Omega_i^s \rangle}{\langle \dot{p}_i \dot{p}_i \rangle} \sim \frac{\alpha^{4/3}}{2}$$



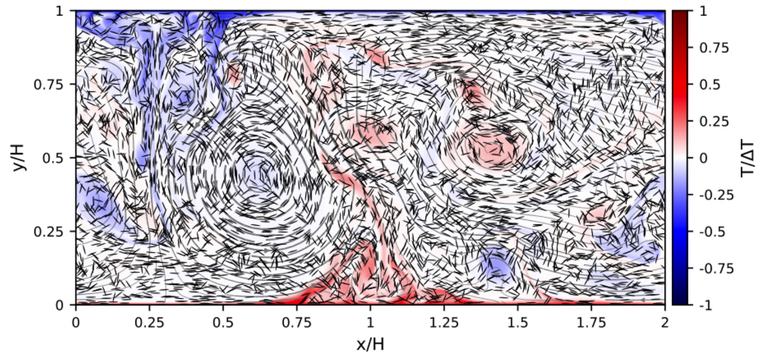


Observation:
Large particles spin less and tumble more

L. Jiang, C. Wang, S. Liu, C. Sun, EC, JFM (2022)

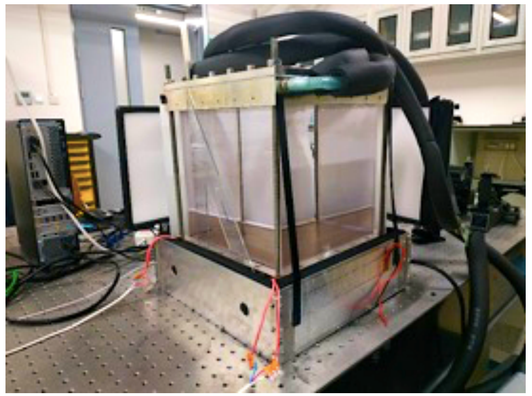
Rotations of particles in thermally driven turbulence

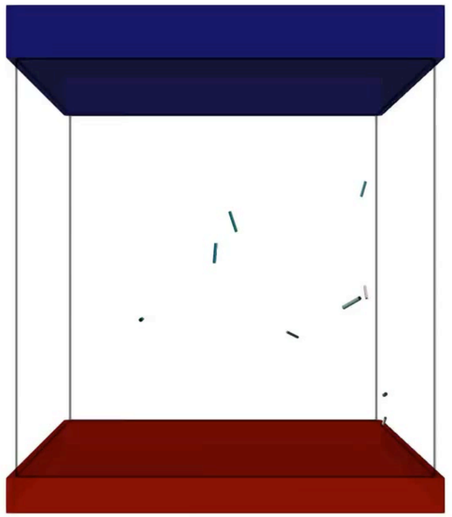
2D



3D



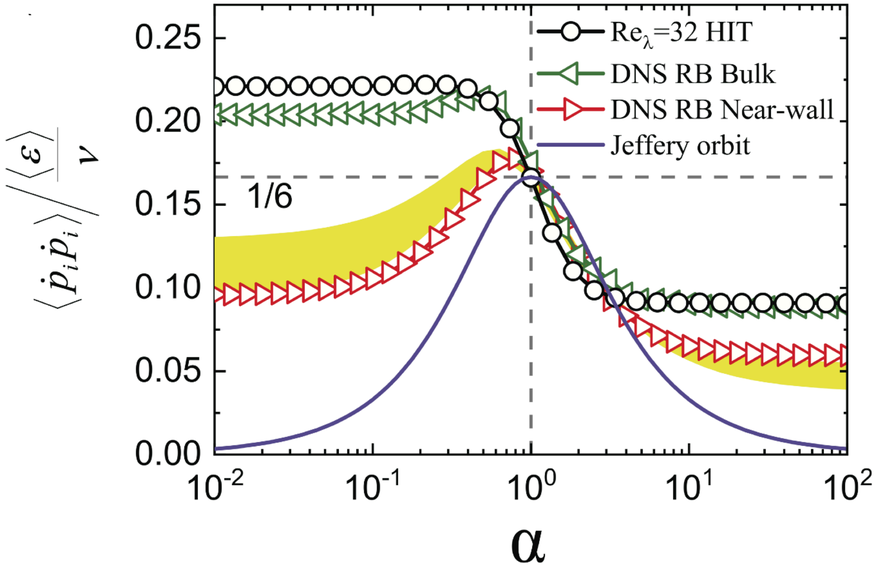




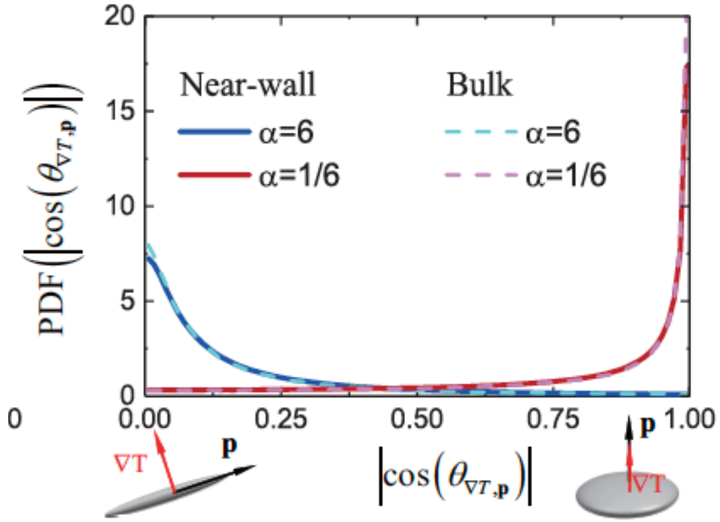


Collab. Chao Sun

L. Jiang, E.C., C.Sun, JFM (2020)
E.C, L. Jiang, and C. Sun, Phys.Fluids (2020)



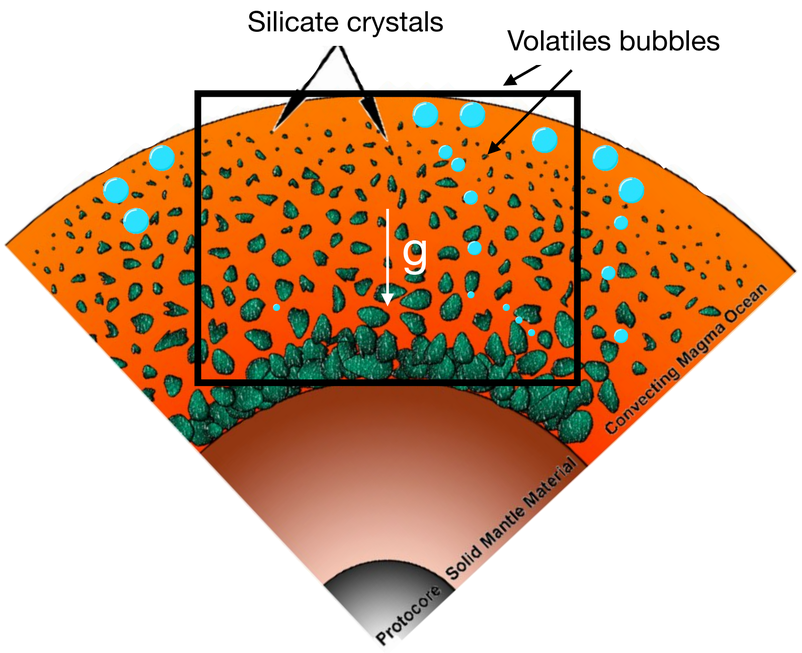
Spinning in **bulk** vs. **near-wall**

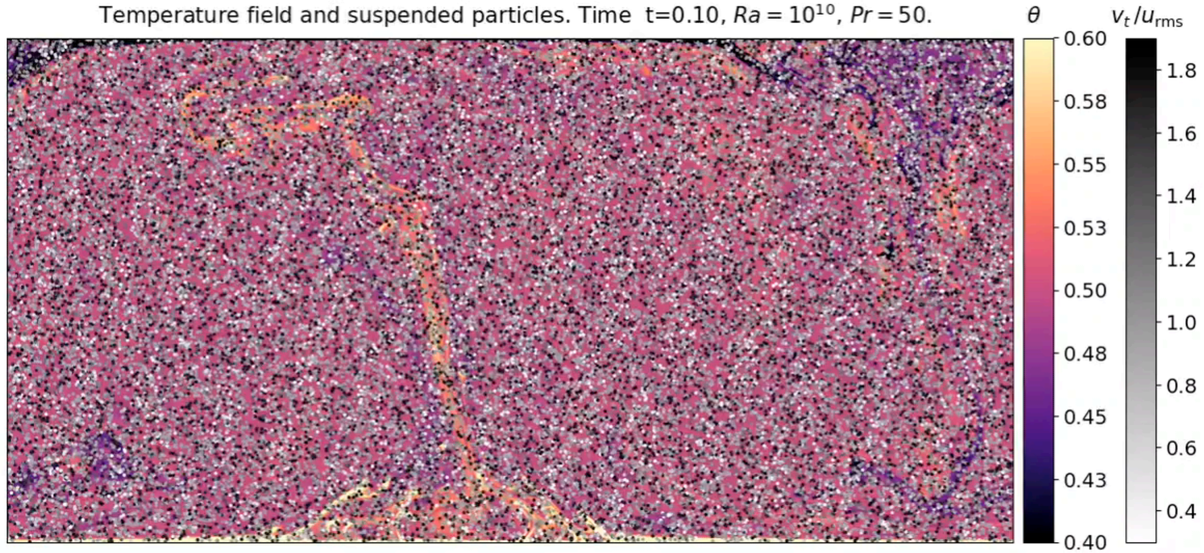


Particle - **thermal gradient** alignment

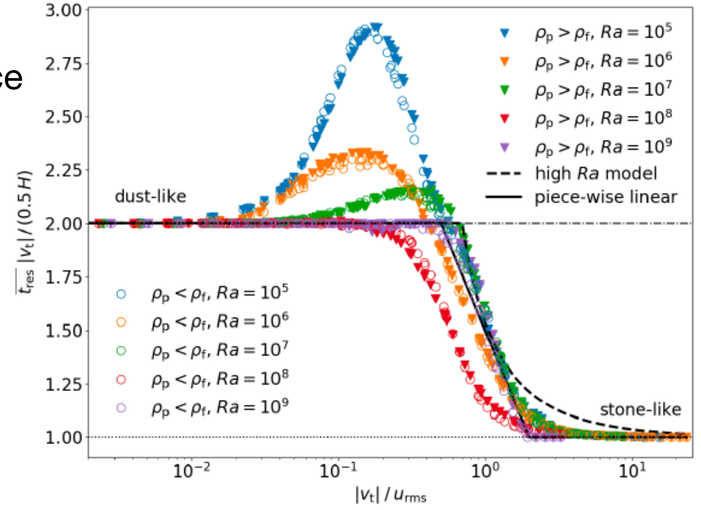
Settling of particles in thermally driven turbulence

