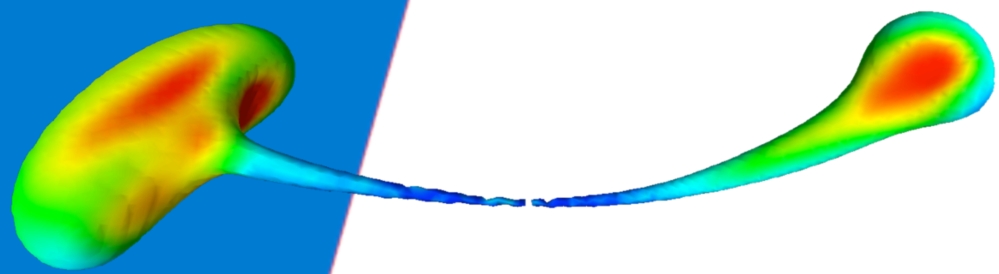
Droplets dynamics and breakup in turbulence



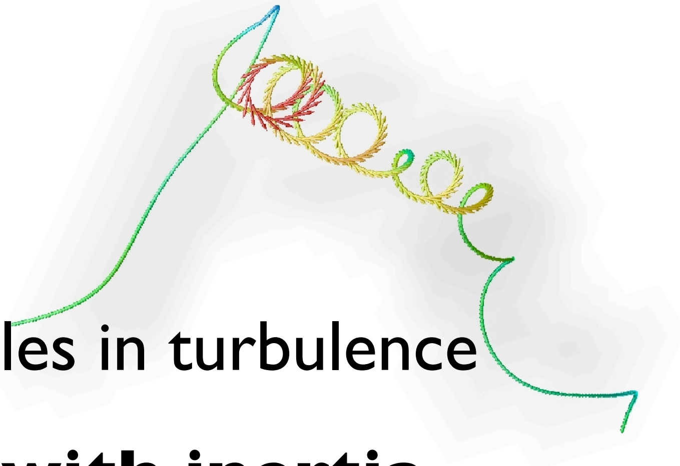
Federico Toschi

Technische Universiteit Eindhoven University of Technology

Euromech colloquium 513
Dynamics of non-spherical particles in fluid turbulence
Udine, Italy (anno 2011)

Where innovation starts

Aim & TOC



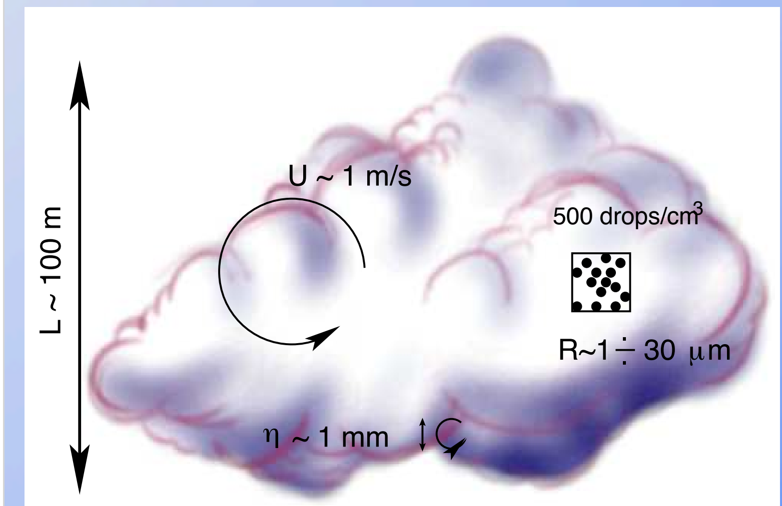
- Motivations to study particles in turbulence
- **Tracers and particles with inertia**
- **Finite size (non deformable) particles**
- **Finite size (deformable) droplets**
- **Rodlike particles (and why?)**

Rain Drops, Cloud Droplets, and CCN

Raind drop size
2mm

Droplet size
0.02mm

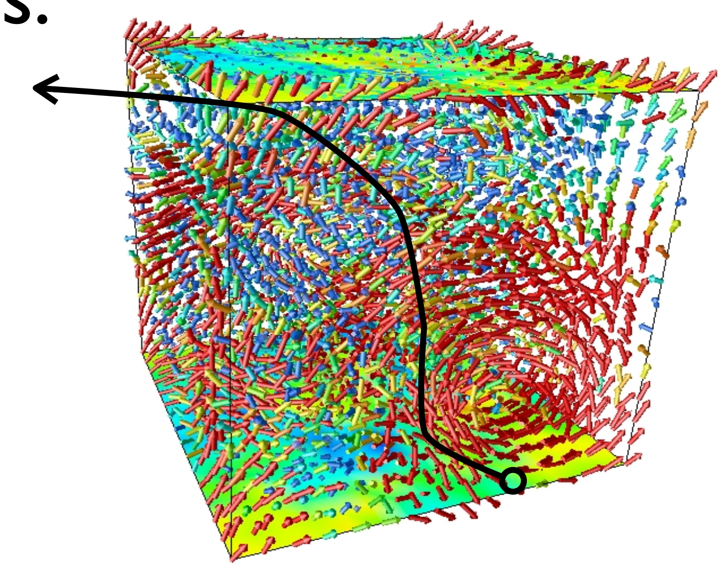
CCN size
2micron



Aerosol particles: 1micron - 0.1mm

Tracers

Particles small "enough" can be described as "neutral" tracers.

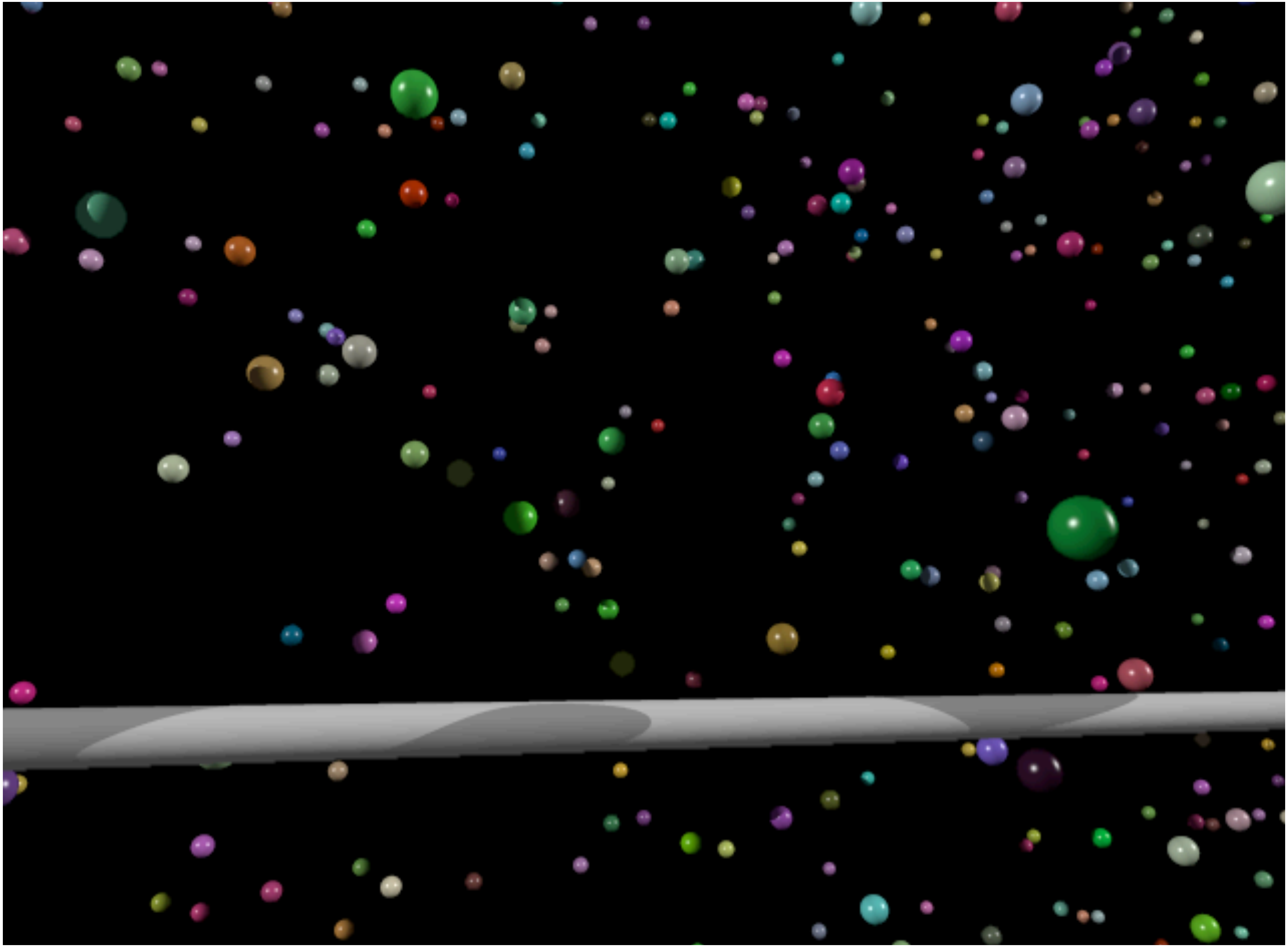


No modeling needed !!

