Exploring turbulence through particles:
statistical properties of spheroids in turbulent flows

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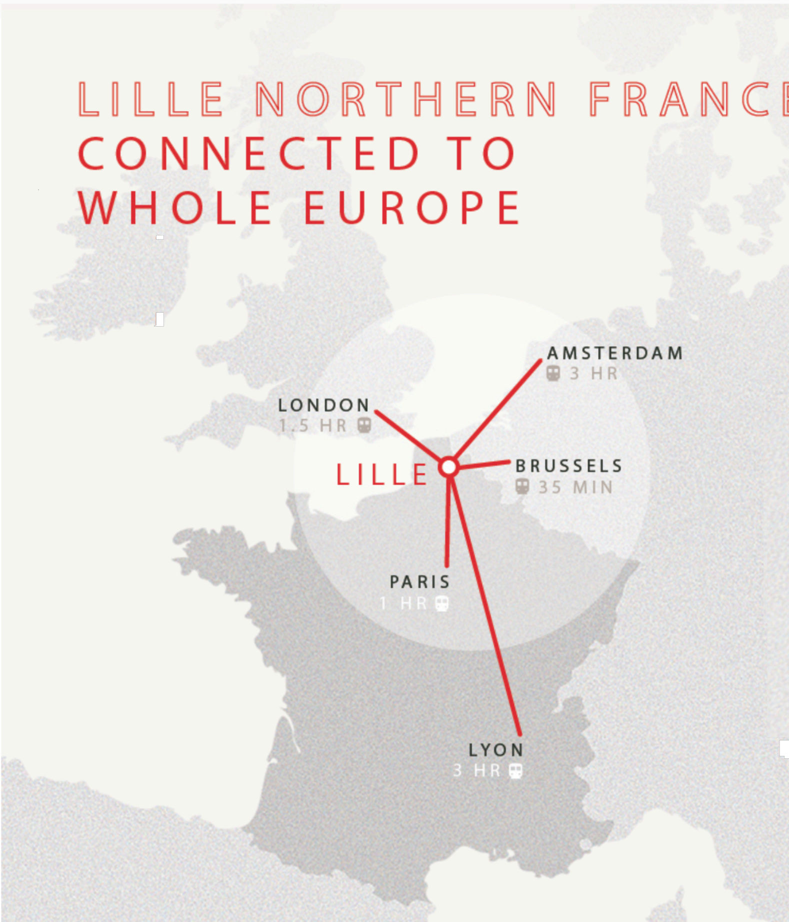
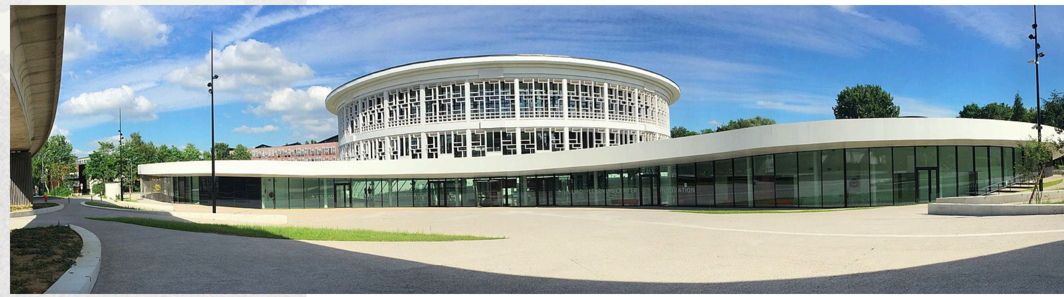
16/05/2023 Bangalore, ICTS International Centre for Theoretical Sciences