Solidifying magma oceans





Residence time



Settling speed



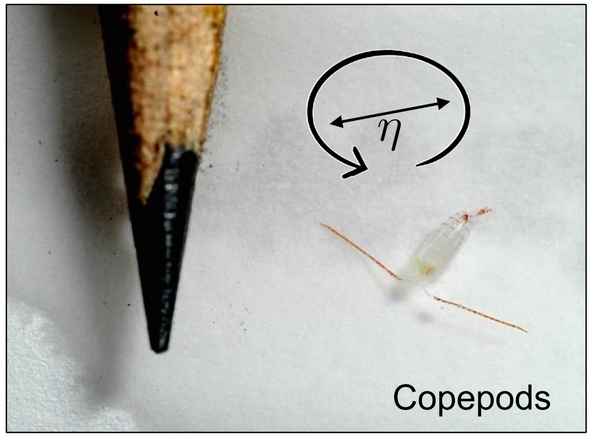
Nicola Tosi (DLR, Berlin)

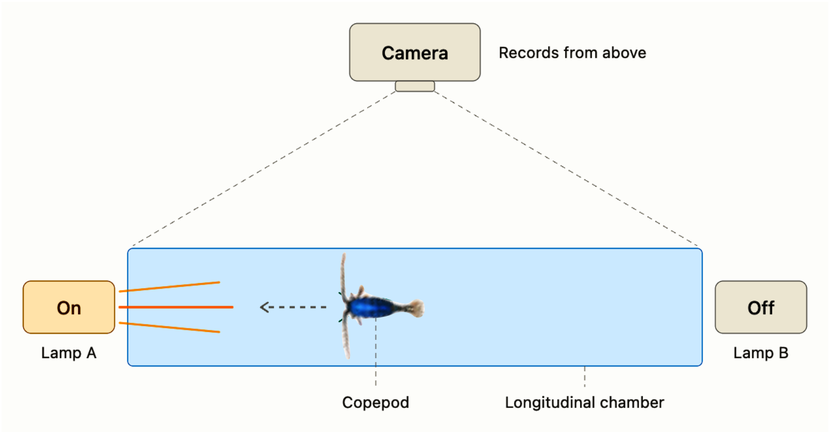


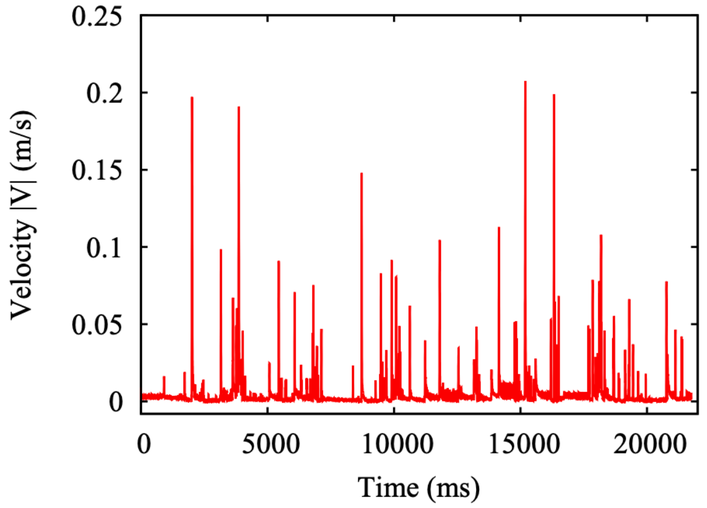
+ V. Patocka (Pdoc)

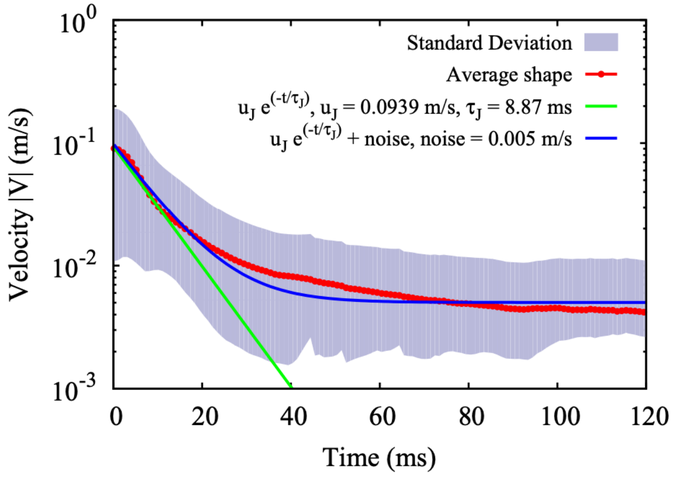
V.Patočka, E.C, N. Tosi Phys. Rev. Fluids (2020).
V.Patočka, Nicola Tosi, E.C. Earth and Planetary Science Lett. (2022)

Swimming Microorganisms in turbulence



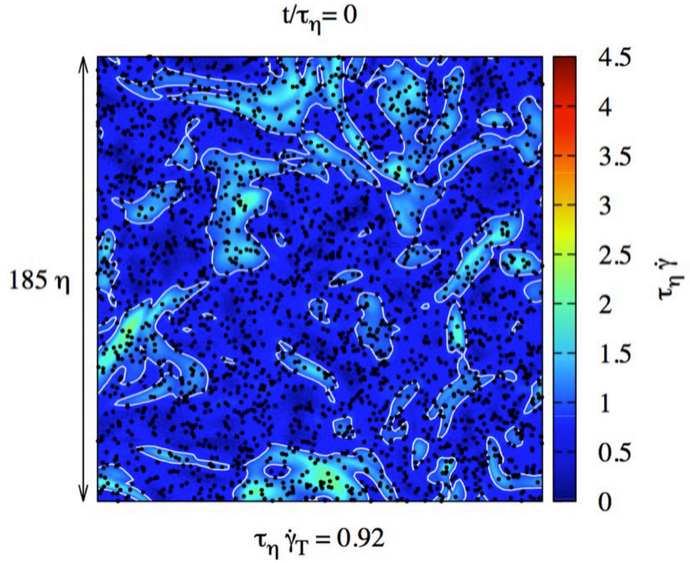






Copepods as motile Lagrangian particles

$$\dot{\mathbf{x}}_c(t) = \mathbf{u}(\mathbf{x_c}(t), t) + \boldsymbol{J}(t, t_i, t_e, \dot{\gamma}, \mathbf{p})$$





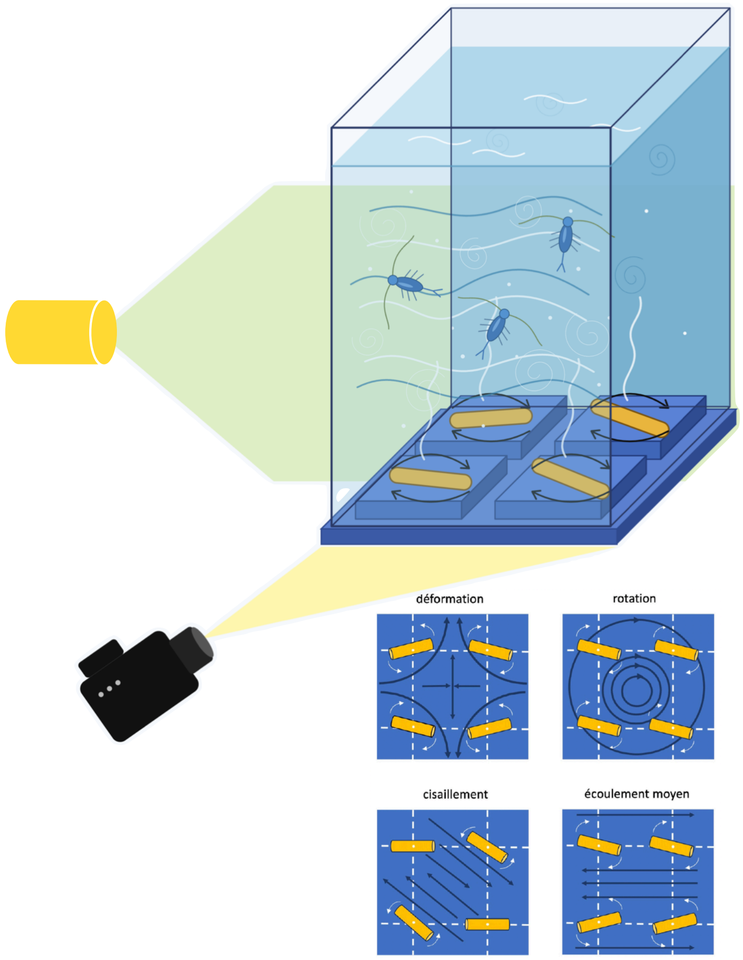
With F. G. Schmitt

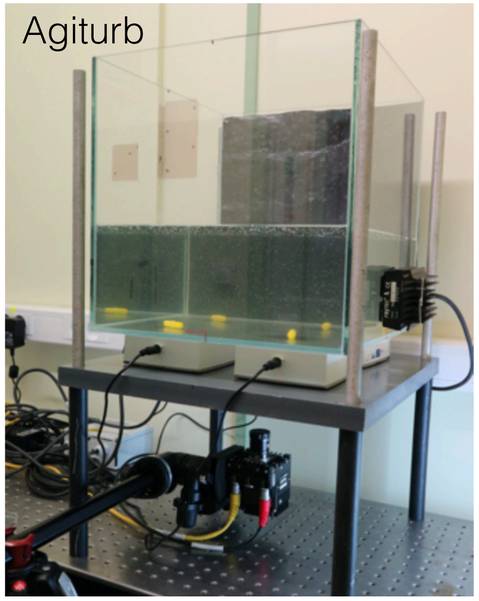


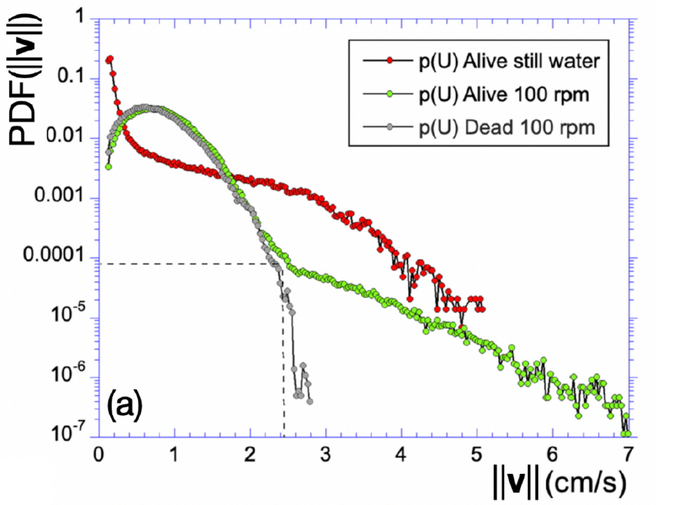


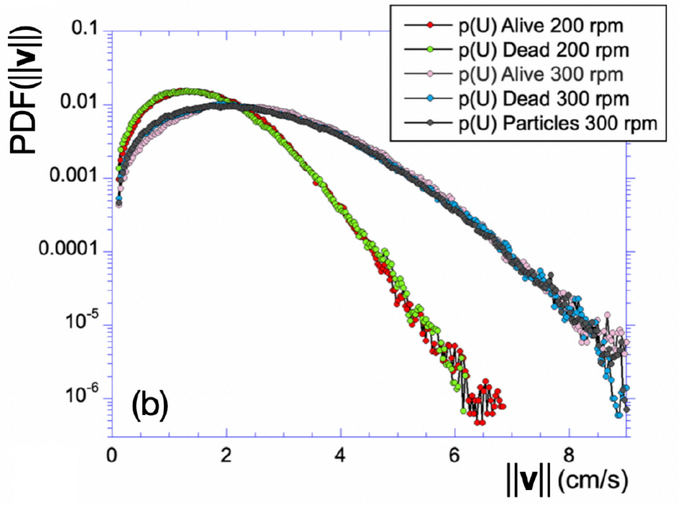
H. Ardeshiri, I. Benkeddad, F. G. Schmitt, S.Souissi, F. Toschi, E.C. , Phys. Rev. E 93, 043117 (2016)
H. Ardeshiri, F.G. Schmitt, S. Souissi, F.Toschi , E.C., J. Plankton Research (2017)