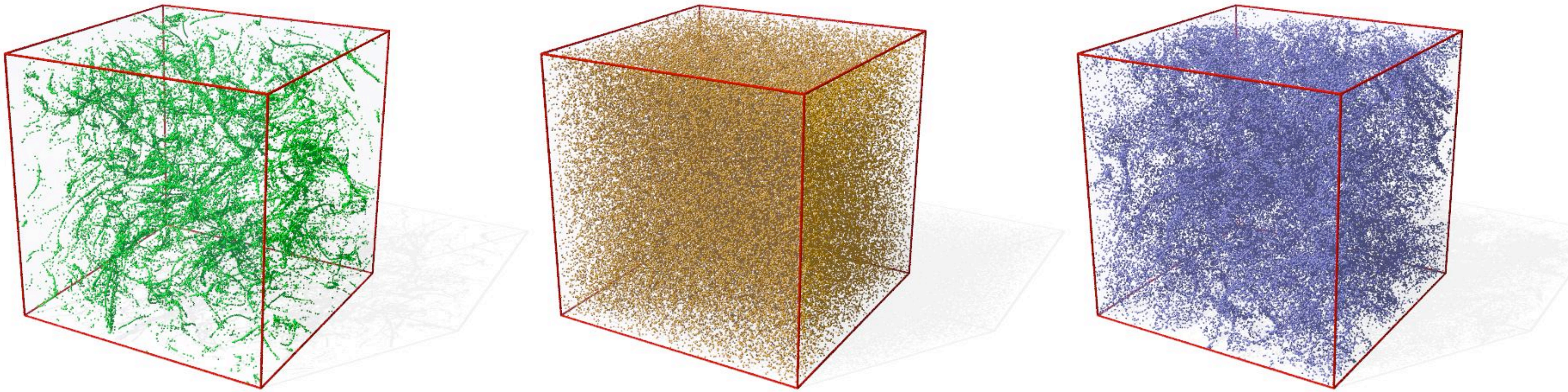
Equation of motion of tracer is:

$$\frac{d\boldsymbol{x}}{dt}(t|\boldsymbol{x}_0, t_0) \equiv \boldsymbol{u}_L(t|\boldsymbol{x}_0, t_0)$$

$$\boldsymbol{u}_L(t|\boldsymbol{x}_0, t_0) \equiv \boldsymbol{u}_E(\boldsymbol{x}(t|x_0, t_0), t)$$



Particles with inertia

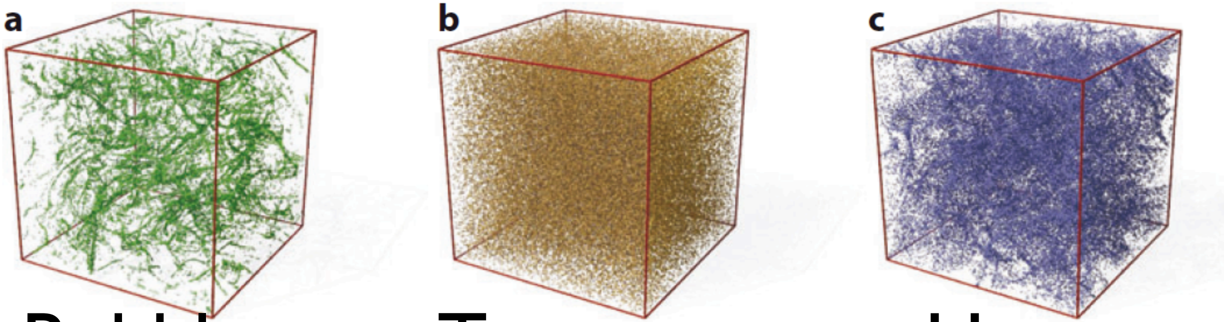


Light Neutral Heavy

$$\frac{d\boldsymbol{v}(t)}{dt} = -\frac{1}{\tau}\left(\boldsymbol{v}(t) - \boldsymbol{u}(\boldsymbol{x}(t);t)\right) + \beta\frac{D\boldsymbol{u}}{Dt}$$

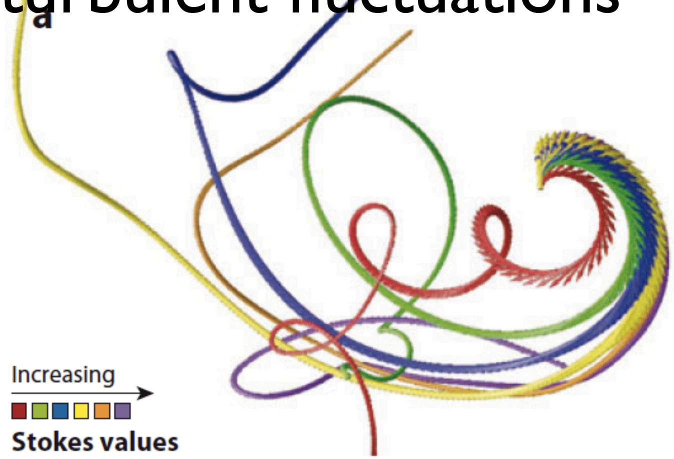
All effects of inertia, in a slide...