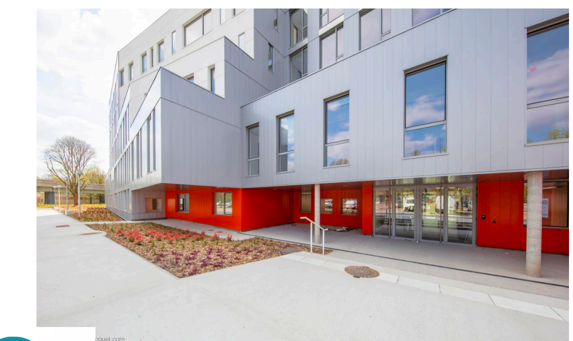
My institute



Université de Lille

74000 students
1800 PhD



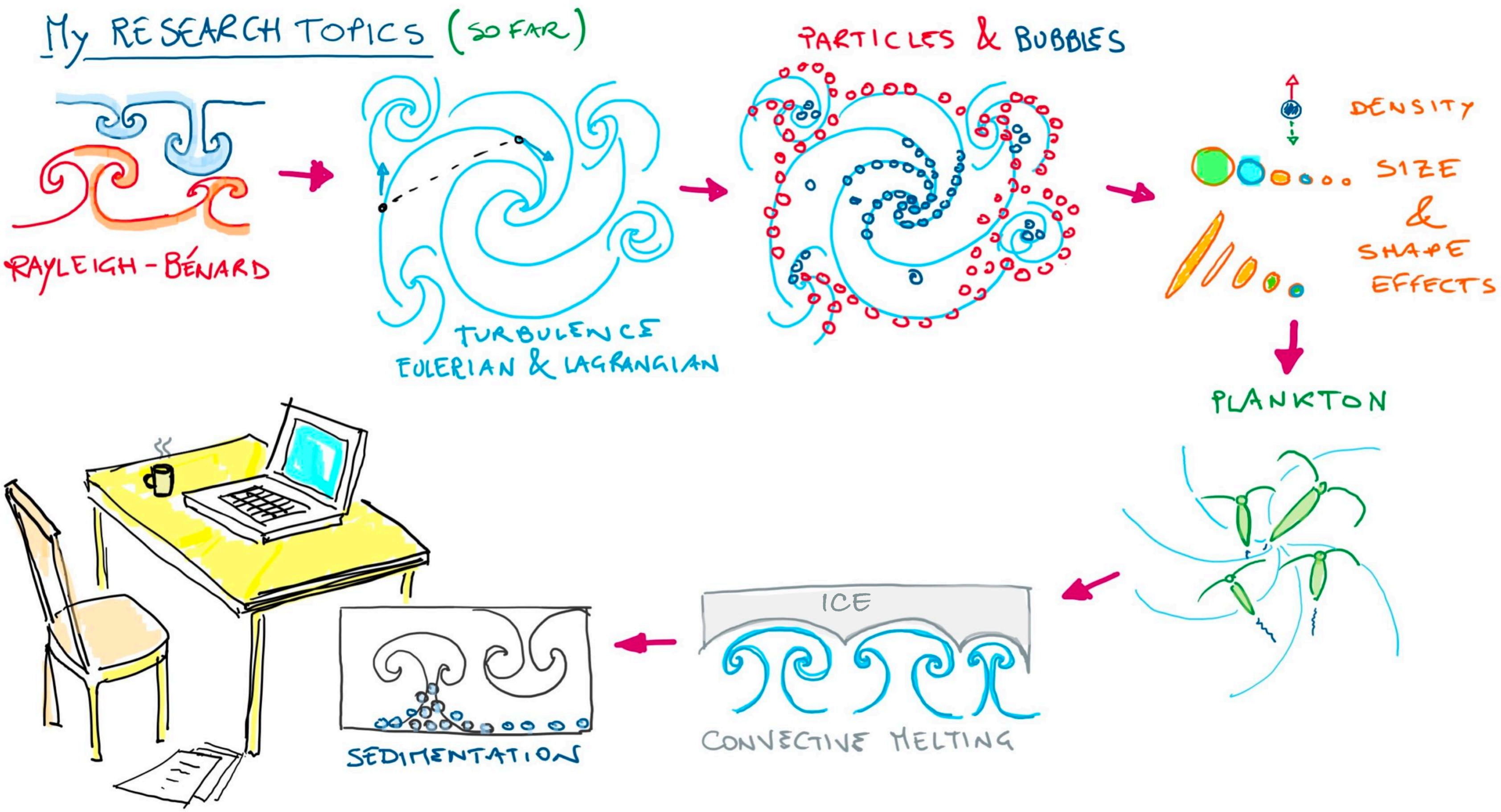


Unité Mécanique Lille
UML J. Boussinesq

uml.univ-lille.fr

20 faculty, 12 PhD , 2 teams: a) complex fluids (numerics, theory)
b) solids and structures (numerics, experiments)