Swimming Microorganisms in turbulence









With F. G. Schmitt

Postdoc: Clotilde Le Quinou

C. Le Quinou, F. G. Schmitt, Y. Huang, E. C. , S.Souissi, Eur. Phys. J. Plus (2022)

Part 2:
Phase-change processes in the presence of flows



Melting, freezing and… aging

Melting and Thermal Convection

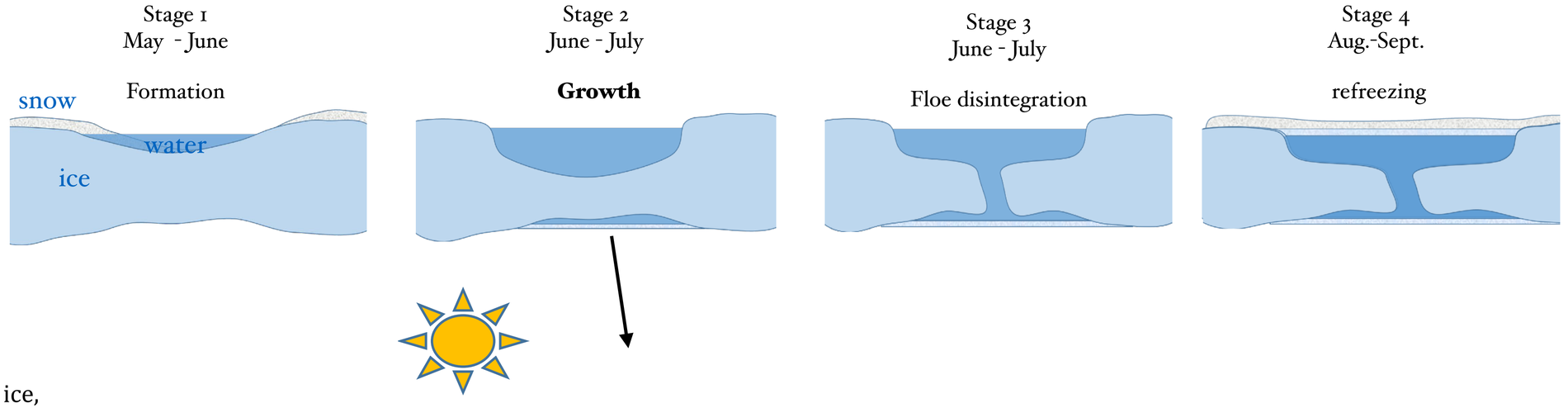
Motivation: Global warming and Arctic melt ponds

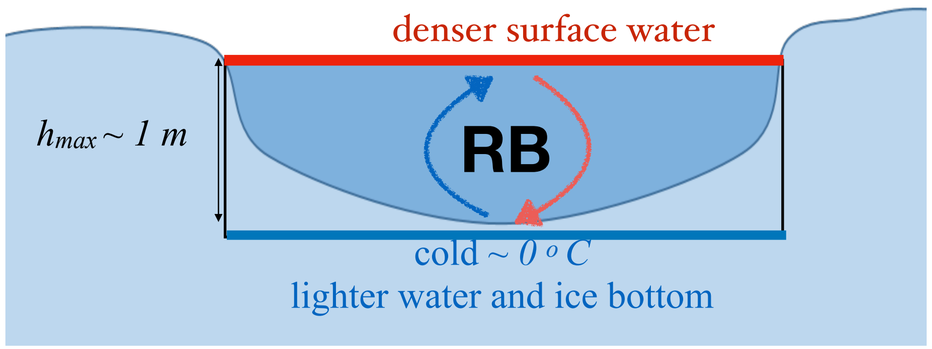


Fetterer, F., and N. Untersteiner,

Observations of melt ponds on Arctic sea ice,

J. Geophys. Res., 103, (1998)



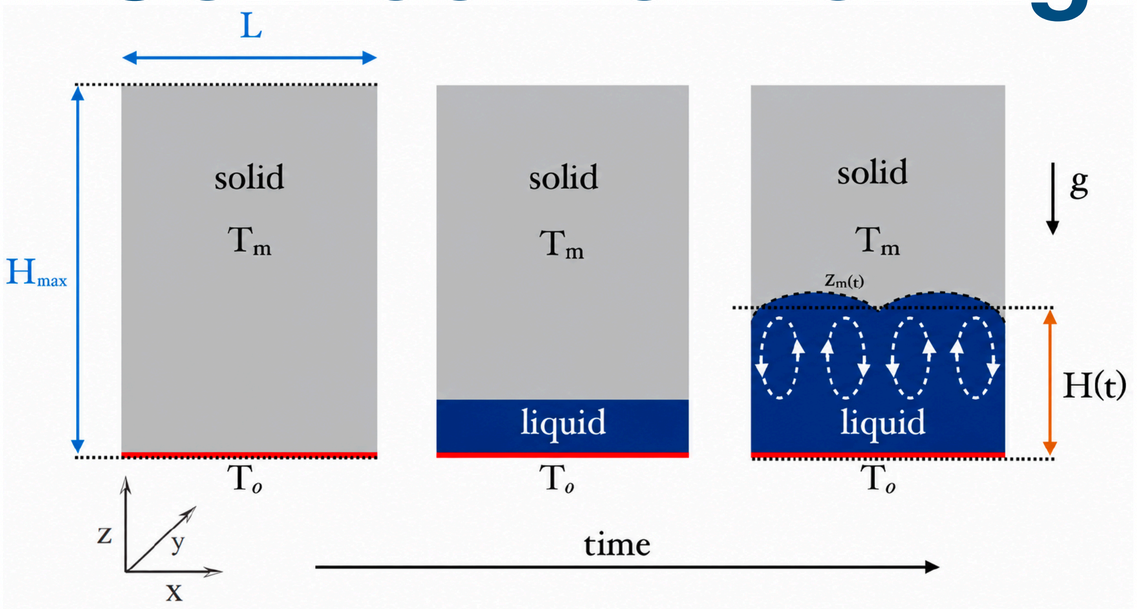




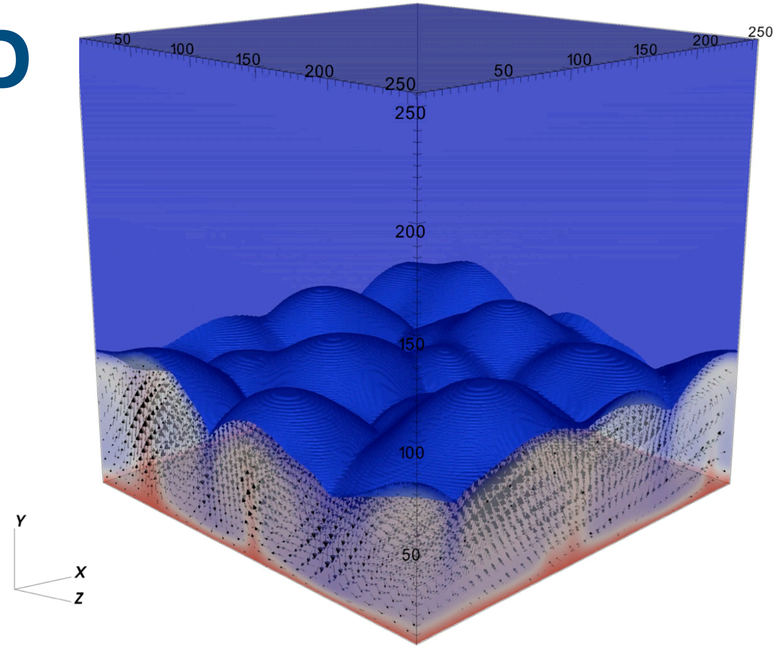
Silvia Hirata

Arctic ice melt ponds are unstably stratified → Thermal convection speeds up melting