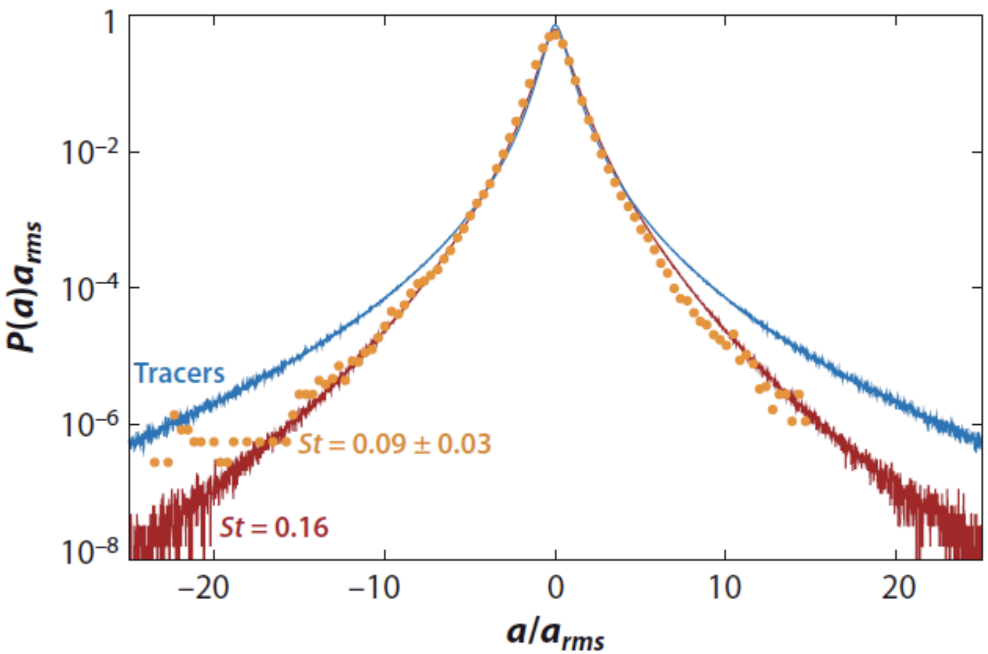
Preferential concentration

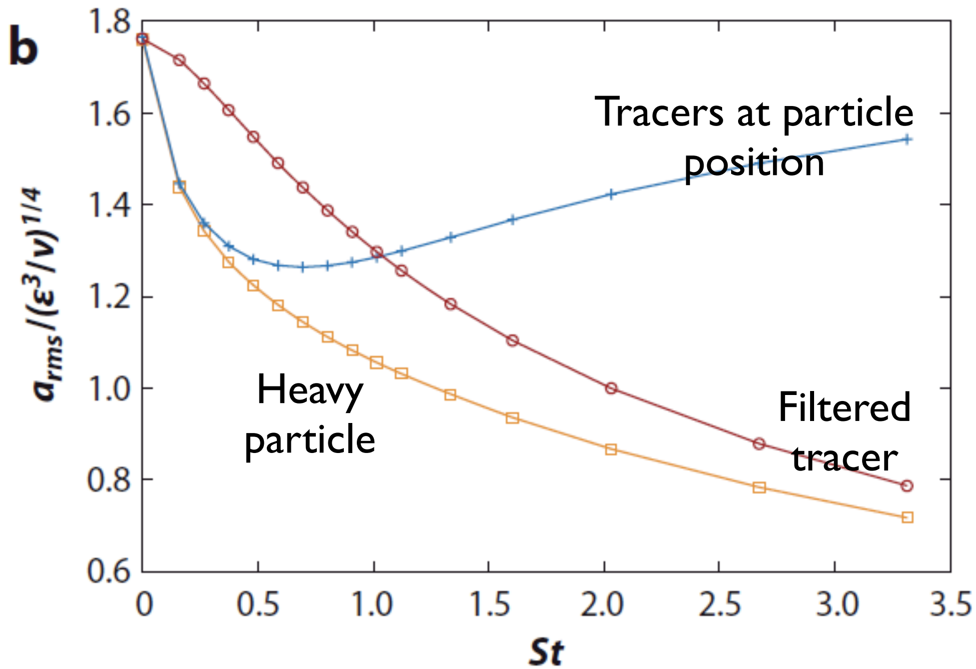


Bubbles Tracers Heavy

Filtering of turbulent fluctuations

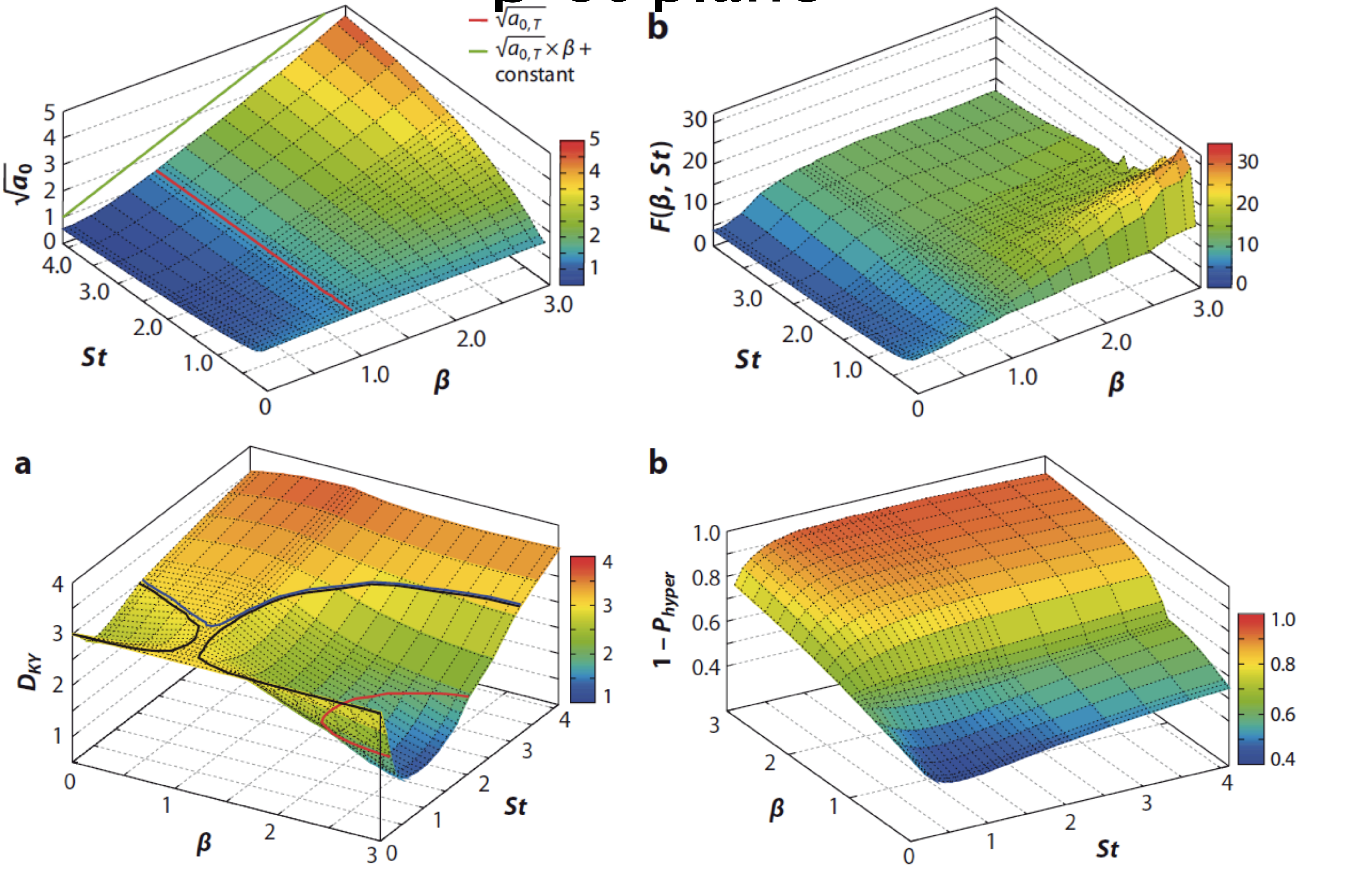






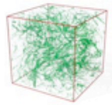
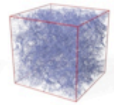
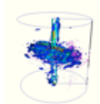
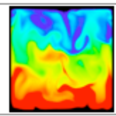
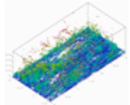
Toschi and Bodenschatz. Lagrangian properties of particles in Turbulence. Ann. Rev. Fluid Mech. (2009) vol. 41 pp. 375-404

β-St plane



b
a
b
$\sqrt{a_{0,T}}$
$\sqrt{a_{0,T}} \times \beta +$ constant
$\sqrt{a_0}$
St
β
F(β, St)
D_{KY}
$1 - P_{hyper}$

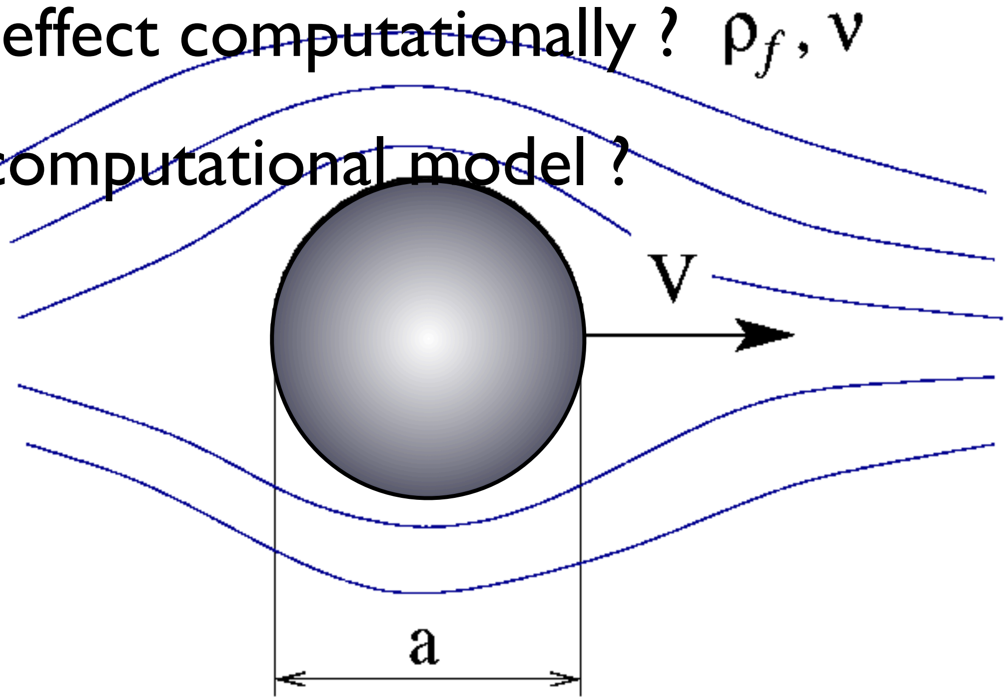
iCFDdatabase2

Parent dataset	Dataset or datafile	Contact person	Size	Info	URIs	metalink
iCFDdatabase2	iCFDdatabase2	Federico Toschi	1.7 TB			
iCFDdatabase2	Inverse cascade turbulence	Guido Boffetta	1.19 GB			
Lagrangian turbulence	Lagrangian tracers in 3D homogeneous and isotropic turbulent velocity field	Federico Toschi	0 B			
Lagrangian turbulence	Heavy point-wise Lagrangian particle evolution in homogeneous and isotropic turbulent velocity field from a 2048 cubed DNS	Federico Toschi	1.4 TB		  	
iCFDdatabase2	Lagrangian turbulence	Federico Toschi	1.55 TB			
iCFDdatabase2	Database of Particles Dispersed in Turbulent Channel Flow	Cristian Marchioli	144.19 GB			
iCFDdatabase2	Passive tracers	Federico Toschi	0 B			
iCFDdatabase2	2D Turbulence	Alessandra Lanotte	5.18 MB			
iCFDdatabase2	Database of Particles Dispersed in a Stirred-Tank Reactor	Valentina Lavezzo	57.97 MB			
iCFDdatabase2	DNS of a spatially-developing turbulent boundary layer over a flat plate	Antonino Ferrante	9.3 GB			
iCFDdatabase2	Thermal convection	Federico Toschi	2.85 GB			
iCFDdatabase2	STATISTICS FROM DNS OF TURBULENT CHANNEL FLOW IN VERY LARGE NUMERICAL BOXES Re_tau = 180-550-950-2000	Javier Jimenez	2.13 GB			

http://mp0806.cineca.it/icfd.php

Finite size (non deformable)

- Particles that are large with respect to turbulent scales do have an effective inertia even when neutrally buoyant (e.g. plankton aggregates)
- What is the relations between size-induced and density-induced inertia ?
- How to model these effect computationally ?
- How to validate the computational model ?



Minimal bibliography

- Maxey MR, Riley JJ. Equation of motion for a small rigid sphere in a nonuniform flow. Phys Fluids 1983;26(4):883–889.
- Gatignol R. The faxén formulae for a rigid particle in an unsteady non- uniform stokes flow. J Mecanique Theorique et Applique´ e 1983;1(2):143– 160.
- Auton T, Hunt J, Prud'homme M. The force exerted on a body in inviscid unsteady non-uniform rotational flow. J Fluid Mech 1988;197:241–257.
- Lovalenti PM, Brady JF. The hydrodynamic force on a rigid particle undergoing arbitrary time-dependent motion at small reynolds number. J Fluid Mech 1993;545:561–605.

Equation of motion

$$\frac{d\mathbf{v}}{dt} = \beta \left[\frac{D\mathbf{u}}{Dt}\right]_V + \frac{3\nu\beta}{{r_p}^2}\left([\mathbf{u}]_S - \mathbf{v}\right)$$

$$+ \frac{3\beta}{r_p}\int_{t-t_h}^{t}\left(\frac{\nu}{\pi(t-\tau)}\right)^{\frac{1}{2}}\frac{d}{d\tau}\left([\mathbf{u}]_S - \mathbf{v}\right)d\tau$$

$$+ c_{Re_p}\frac{3\nu\beta}{{r_p}^2}\left([\mathbf{u}]_S - \mathbf{v}\right) + \left(1 - \frac{3\ \rho_f}{\rho_f + 2\ \rho_p}\right)\ \mathbf{g}$$