My research in a doodle



www.ecalzavarini.info

Talk's outline

Introduction

- Recap on *models*, *simulations & experiments* on particles in turbulence
- Interesting questions

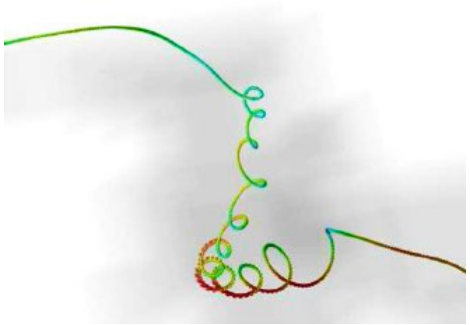
New results

- Our numerical study on *large neutral (a)spherical* particles in turbulence
- Acceleration statistics
- Rotation statistics

Conclusions

A brief recap:
Models for the motion of a particle in a flow (1)

- Fluid tracers, *or the Lagrangian point of view*



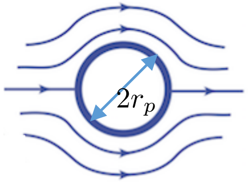
$$\frac{d\mathbf{x_f}}{dt} = \mathbf{u}(\mathbf{x_f}(t), t) \qquad \mathbf{a}_f \equiv \frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho_f}\nabla p + \nu\Delta\mathbf{u} + \mathbf{f}$$

- Small inertial particles, *an equation with many authors and many names*

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

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

drag — fluid acceleration — added mass — history — buoyancy



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

$$Re_s = \frac{||\nabla\mathbf{u}||(2r_p)^2}{\nu} \ll 1$$

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*

A brief recap:
Models for the motion of a particle in a flow (2)

- Corrections to the point-particle equation

Finite-size effect (Faxén laws 1922)

$$\mathbf{u} \to [\mathbf{u}]_S \simeq \mathbf{u} + \frac{r_p^2}{6}\Delta\mathbf{u}$$

in drag , history

$$\mathbf{u} \to [\mathbf{u}]_V \simeq \mathbf{u} + \frac{r_p^2}{10}\Delta\mathbf{u}$$

in fluid acceleration , added mass

Finite-Reynolds effect (Shiller-Neumann 1935) wake drag empirical correlation

$$6\pi\mu r_p \to 6\pi\mu r_p(1 + 0.15 Re_p^{0.687}) \qquad Re_p \lesssim 10^3$$

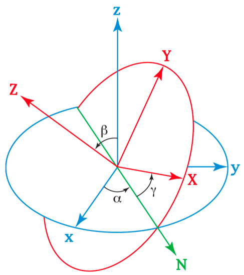
Lift force for light particles (Auton JFM 1987, inviscid calculation)

$$\mathbf{f}_{lift} = \frac{m_f}{2}(\mathbf{u} - \mathbf{v}) \times (\nabla \times \mathbf{u})$$

- If particles are even larger: rigid body equations

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

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



A brief recap:
Acceleration statistics in numerics and experiments (1)