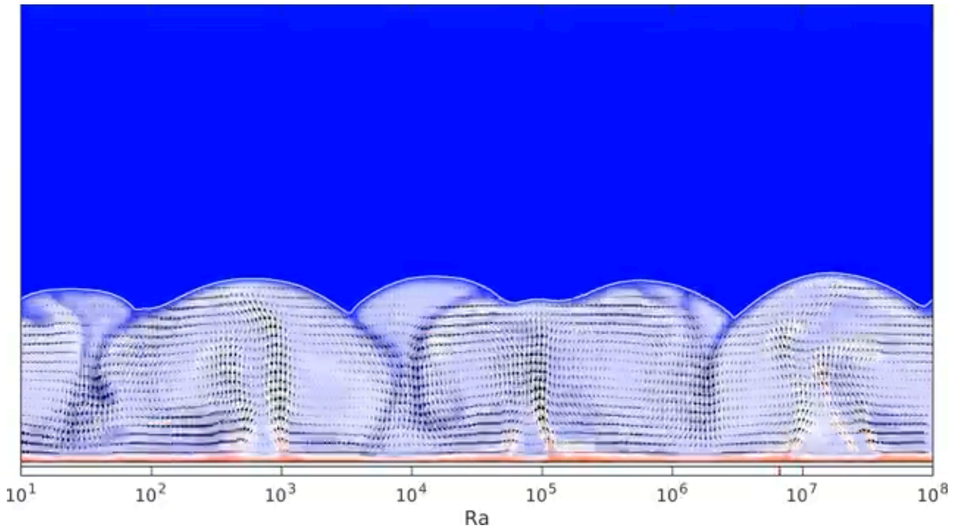
Convective melting



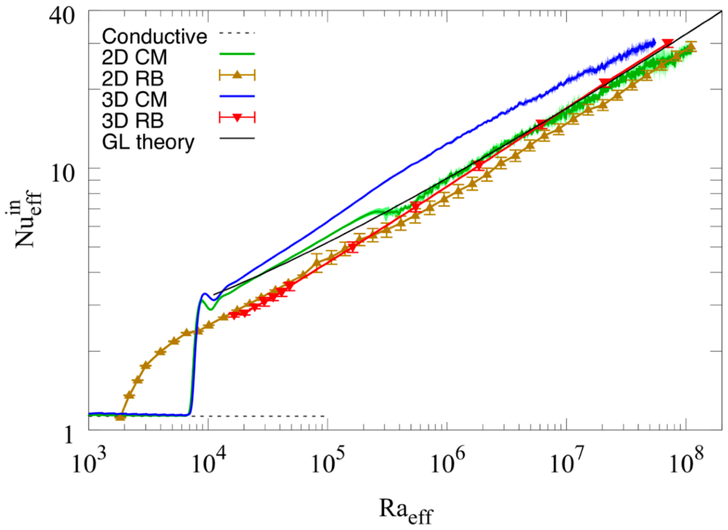
3D

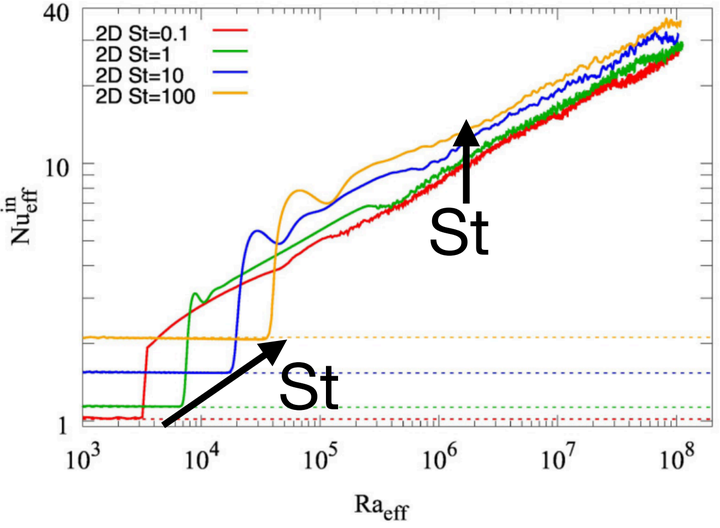


2D



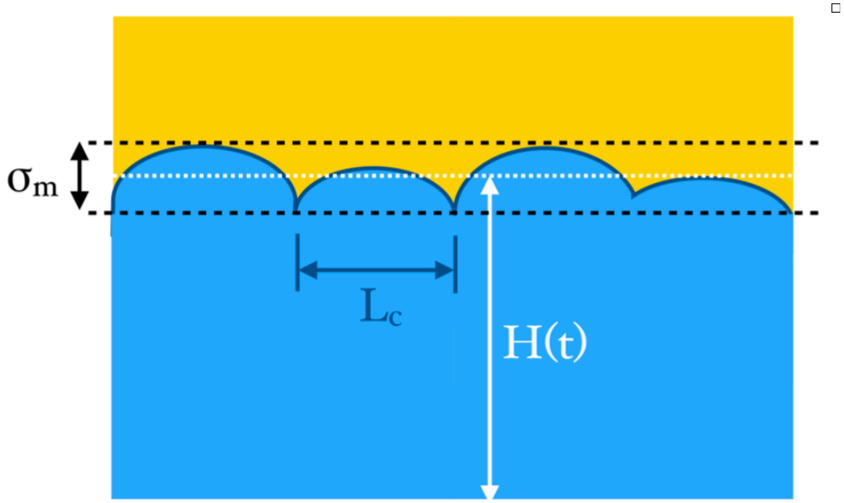
Global scaling laws



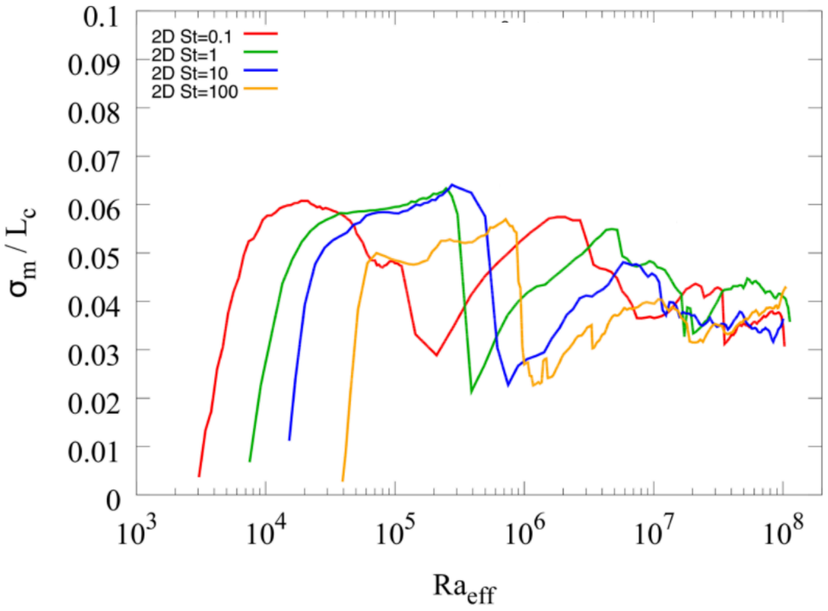


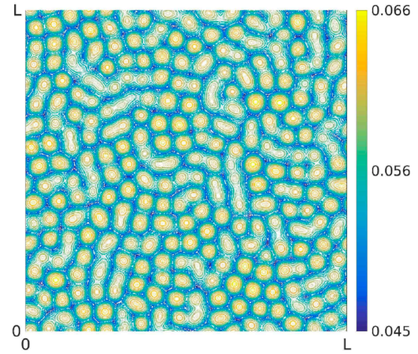
B. Rabbanipour, S.Hirata, S.Berti, EC. **Phys. Rev. Fluids** (2018)

Melting topography

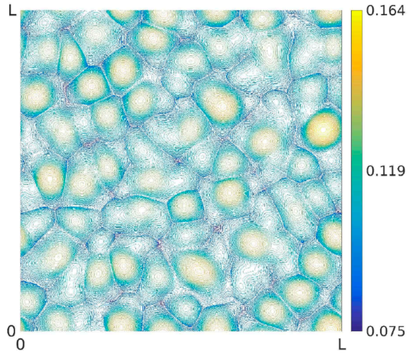


Roughness depth / lenght

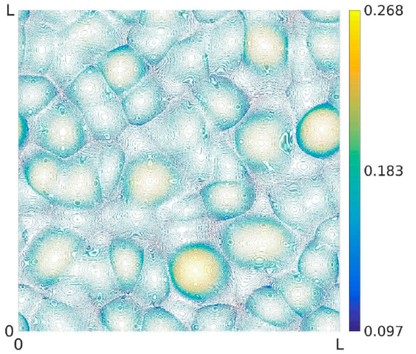




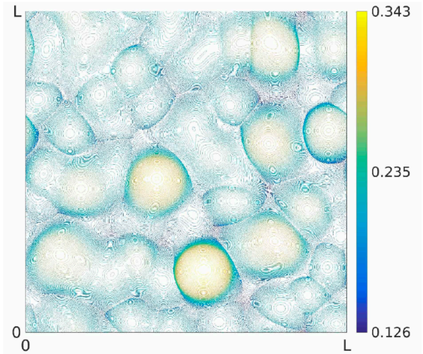
(a) $Ra_{\text{eff}} = 1.76 \times 10^4$



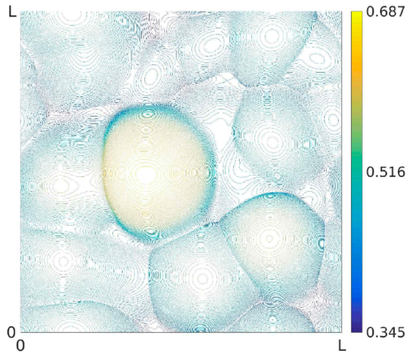
(b) $Ra_{\text{eff}} = 1.41 \times 10^5$



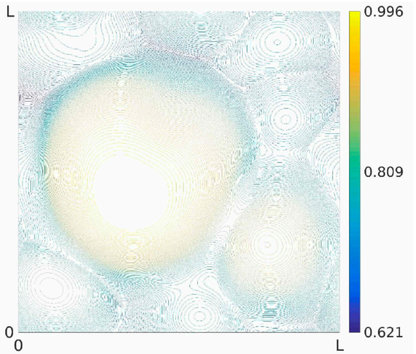
(c) $Ra_{\text{eff}} = 4.57 \times 10^5$



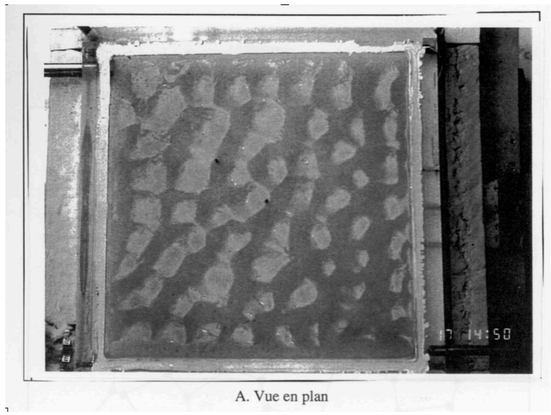
(d) $Ra_{\text{eff}} = 1.04 \times 10^6$

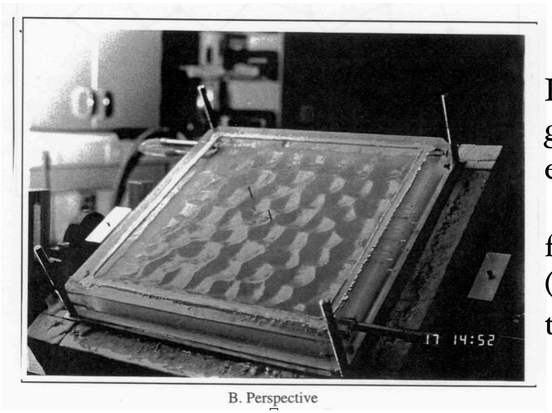


(e) $Ra_{\text{eff}} = 1.15 \times 10^7$



(f) $Ra_{\text{eff}} = 5.54 \times 10^7$





Hill & Jaupart glycerol experiment

from X.Hill (1996) PhD thesis

B. Rabbanipour, S.Hirata, S.Berti, EC. **Phys. Rev. Fluids** (2018)

Melting of multiple melt ponds

Sensitivity to small scale heat transfer mechanism



A. Scagliarini (CNR, Rome)

$$h(x,y,t),\ w(x,y,t)$$



ice thickness

$$\partial_t h = -\dot{f}$$

Melting rate

water thickness (=pond depth)

$$\partial_t w = -\nabla \cdot (\mathbf{u}w) + \frac{\rho_i}{\rho_w}\dot{f} - s$$

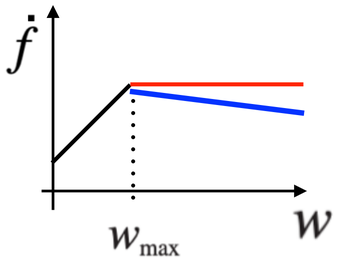
Meltwater flux

Seepage rate

$$\dot{f} = \dot{m}_i + \dot{m}_p \left(\frac{w}{w_{\max}}\right)^{\alpha}, \quad \text{with } \alpha = \begin{cases} 1 & \text{if } w \in [0, w_{\max}] \\ 3c-1 & \text{if } w > w_{\max}, \end{cases}$$