Particle radius r_p

Particle diameter $d_p = 2r_p$

$$Re_p \equiv |[\mathbf{u}]_S - \mathbf{v}|\, d_p/\nu$$

$$\beta \equiv \frac{3\ \rho_f}{(\rho_f + 2\ \rho_p)}$$

PP vs. FC models

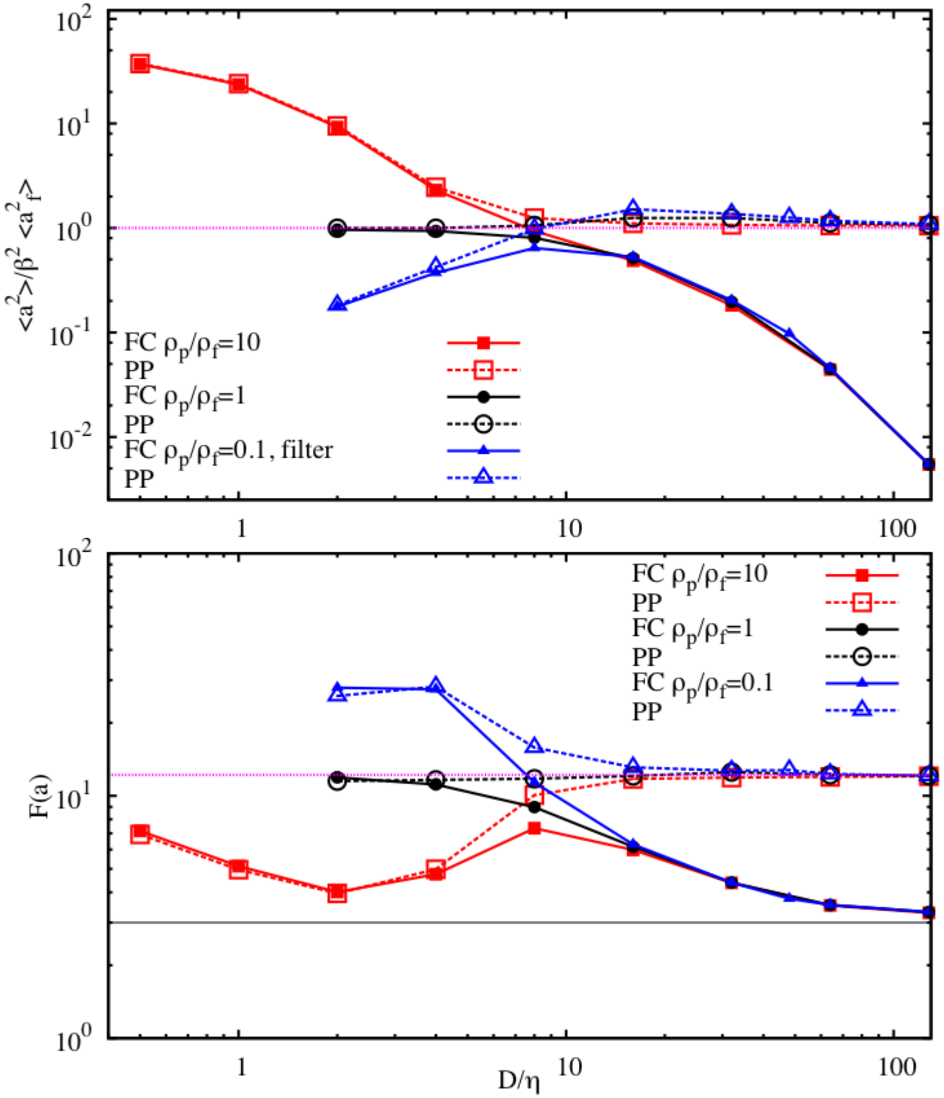
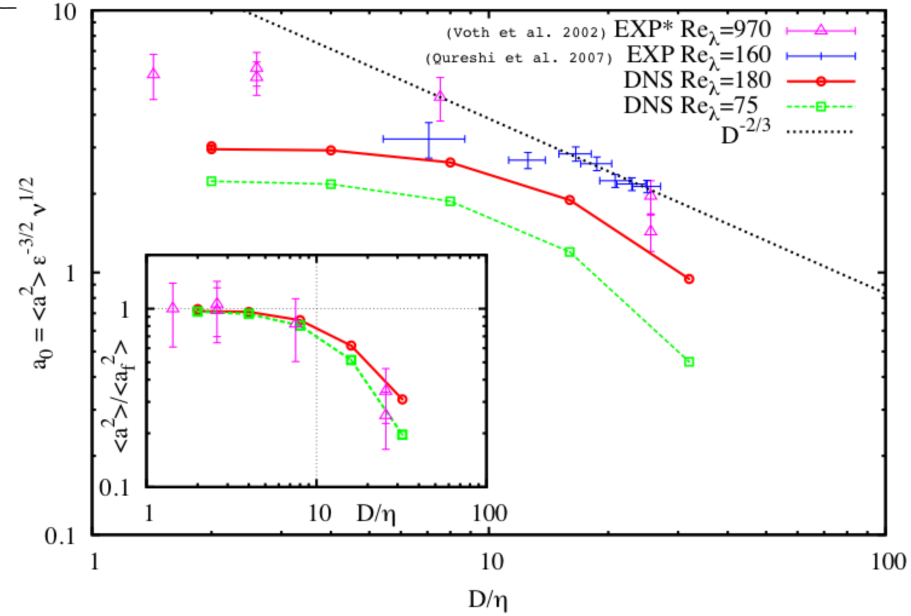
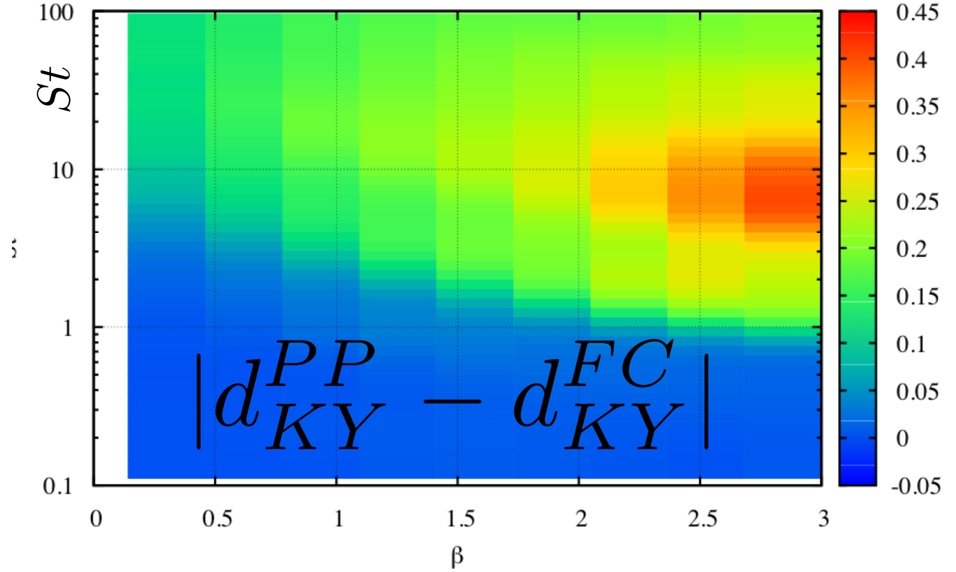


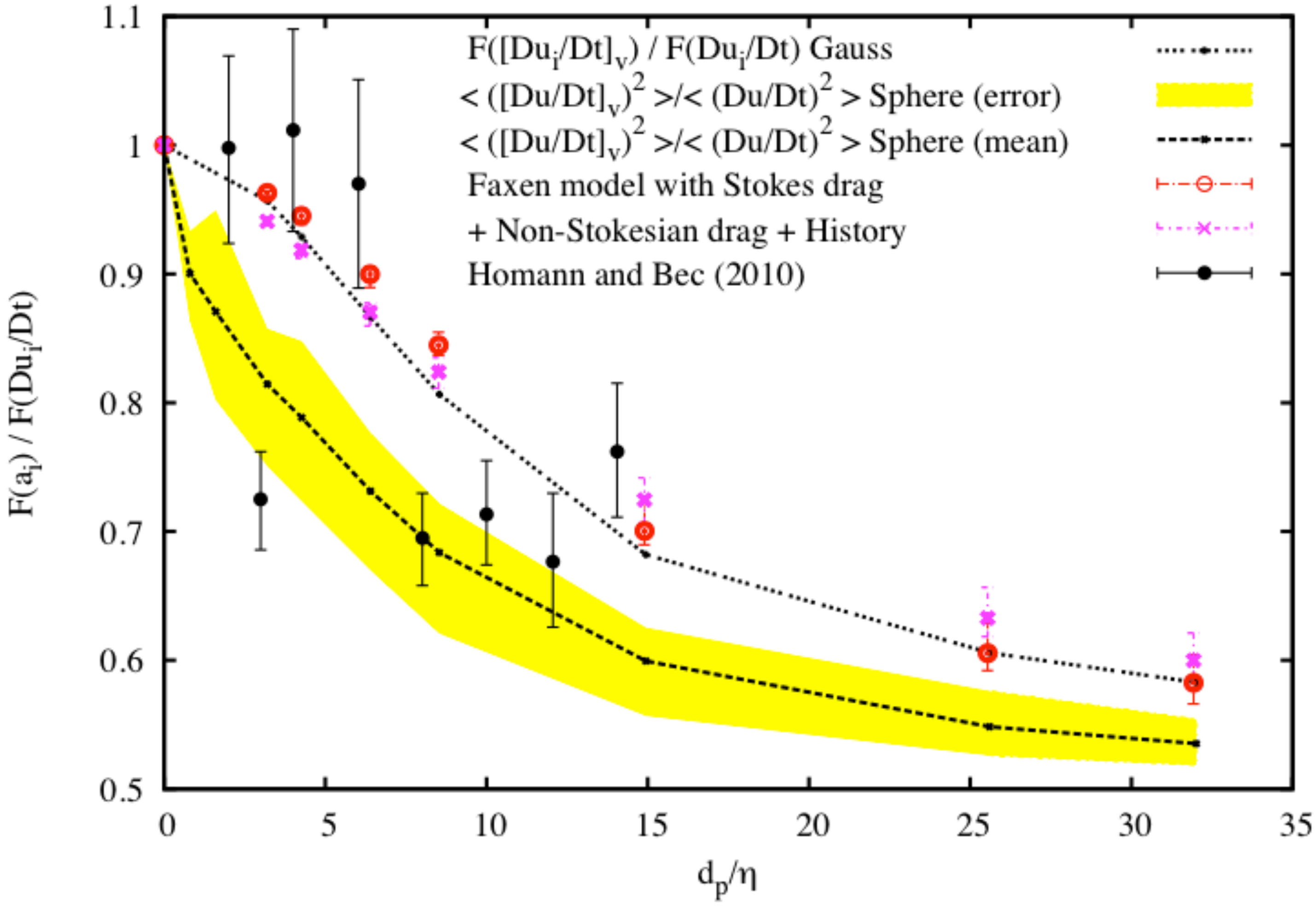
FIGURE 1. (*a*) The acceleration variance $\overline{a^2}$ normalized by $\beta^2\overline{a_f^2}$ versus the particle diameter as derived from the FC model (solid lines/symbols) and from PP the model system (dashed lines/empty symbols). Density ratios shown are $\rho_p/\rho_f = 0.1, 1, 10$, i.e. heavy (□), neutral (○) and light (△) particles. (*b*) Same as above for the acceleration flatness $F(a) = \overline{a^4}/(\overline{a^2})^2$. Horizontal lines shows the flatness of the fluid acceleration $F(a_f)$ and the flatness value for Gaussian distribution $F(a) = 3$. Data from simulations at $Re_\lambda = 75$.