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

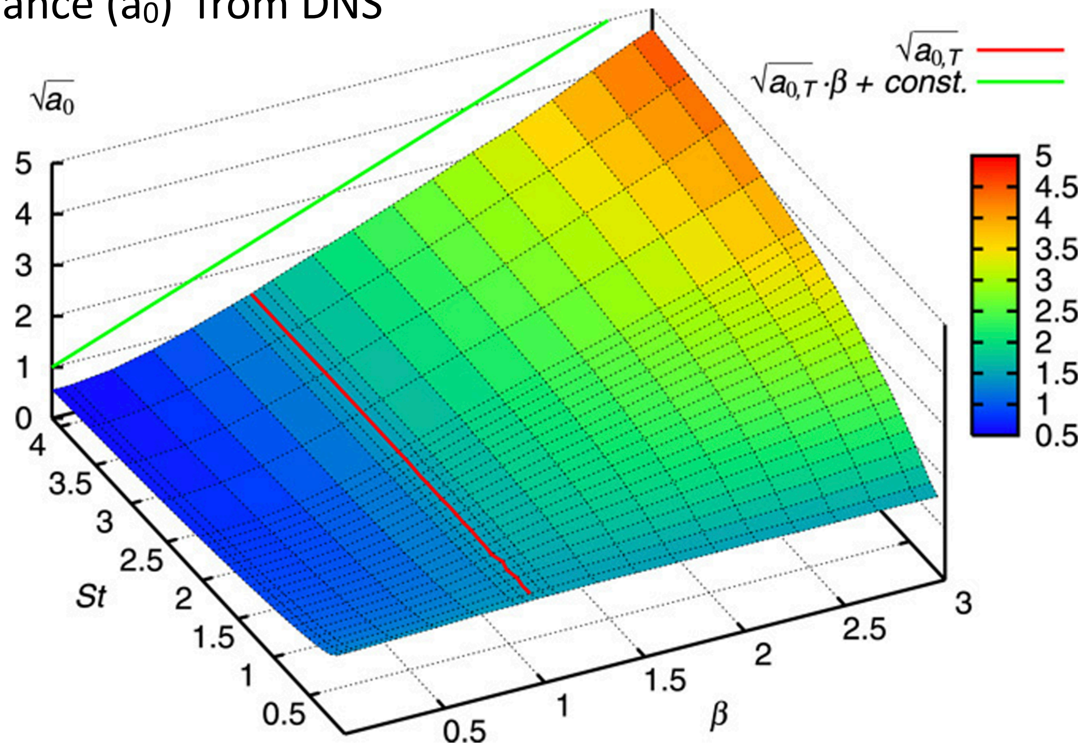
- Point-particle model & experiments

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

$$\beta = 3\rho_f/(\rho_f + 2\rho_p)$$

$$\tau_p = r_p^2/(3\nu\beta)$$

Acceleration variance (a_0) from DNS



A brief recap:
Acceleration statistics in numerics and experiments (1)

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

- Point-particle model & experiments


tracer
d = 1.8 η


neutral
d=15 η

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

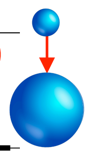
$$\beta = 3\rho_f/(\rho_f + 2\rho_p)$$

$$\tau_p = r_p^2/(3\nu\beta)$$

Variance (a_0)

Experiment

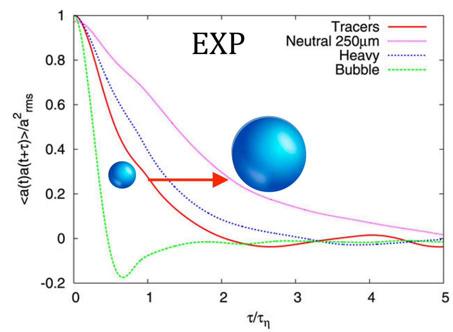
	$St = \frac{\tau_p}{\tau_\eta}$	a_0
Tracers	0.24	6.4 ± 1
Neutral	16	2.2 ± 1
Heavy	0.58	4.3 ± 1
Bubble	1.85	26 ± 5

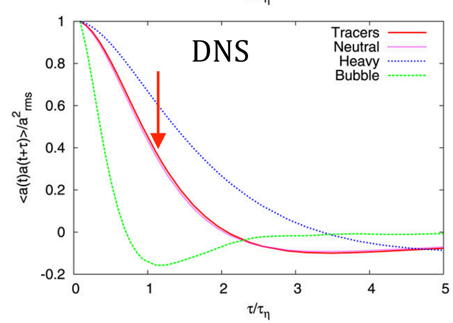


Numerics

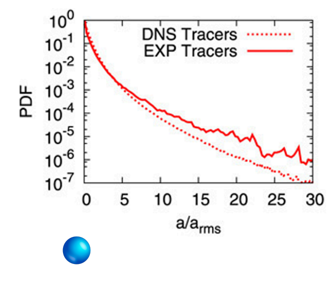
	$St = \frac{\tau_p}{\tau_\eta}$	a_0
Tracers	0.31	2.85 ± 0.07
Neutral	4.1	2.94 ± 0.07
Heavy	1.03	2.63 ± 0.12
Bubble	1.64	25.9 ± 0.46