$w_{\max} \approx 0.1\text{m}$ radiation-conduction

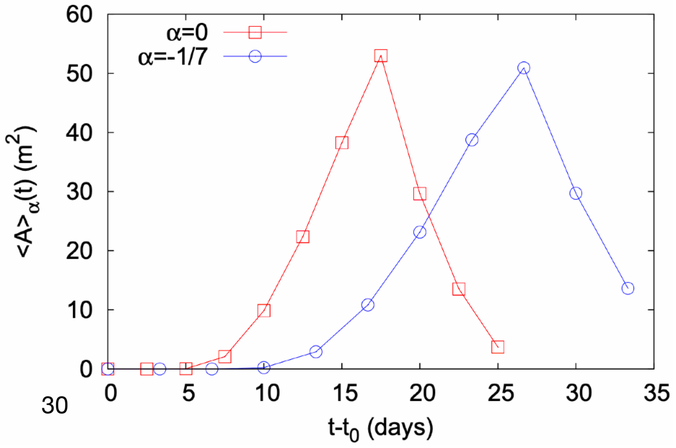
convection

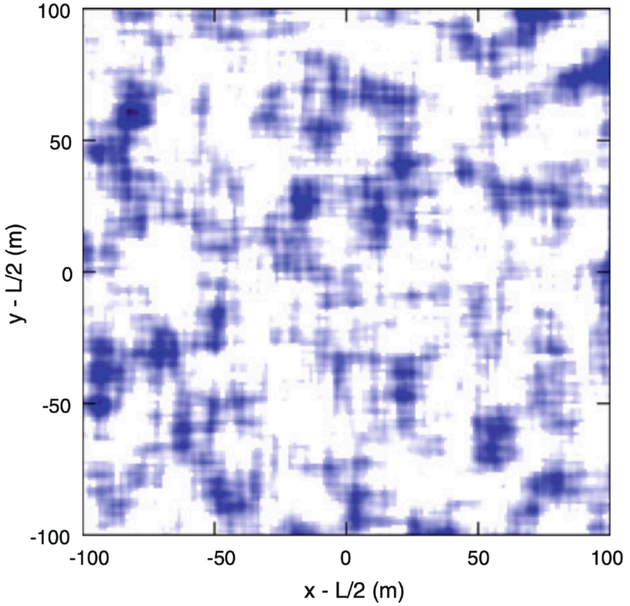


$$Nu_{eff} \sim Ra_{eff}^{c}$$

$c = \frac{1}{3}$ classical

$c = \frac{2}{7}$ anomalous

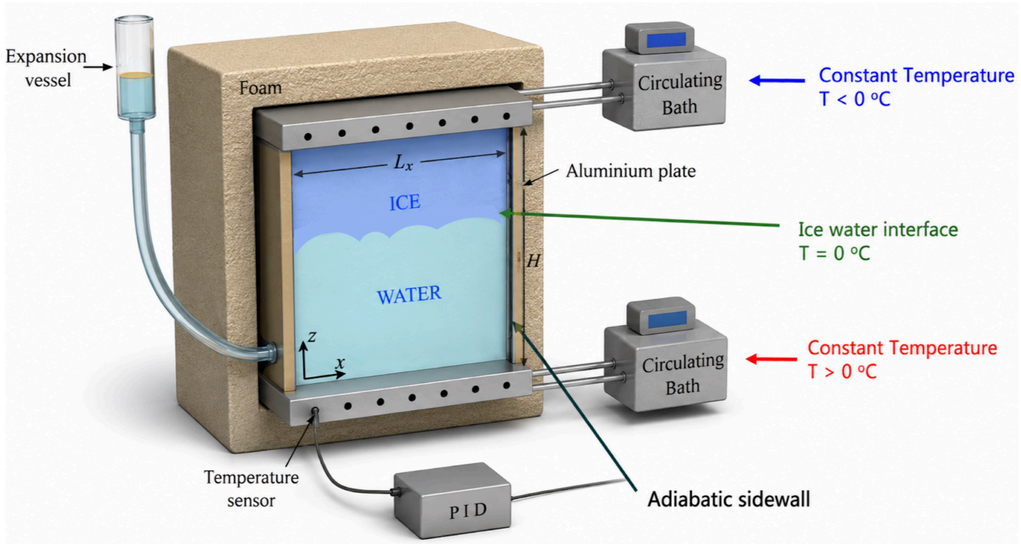




A. Scagliarini, EC, D. Mansutti and F. Toschi Springer INdAM Series, (2020)

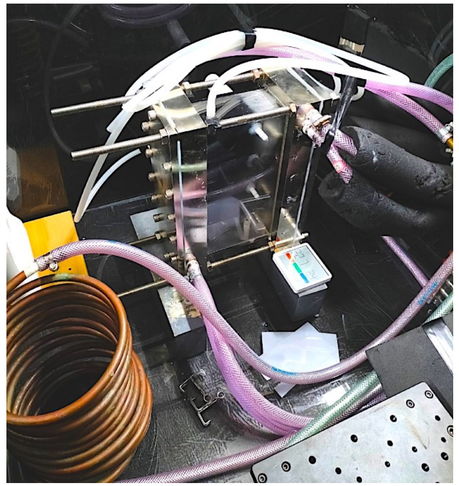
Convective Freezing in the lab

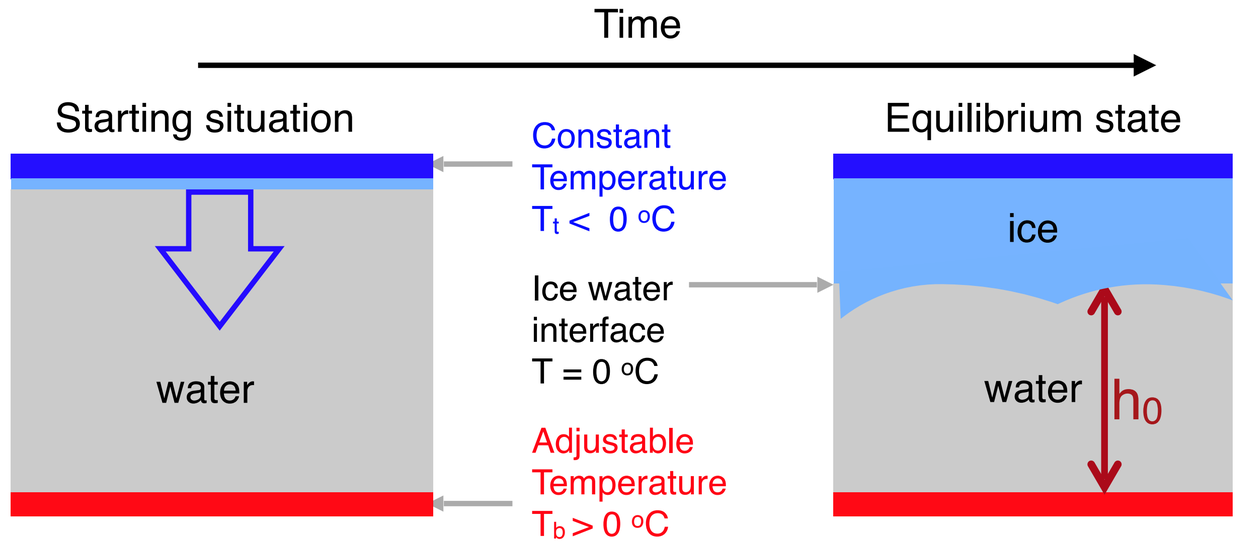
Experimentalists prefer freezing

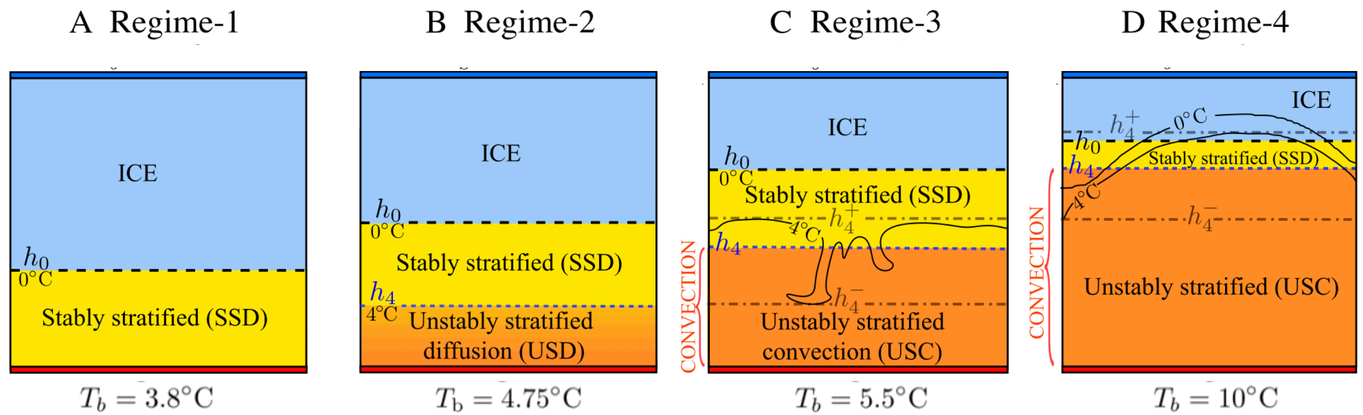




Chao Sun



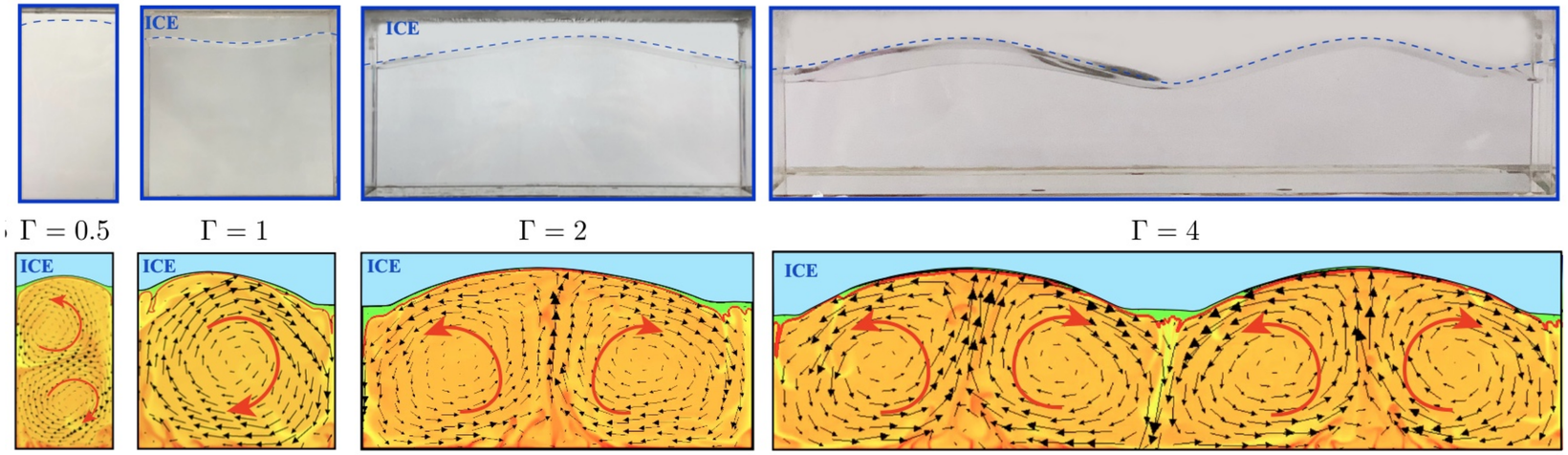




Z. Wang, EC, C. Sun, F. Toschi, PNAS (2021)

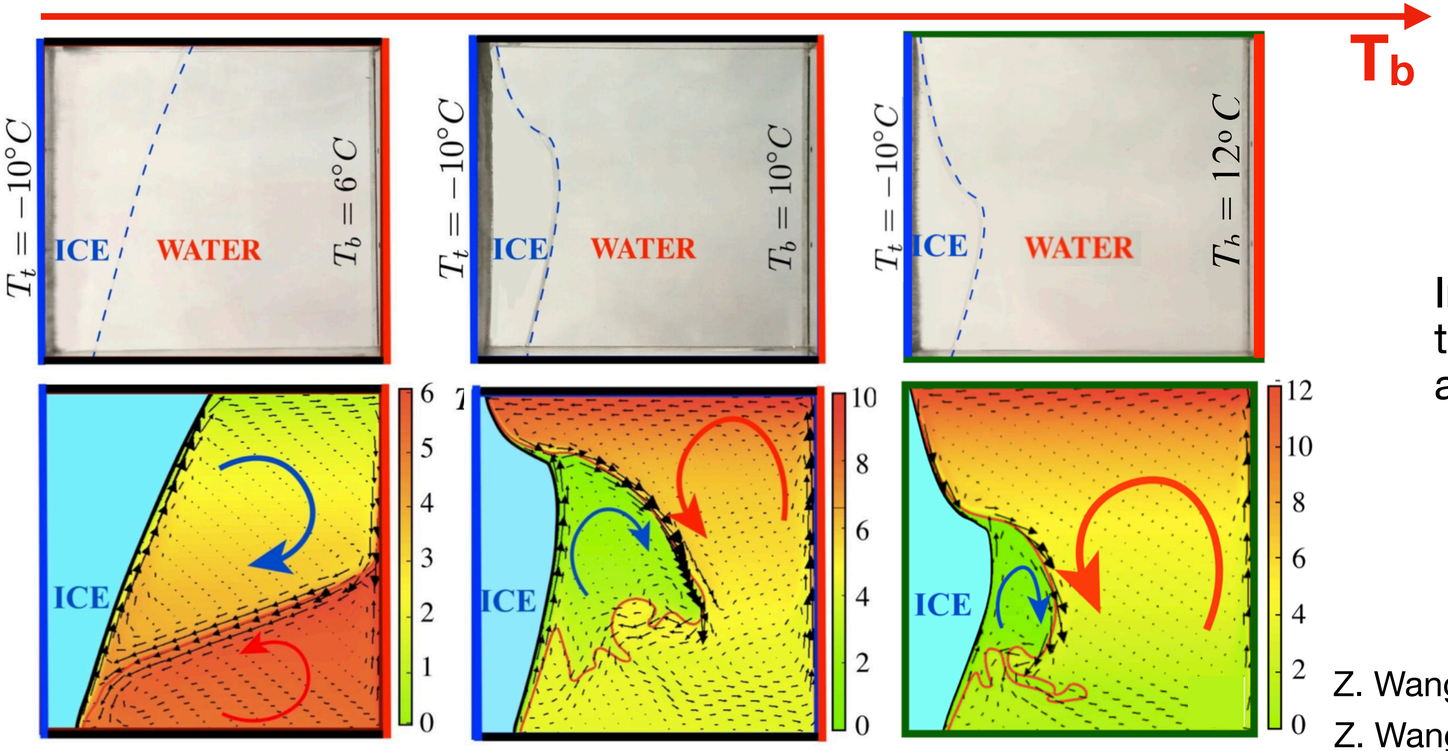
Boxes of all kinds

RB varying box aspect ratio Γ