Calzavarini et al. Acceleration statistics of finite-sized particles in turbulent flow: the role of Faxén forces. J Fluid Mech (2009) vol. 630 pp. 179

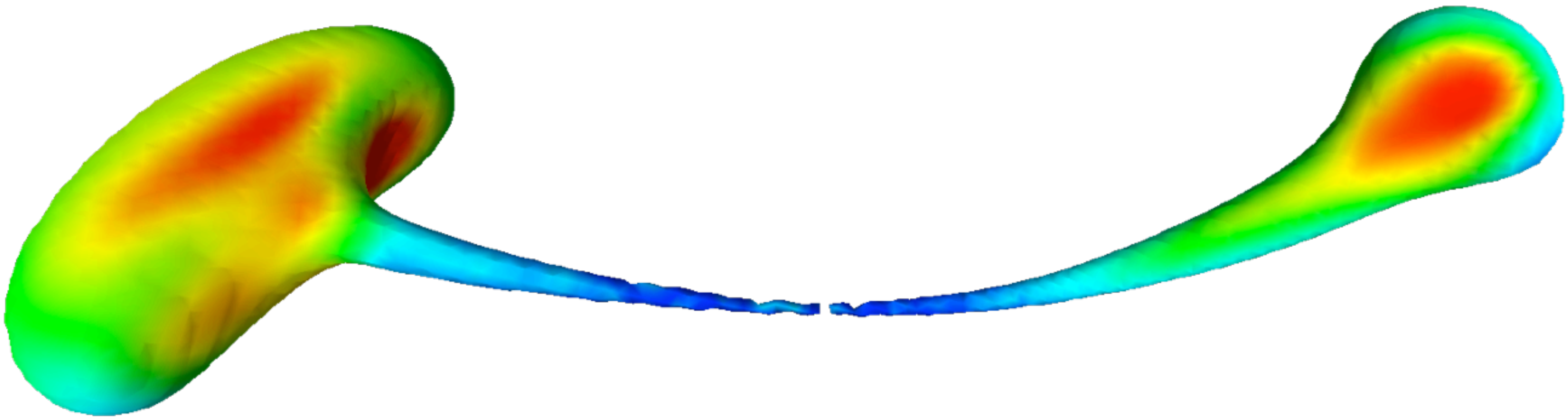
Large "pointwise" particles: flatness of acceleration



Impact of trailing wake drag on the statistical properties and dynamics of finite-sized particle in turbulence
Enrico Calzavarini, Romain Volk, Emmanuel Leveque, Jean-Francois Pinton, Federico Toschi http://lanl.arxiv.org/abs/1008.2888

Finite size deformable droplets

- Physics of finite size particles **plus** surface tension
- Transfer of energy **from** fluid **to** elastic modes (and **viceversa**)
- How is turbulence affected by the presence of droplets?
- How do properties of (deformable) droplets differ from rigid droplets ?



Dimensionless numbers

- Turbulence
- Inertial force
- Surface tension force
- Weber number

$$Re = \frac{u' L}{\nu}$$

$$Re_d = \frac{u_d d}{\nu}$$

$$Ca = \frac{\mu u_d}{\sigma}$$

$$We = \frac{\rho u_d^2 d}{\sigma}$$

J.O. Hinze, A.I.Ch.E, (1955)

Hinze 1955

$$We = \frac{\rho u_d^2 d}{\sigma}$$

K41

$$u_d^2 \sim d^{2/3} \varepsilon^{2/3}$$

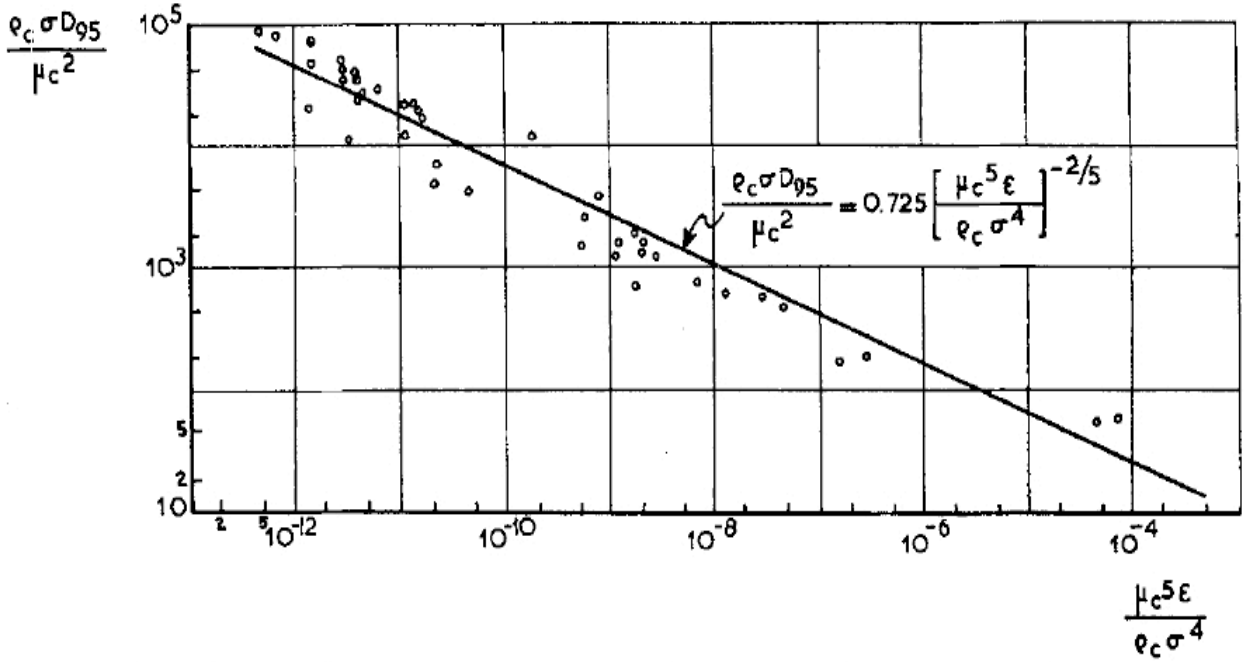


Fig. 6. Maximum drop size as a function of the energy input according to experimental data by Clay.

$$d_{max} = 0.75 \left(\frac{\rho}{\sigma}\right)^{-3/5} \varepsilon^{-2/5}$$

d > d_{max}: Droplet breaks

d < d_{max}: Droplet does not break

J.O. Hinze, A.I.Ch.E, (1955)

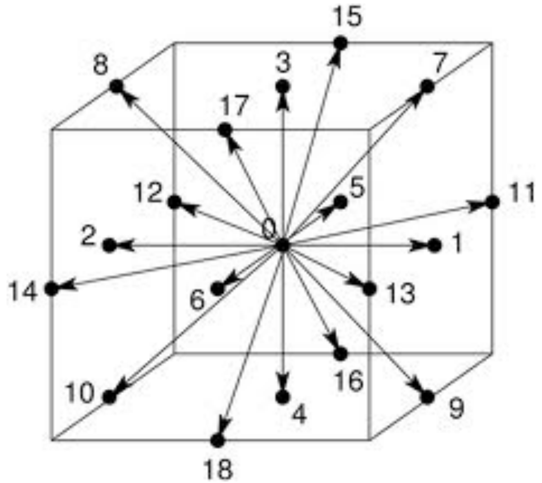
Numerical approach

Lattice Boltzmann Method (LBM)

We use D3Q19 BGK LB model

$$f_\alpha(x+e_\alpha,t+1) = f_\alpha(x,t) - \frac{f_\alpha(x,t) - f_\alpha^{(eq)}(x,t)}{\tau}$$

with **multicomponent** Shan-Chen



Technique inspired to the continuum Boltzmann equation

$$f \equiv f(x,v,t)$$

$$\partial_t f + (v\cdot\nabla)f = \Omega - (F\cdot\nabla)f$$

LBM: multicomponent SC

$$f_\alpha^\beta(\mathbf{x}+\mathbf{c}_\alpha, t+1) = f_\alpha^\beta(\mathbf{x}, t) - \frac{1}{\tau_\beta}\left[f_\alpha^\beta(\mathbf{x}, t) - f_\alpha^{eq,\beta}(\mathbf{x}, t)\right]$$

$$\mathbf{u}^\beta(\mathbf{x}, t) = \mathbf{u}^\beta(\mathbf{x}, t) + \frac{\tau \mathbf{F}(\mathbf{x}, t)}{\rho^\beta}$$

$\alpha = \{0, \ldots, 18\}$

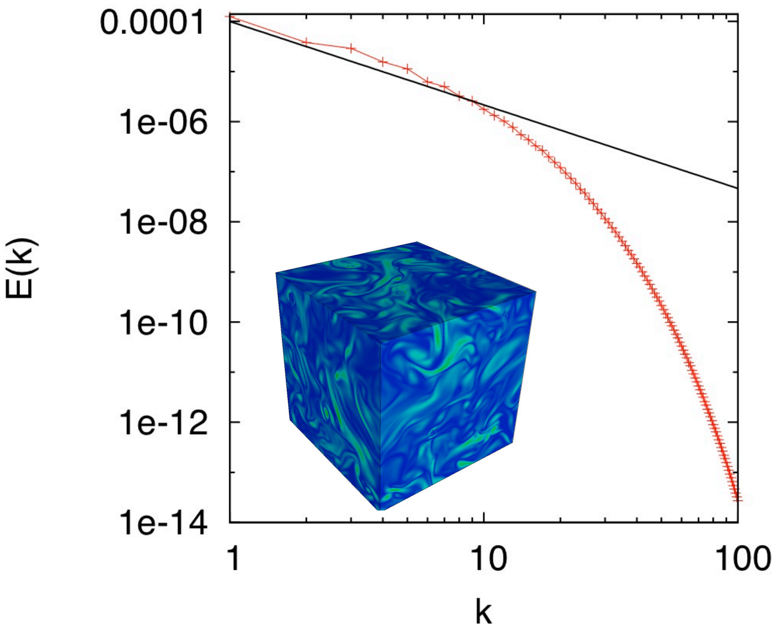
$c_s^2 = 1/3$

$$\mathbf{F}^{\alpha\beta} = -G\rho^\alpha(\mathbf{x}) \cdot \sum_\gamma \rho^\beta(\mathbf{x}+\mathbf{e}_\gamma)$$

$$\rho = \sum_\beta \rho^\beta \qquad \rho u = \sum_\beta \rho^\beta u^\beta$$

Shan and Chen. Lattice Boltzmann Model for Simulating Flows with Multiple Phases and Components. Phys. Rev. E 47, 1815 (1993).