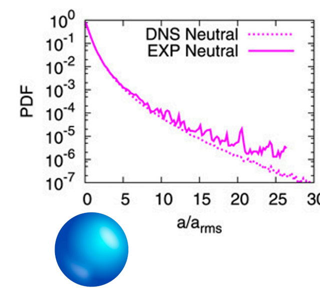
Temporal correlation





Probability density function



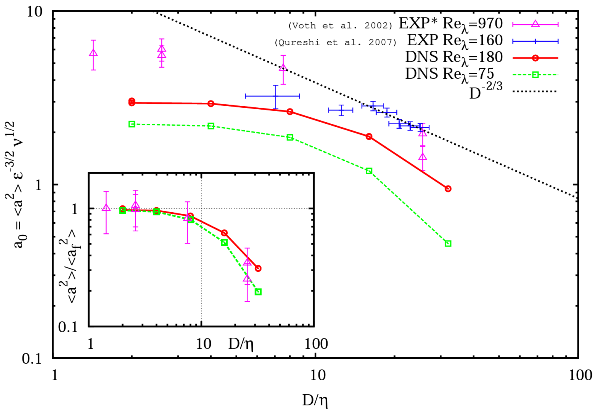


A brief recap:
Acceleration statistics in numerics and experiments (2)

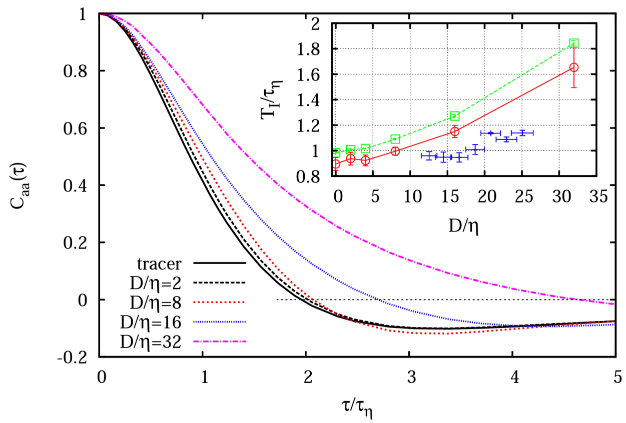
EC, Volk, Bourgoin, Leveque, Pinton, Toschi, JFM (2009)

- Faxén-finite-size model & experiments $\frac{d\mathbf{v}}{dt} = \beta \left[\frac{D\mathbf{u}}{Dt}\right]_V + \frac{1}{\tau_p}([\mathbf{u}]_S - \mathbf{v})$ $\left[\frac{D\mathbf{u}}{Dt}(\mathbf{x},t)\right]_V \simeq \int_{L^3} G(\mathbf{x}')\frac{D\mathbf{u}}{Dt}(\mathbf{x}-\mathbf{x}',t)\,\mathrm{d}^3x'$

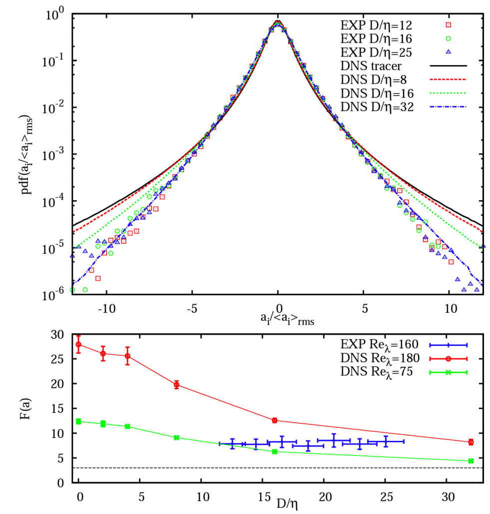
Variance



Temporal correlation



PDF and flatness



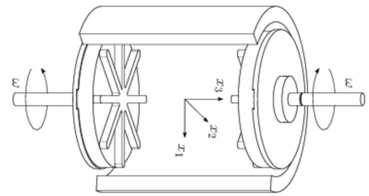
The coarse grained turbulence hypothesis (CGH)

$$a(D) \sim \frac{\delta_D p}{D} \sim \frac{(\delta_D u)^2}{D} \qquad \tau_a(D) \sim \frac{D}{\delta_D u} \sim D^{2/3} \qquad \mathcal{F}_a(D) = \frac{\langle a(D)^4\rangle}{\langle a(D)^2\rangle^2} \sim D^{\underset{(-0.42)}{\zeta_8 - 2\zeta_4 < 0}}$$