the Large Scale Circulation determines the topography

VC varying heating temperature



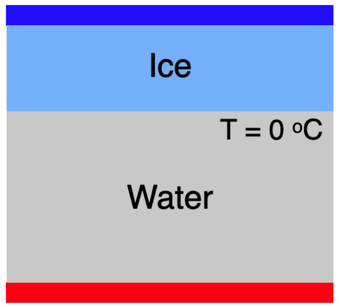
Inflexion point due to density anomaly

Z. Wang, EC, C. Sun, **EPL (**2021)

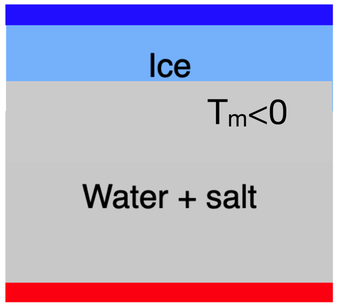
Z. Wang, L. Jiang, Y. Du, C. Sun, EC **Phys. Rev. Fluids** (2021)

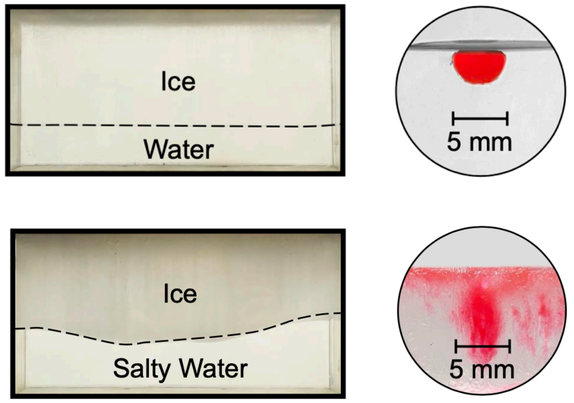
Just adding some salt

Icing in pure water



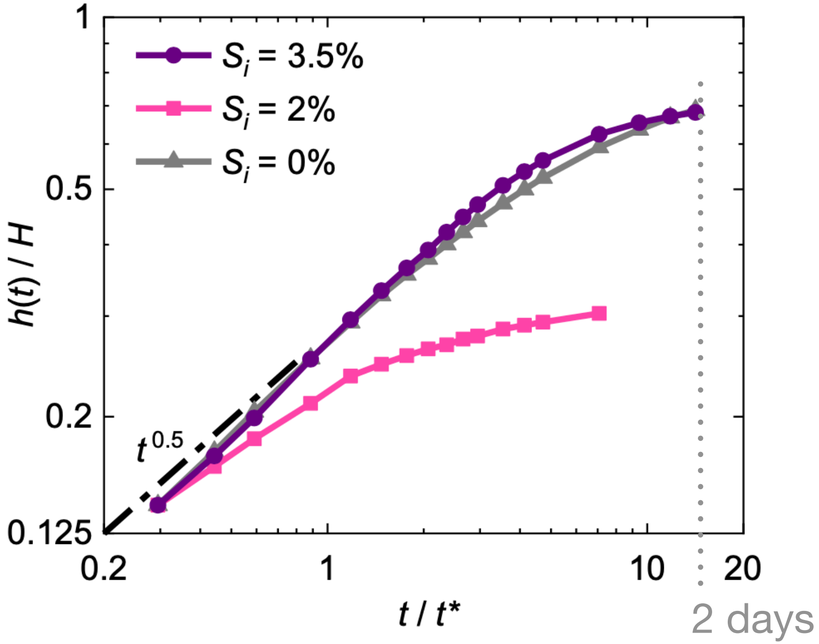
Icing in salty water

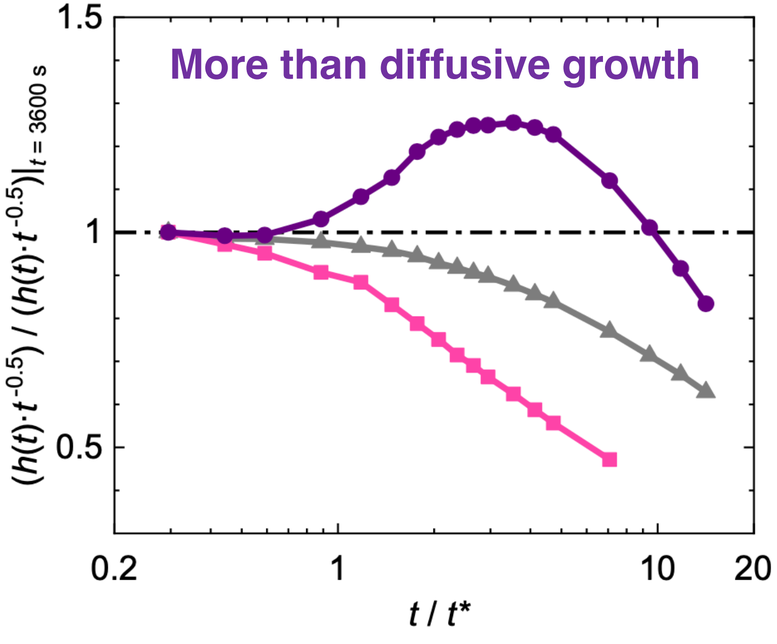


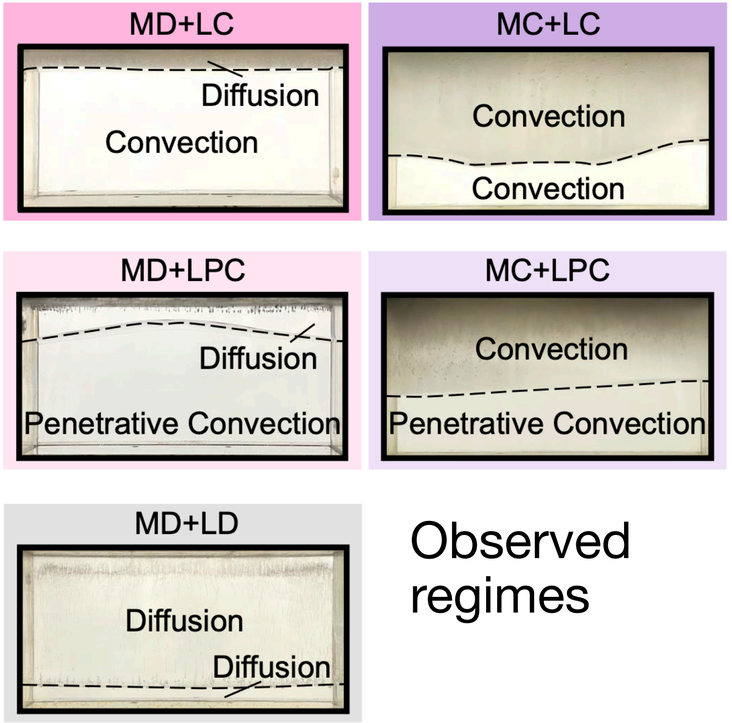


The ice is porous,
is a **mushy layer**

Ice layer growth in salty water







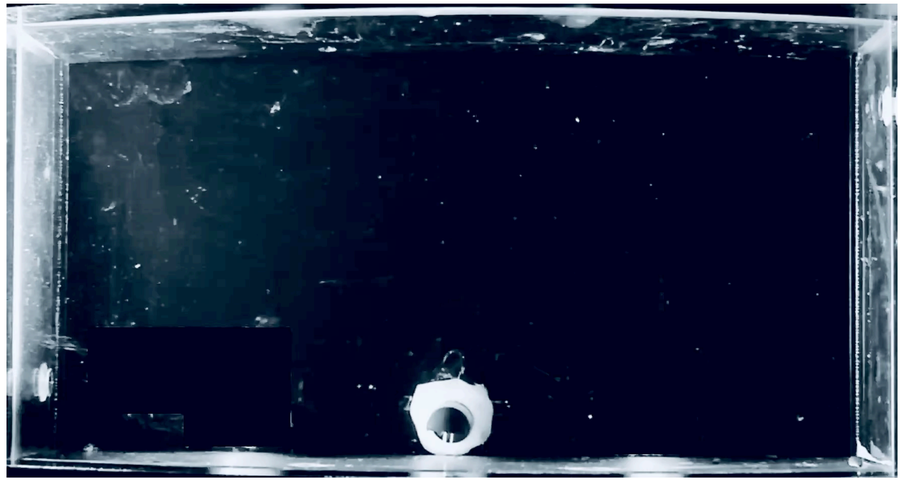
Observed regimes

Y.Du, Z.Wang, L.Jiang, EC, C.Sun, JFM (2023)