Convincing LBM to go turbulent



$$f_x = \sum_{k \le \sqrt{2}} f_0[\sin(k_y y + \phi_k^2) + \sin(k_z z + \phi_k^3)]$$

$$f_y = \sum_{k \le \sqrt{2}} f_0[\sin(k_x x + \phi_k^1) + \sin(k_z z + \phi_k^3)]$$

$$f_z = \sum_{k \le \sqrt{2}} f_0[\sin(k_x x + \phi_k^1) + \sin(k_y y + \phi_k^2)]$$

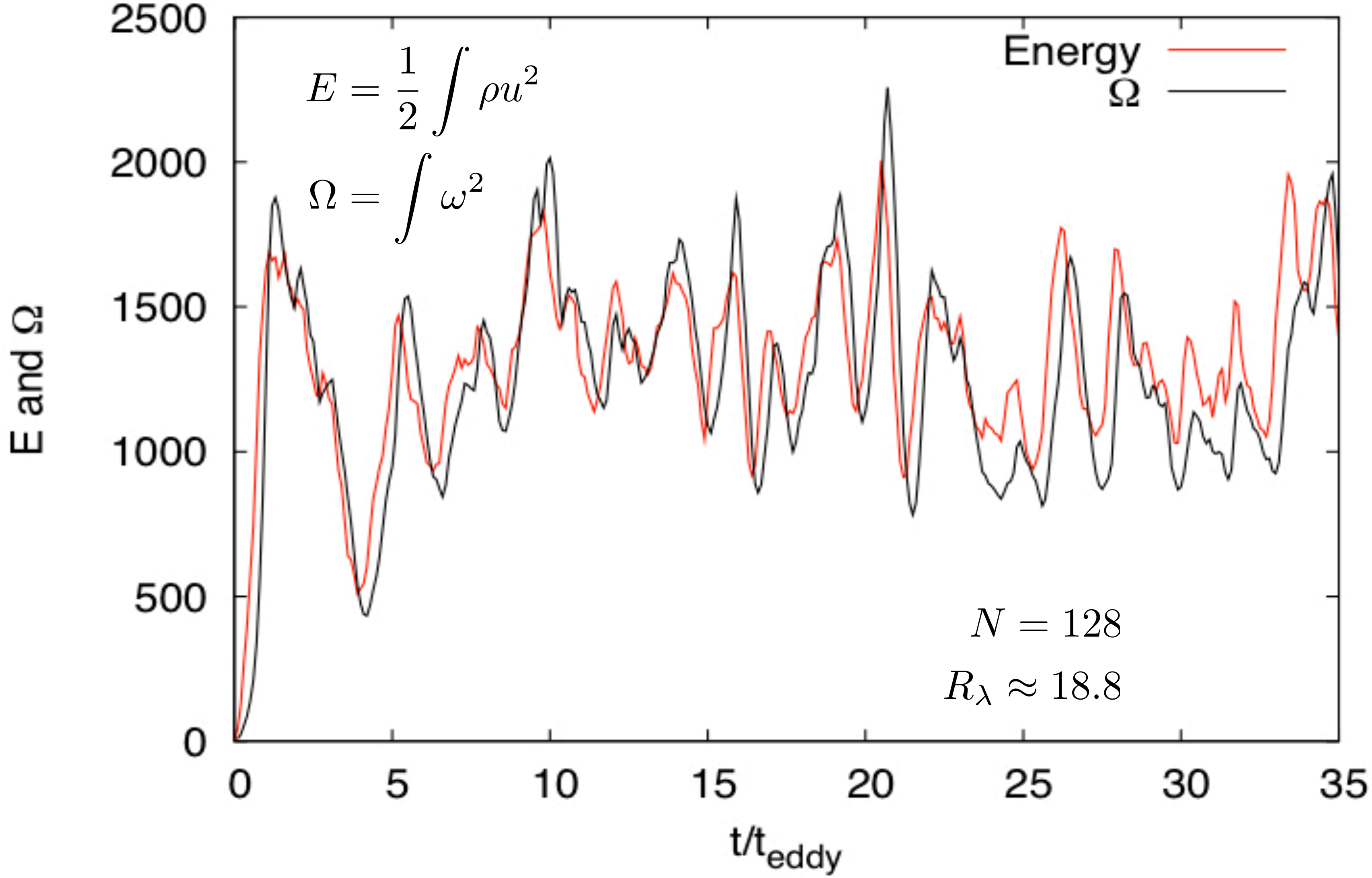
Forcing: Large scale forcing in first two Fourier modes

$$N = 512^3$$
$$\nu = 5 \times 10^{-3}$$
$$\lambda \approx 13.89 lu$$
$$\eta \approx 6 lu$$
$$\sigma \approx 0.028$$
$$Re_\lambda \approx 29.13$$

$$\phi_k^i$$

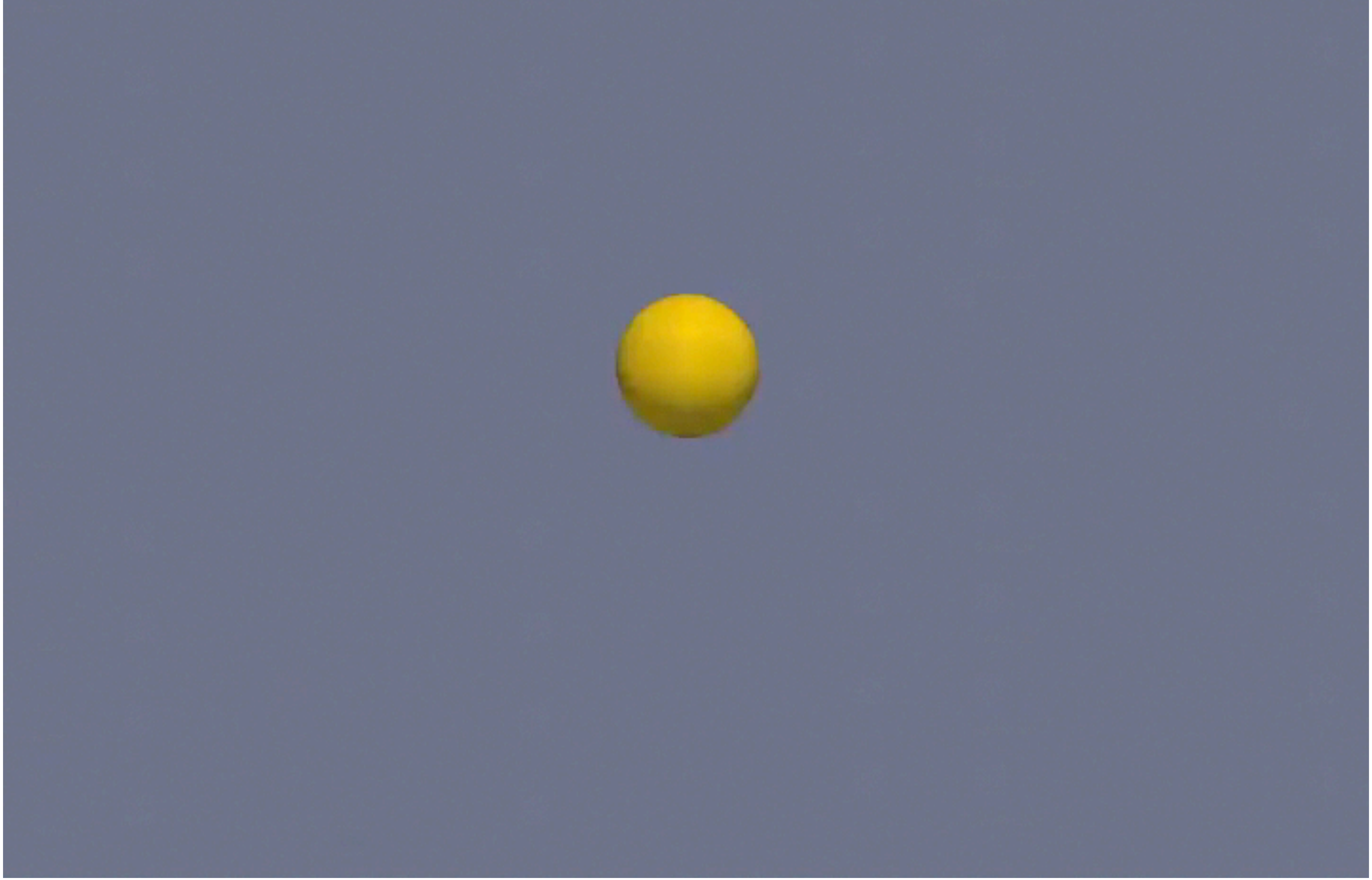
Random phases generated from Ornstein-Uhlenbeck process