K41 $\delta_\ell u \sim \ell^{1/3}$ $\qquad \tau_u(\ell) \sim \frac{\ell}{\delta_\ell u} \sim \ell^{2/3} \qquad \langle(\delta_\ell u)^p\rangle \sim \ell^{\zeta_p}$

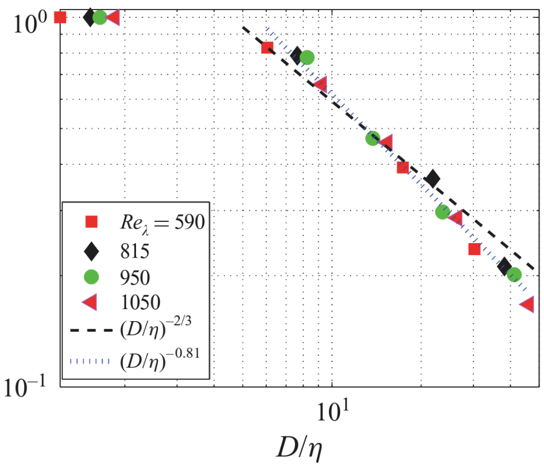
A brief recap:
Acceleration statistics in numerics and experiments (3)

- Von Karman flow experiments (large Re)

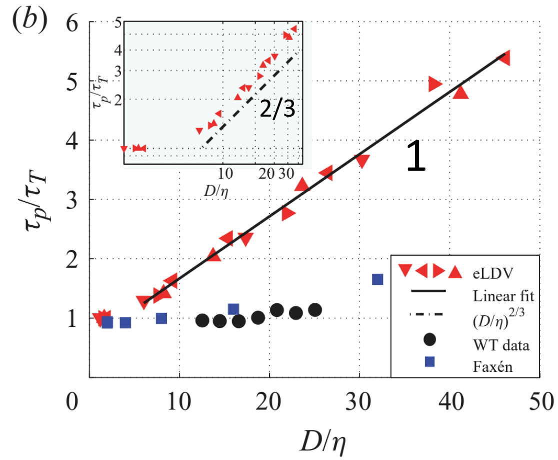


Volk, EC, Leveque, Pinton JFM (2011)

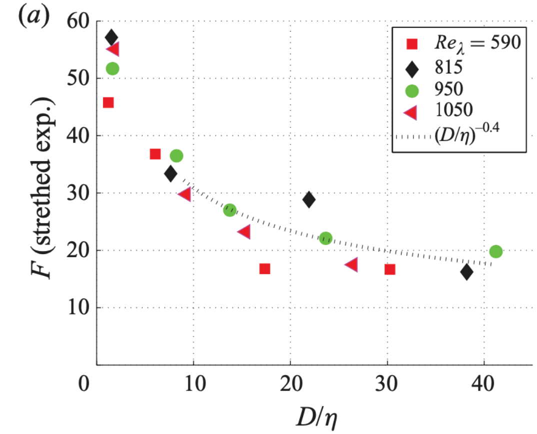
Variance



Temporal correlation



PDF and flatness



$$\langle a(D)^2 \rangle \sim D^{-0.81}$$

$$\tau_a(D) \sim D$$

$$\mathcal{F}_a(D) \sim D^{-0.4(-0.6)}$$

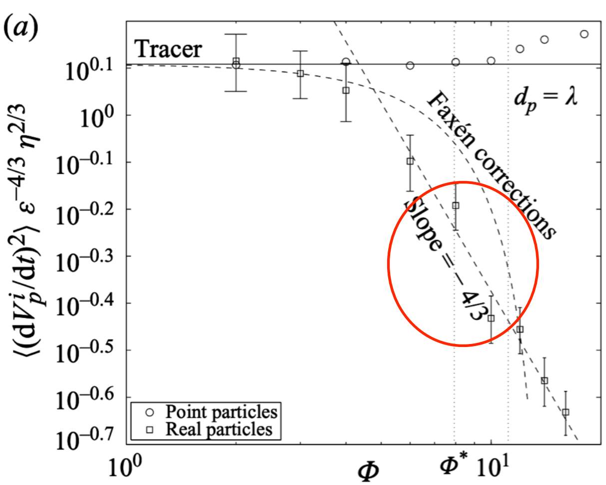
CGH: $\langle a(D)^2 \rangle \sim D^{-2/3}$ $\quad \tau_a \sim D^{2/3}$ $\quad F_a(D) \sim D^{-0.42}$