Ice aging A very long time scale

~20 days experiments

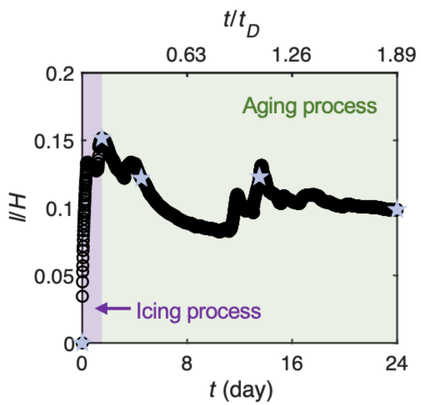
RB



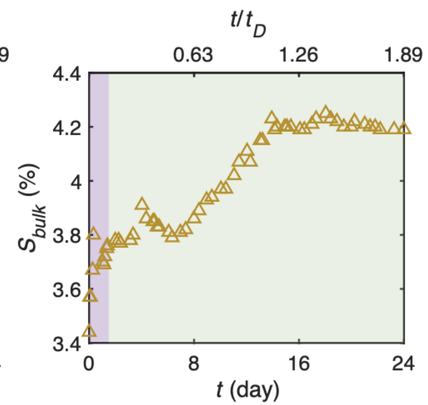
VC



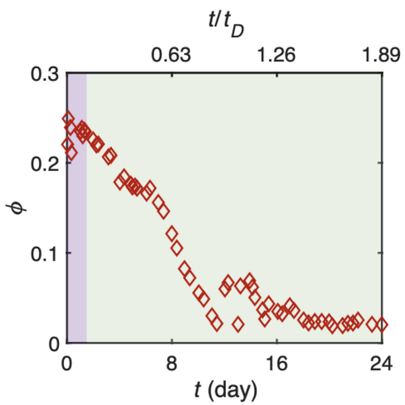
Ice thickness

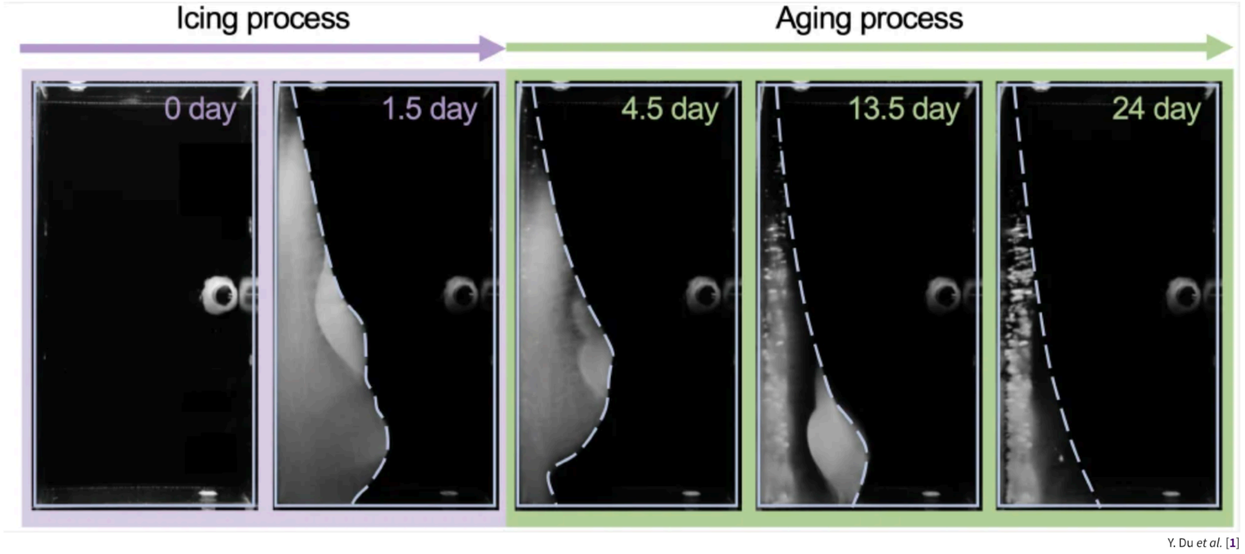


Bulk salinity



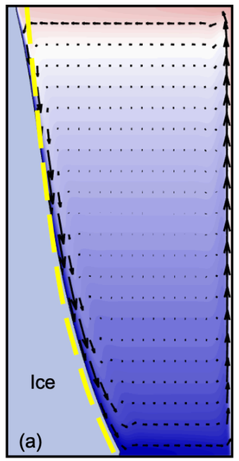
Ice Porosity





Y. Du *et al.* [1]

DNS of final state



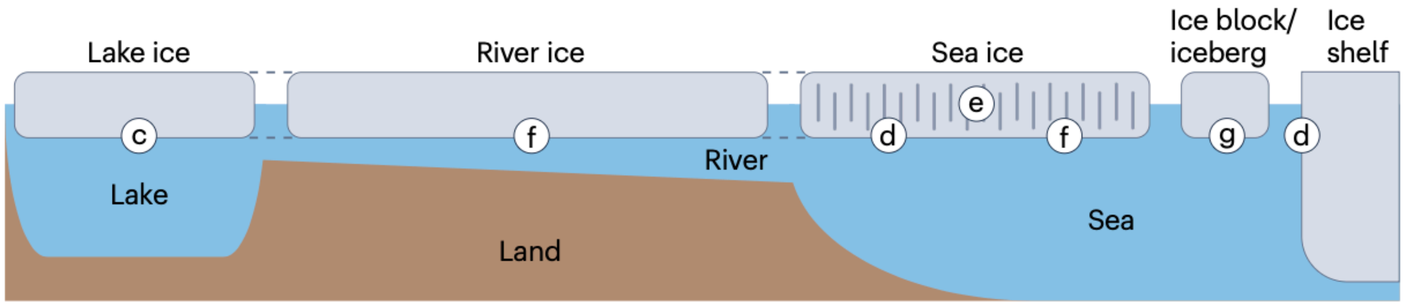
Y.Du, Z.Wang, EC, C.Sun, PRL (2025)

Freezing and melting in the presence of flows

Perspective

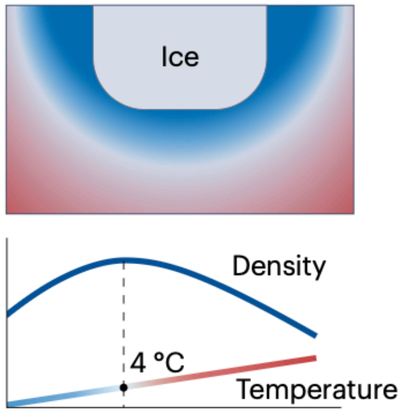
Du, Calzavarini, Sun, Nature Reviews Physics (2024)





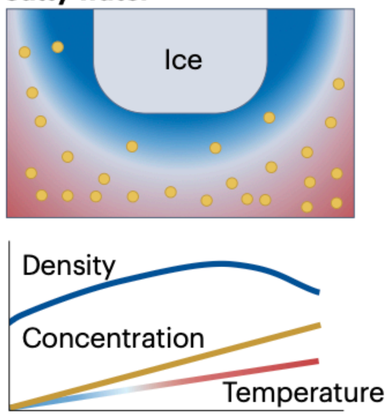
Thermally stratified convection

Fresh water



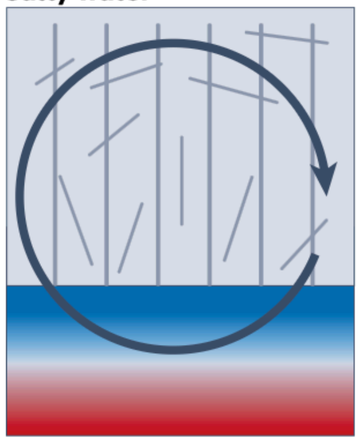
Double-diffusive convection

Salty water

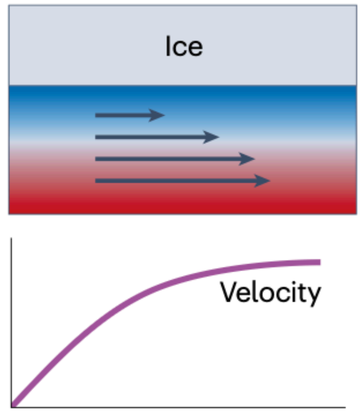


Convection in mushy ice

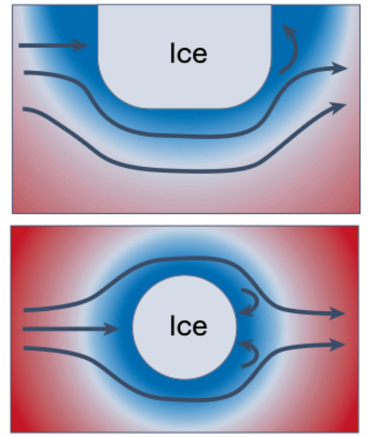
Salty water



Ice layer subject to shearing flows



Dispersed ice bodies in flows



1. My path (a little bit of history)

2. MCF in Lille (2010 -today)

3. The work ahead (some ideas)

Particles

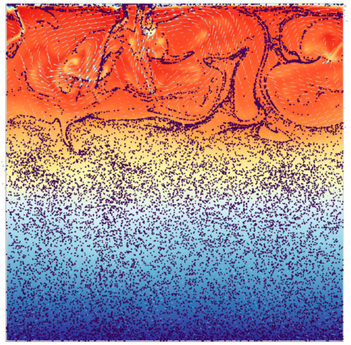
Transport in **non-homogeneous** and **non-stationary** flows