LBM: Energy and enstrophy

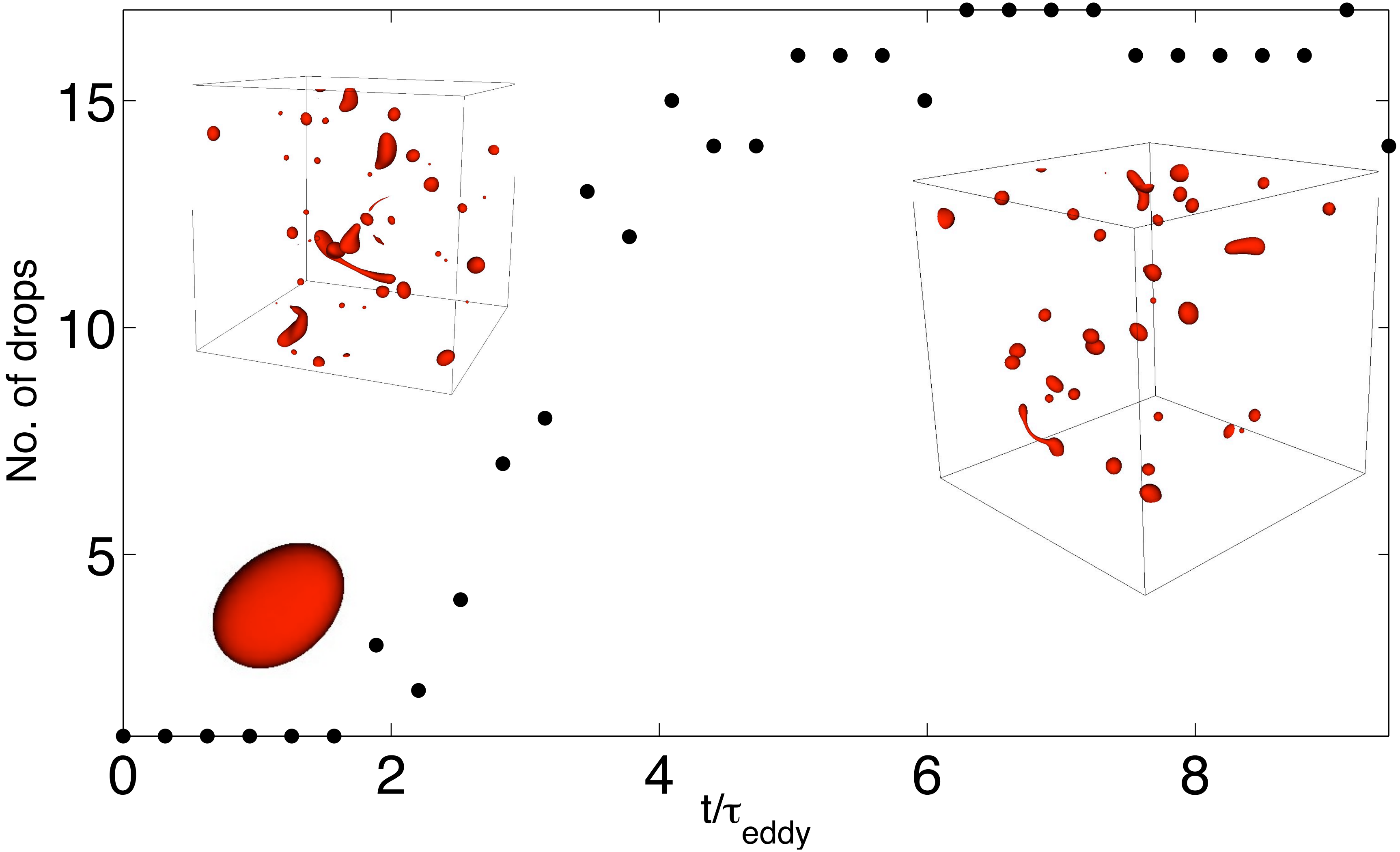


Results

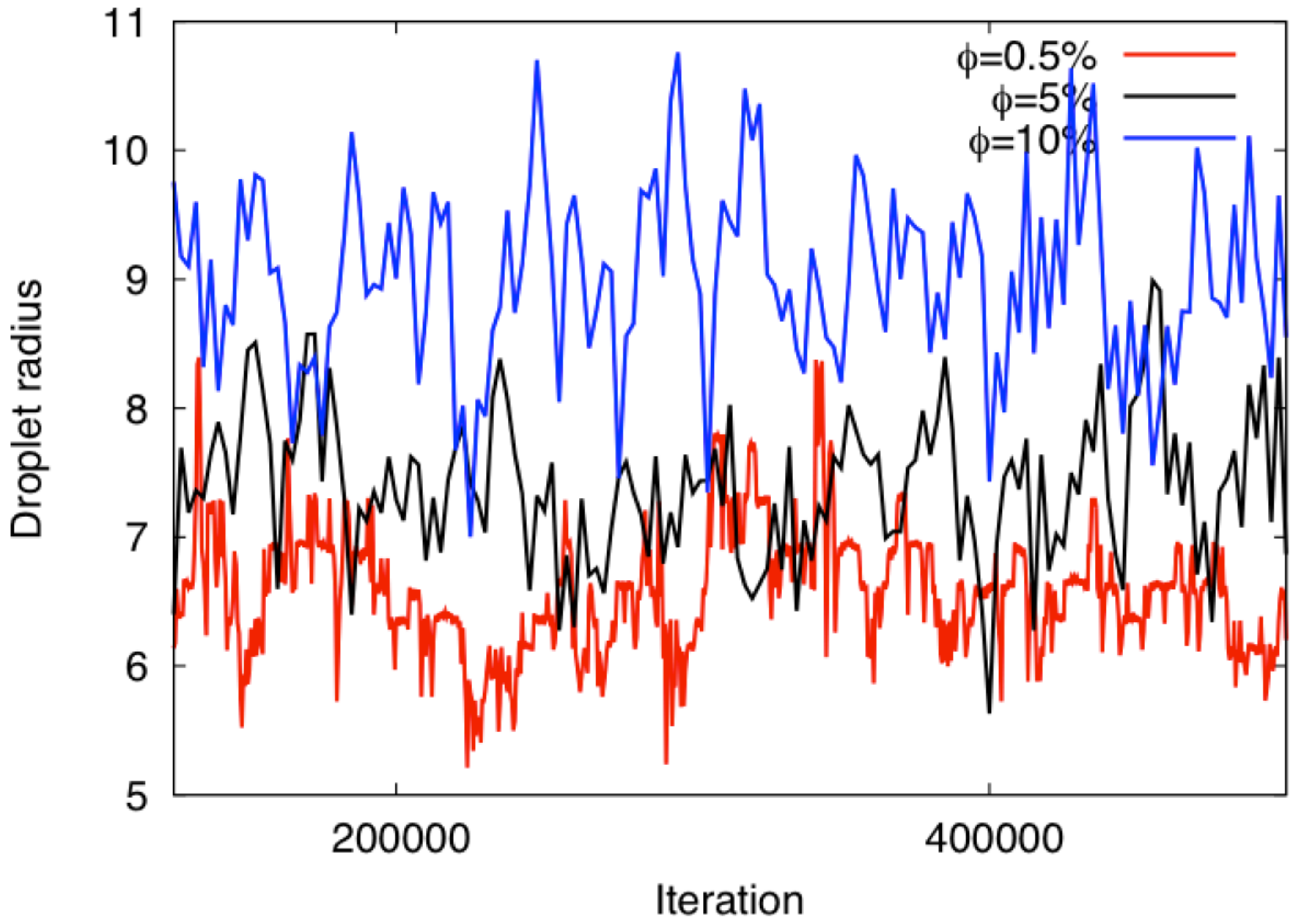
Droplet breakup in turbulence



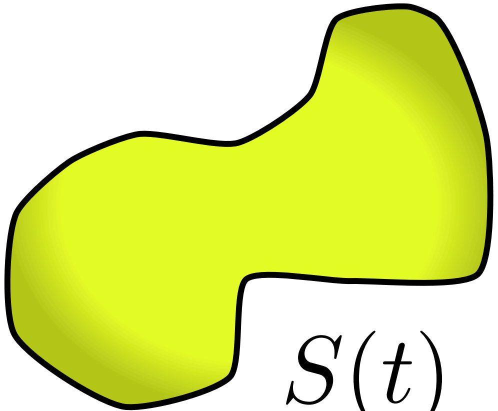
Towards a stationary state…



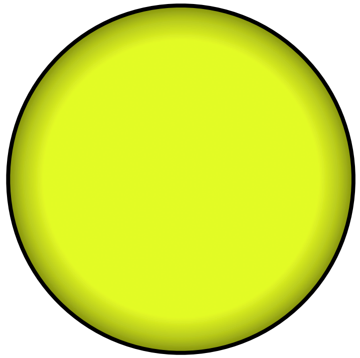
Droplet radius vs. time



Droplet deformation



Volume V

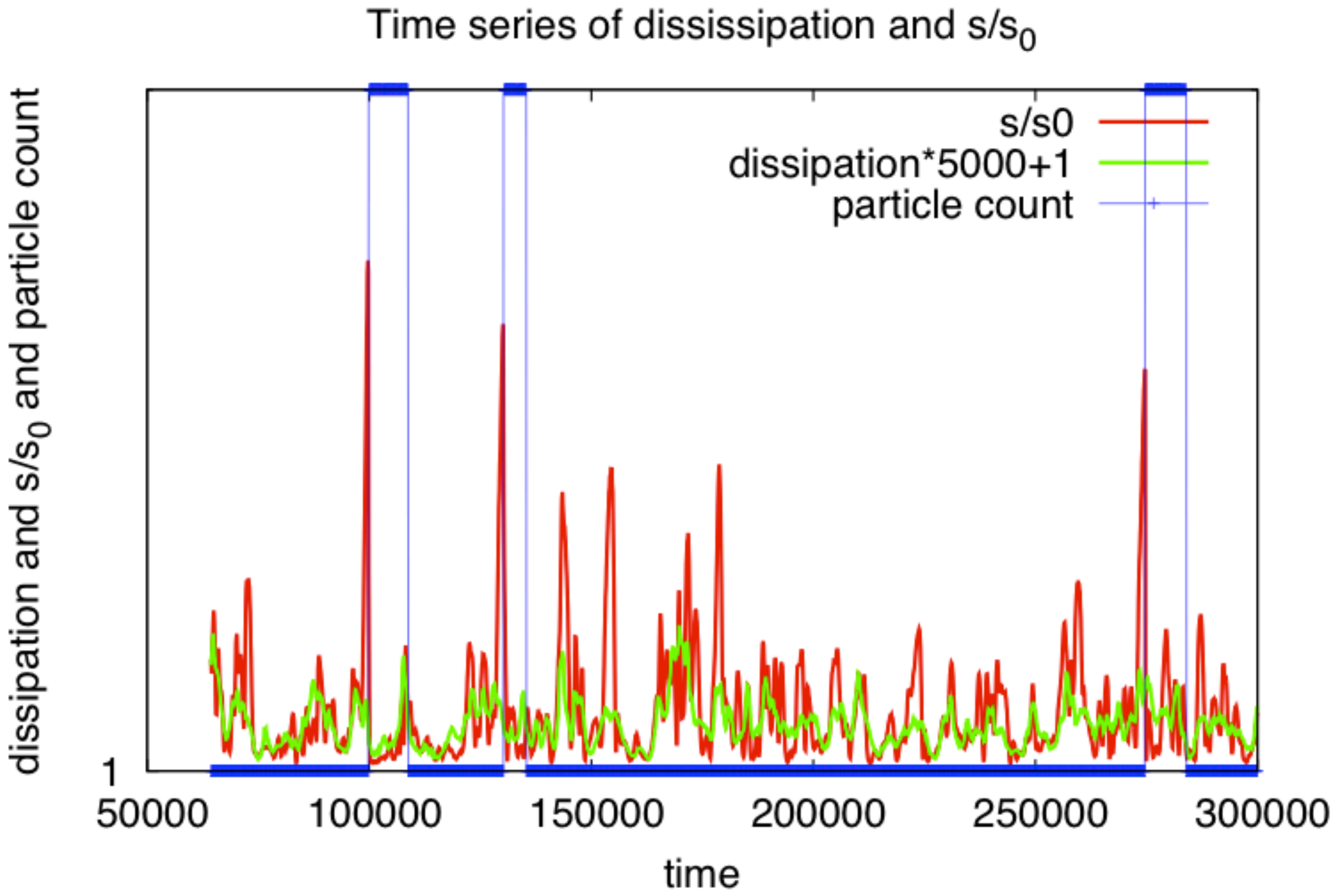


$$S = 4\pi R^2$$

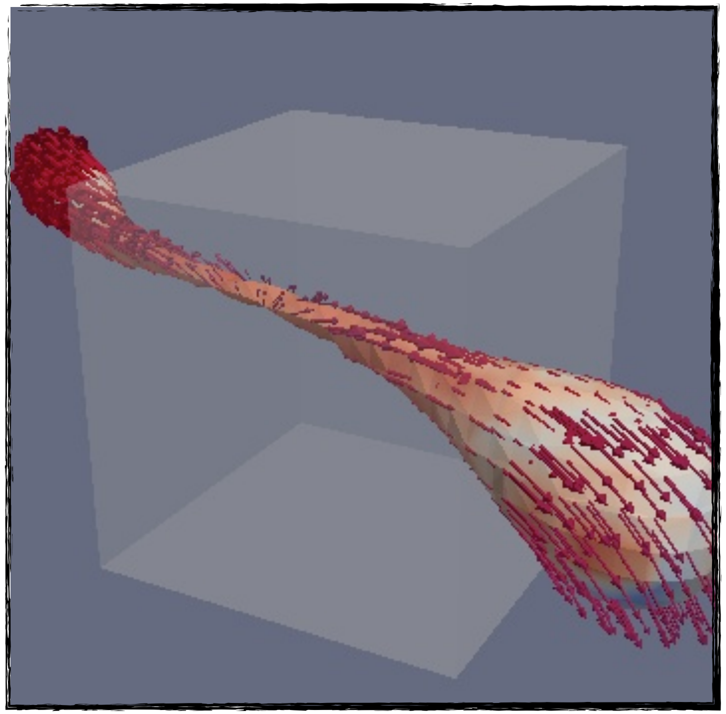
$$V = \frac{4}{3}\pi R^3$$

$$S/S_0$$

Deformation, dissipation and breakups



Rodlike particles (why?)

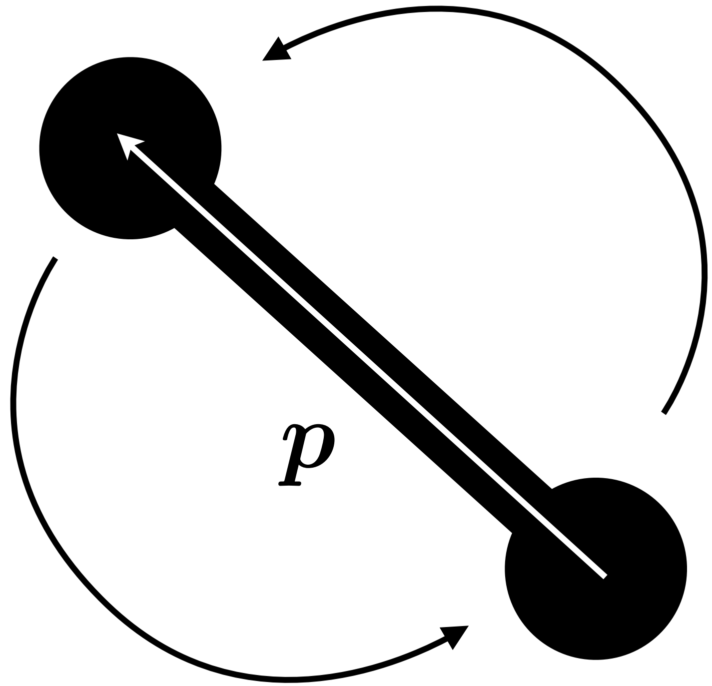