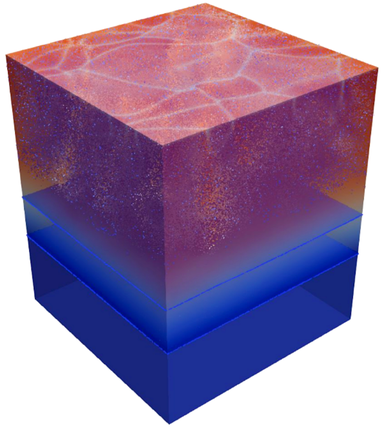
Luz



Stefano Berti

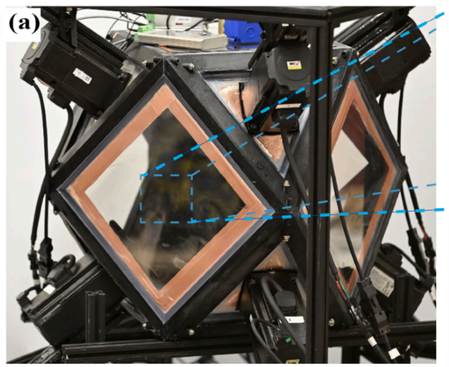


Ocean mixed-layer model



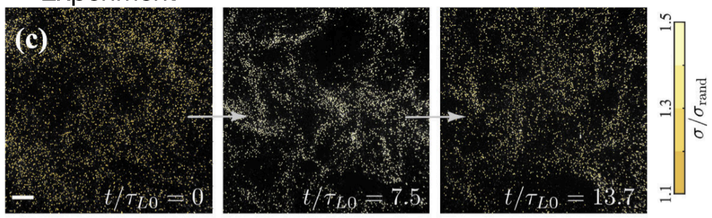


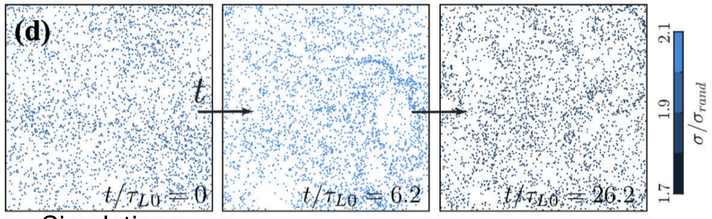
Varghese Mathai
Univ. Massachusetts



Decaying turbulence

Experiment





Simulations

Thermal/mechanical particle feedbacks on convective flows

with applications to thermal energy storage



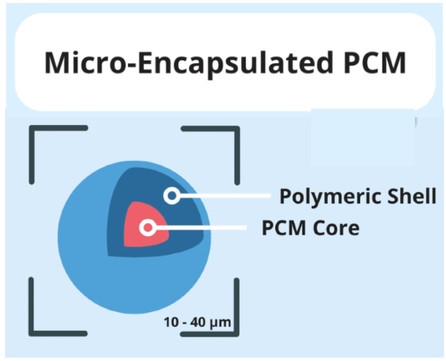
Ousman

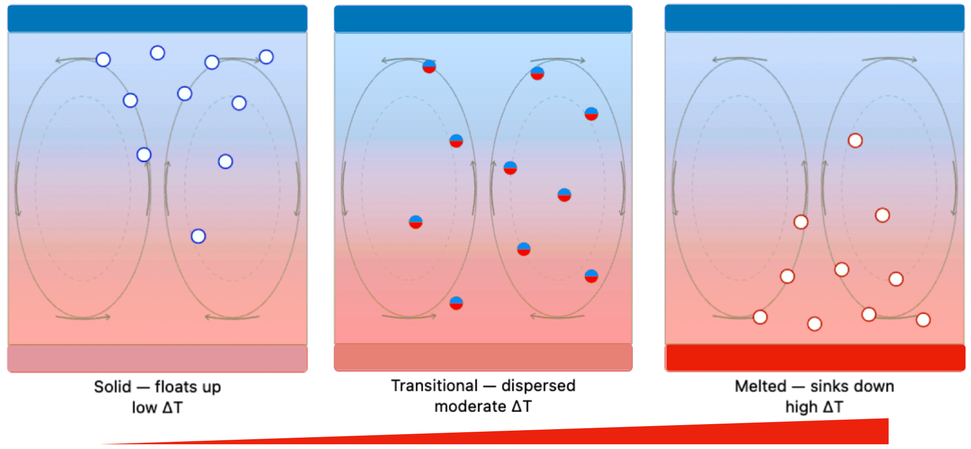


Silvia HIRATA



Particles and convective onset





Tom Lacassagne
Amir Bahrani (IMT)

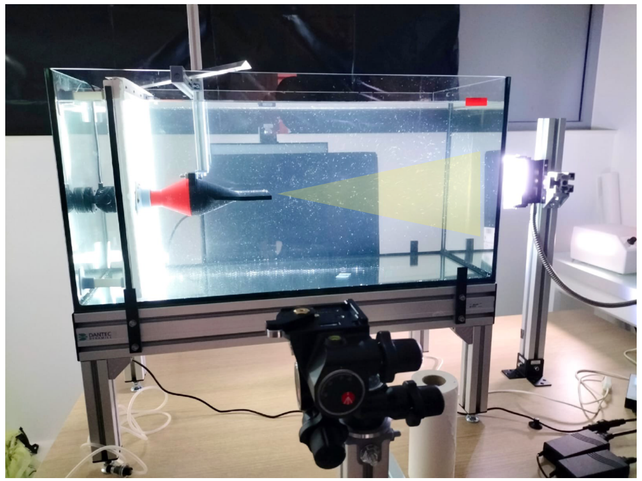
Plankton

Effect of turbulence variability in space and time on copepods: experiments

F.G.Schmitt
A.Delegrange

M.Obligado

Laboratoire de Mécanique des Fluides de Lille Kampé de Fériet

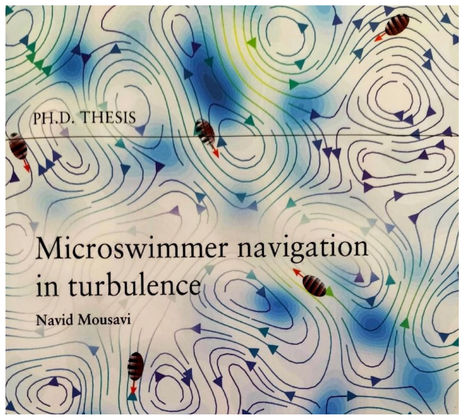




Adrien Defamie



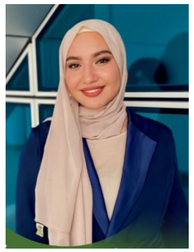
Learning from data to conceive new mechanistic models



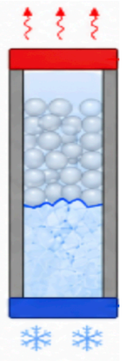
Ice

High-fidelity simulations of salty-ice evolution ↔ lab experiments

Freezing/melting in porous media and mushy-ice



Takwa Abdallah



With
F. Zouestiagh
A. Duchesne
S. Hirata

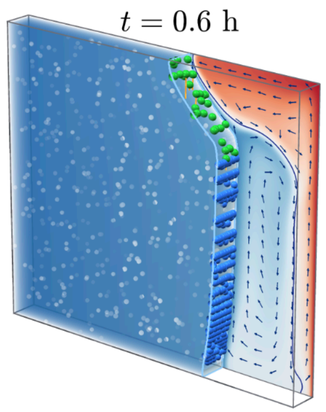
Role of entrapped air bubbles

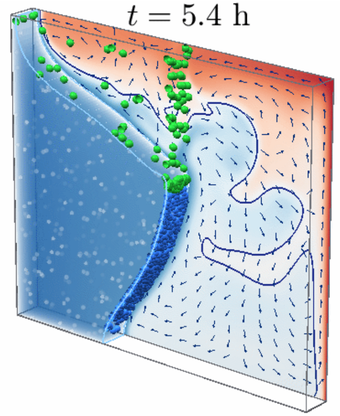
With Chao SUN (Beijing)



Jin Hu (PDoc)







Interact with geoscientists!



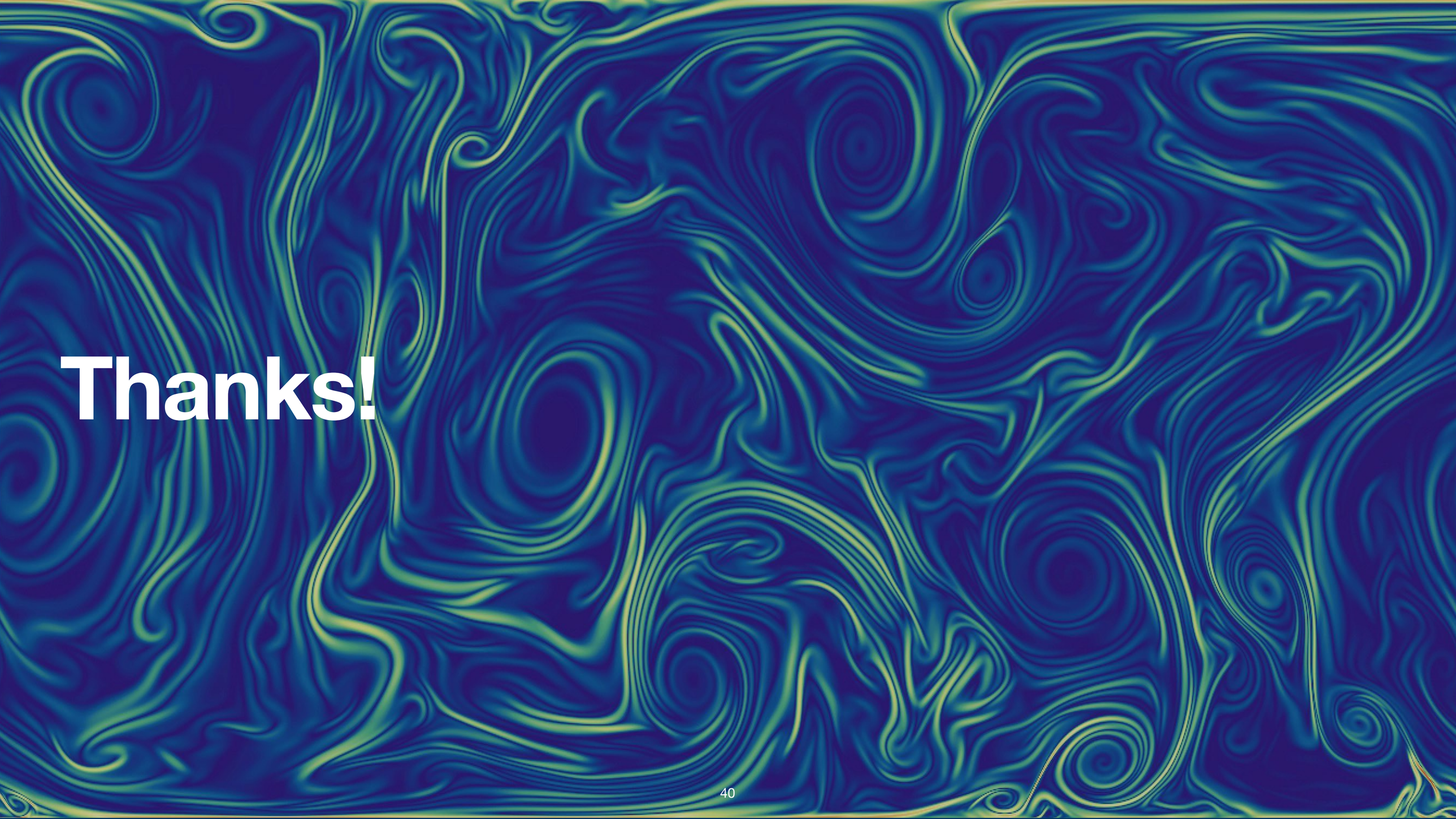
Martin Vancopenolle

sea ice transport dynamics??

Lab-scale analogues of geophysical processes??



Discrete elements model of sea ice
Manucharyan & Montemuro (2022)


Thanks!