Rodlike particles

$$\mathcal{A}_{ij} = \partial_i v_j$$

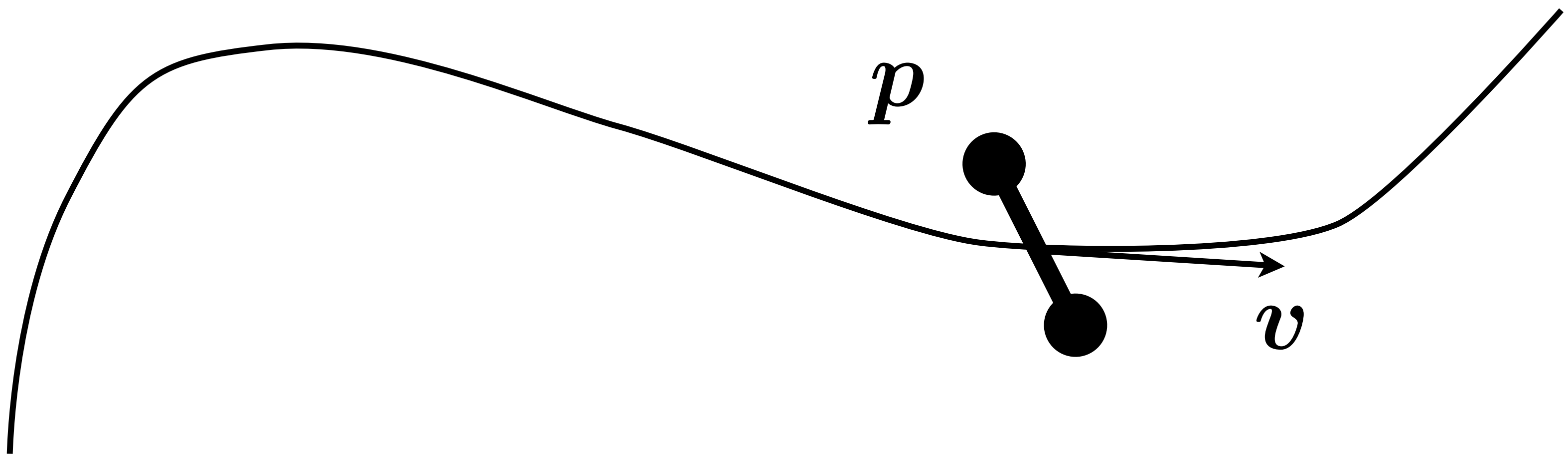
$$\Omega_{ij} = \frac{1}{2}\left(\partial_i v_j - \partial_j v_i\right)$$

$$\mathcal{S}_{ij} = \frac{1}{2}\left(\partial_i v_j + \partial_j v_i\right)$$

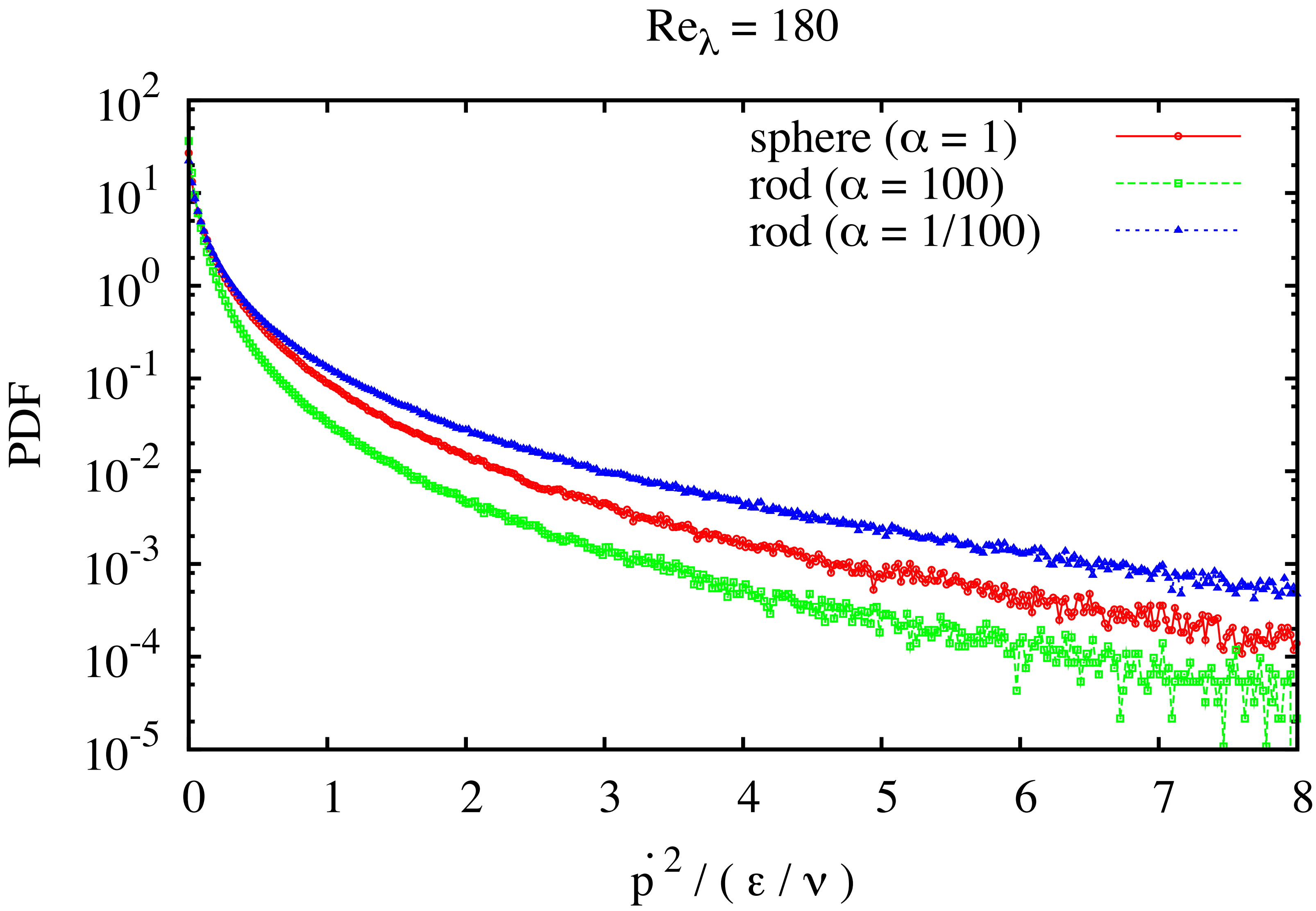


$$\dot{\boldsymbol{p}} = \boldsymbol{\Omega}\cdot\boldsymbol{p} + \frac{r^2-1}{r^2+1}\left[\boldsymbol{S}\cdot\boldsymbol{p} - \boldsymbol{p}\,\boldsymbol{p}\cdot\boldsymbol{S}\cdot\boldsymbol{p}\right]$$

A priori rod evolution



Pdf rotation rate



The end.