A brief recap:
Acceleration statistics in numerics and experiments (4)

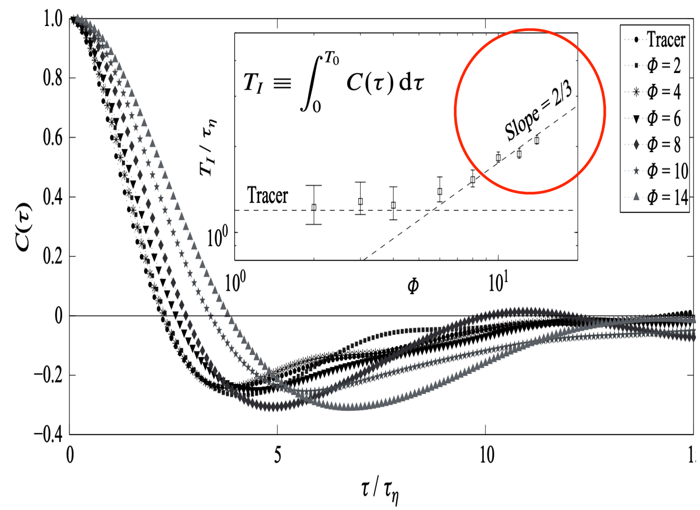
- Fully resolved simulations (low Re) $Re_\lambda = 32$

Homann & Bec JFM (2010)

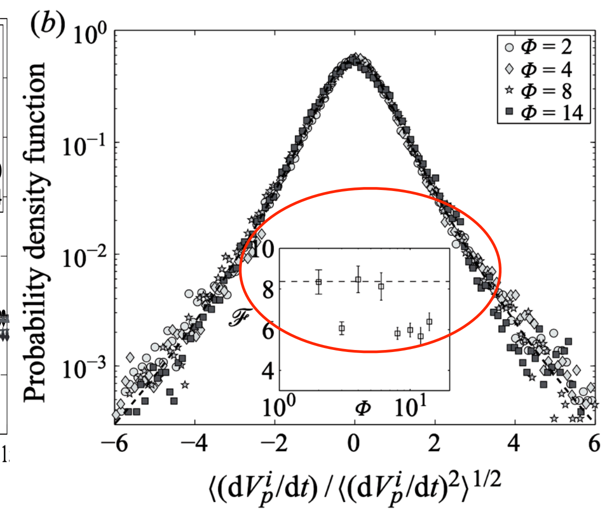
Variance



Temporal correlation



PDF and flatness



$$\langle a(D)^2 \rangle \sim D^{-4/3} \qquad \tau_a(D) \sim D^{2/3} \qquad \mathcal{F}_a(D) \sim const.$$

CGH: $\langle a(D)^2 \rangle \sim D^{-2/3}$ $\quad \tau_a \sim D^{2/3}$ $\quad F_a(D) \sim D^{-0.42}$

Cisse, Homann & Bec JFM (2013) -> slipping motion and particle boundary layer

Uhlmann & Chouippe JFM (2017) -> particle preferential concentration

Interesting questions

- Do **finite-sized particles** experience coarse-grained turbulent flow **accelerations**?

$$a(D) \sim \frac{\delta_D p}{D} \sim \frac{(\delta_D u)^2}{D} \sim D^{-1/3} \qquad \tau_a(D) \sim \frac{D}{\delta_D u} \sim D^{2/3} \qquad \mathcal{F}_a(D) \sim D^{\zeta_8 - 2\zeta_4}$$

or does particle-flow coupling create specific statistical signatures?

- How is the particle finite-size reflected on particle **rotations**?

$$\Omega(D) \sim \frac{1}{\tau(D)} \sim \frac{\delta_D u}{D} \sim D^{-2/3} \quad \text{(CGH)}$$

- What is the effect of **shape anisotropy** on finite-sized particles?

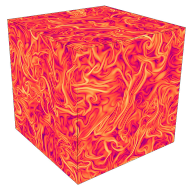
Small *anisotropic particles align with flow structures: For large particles is a randomization of rotations to be expected?*

- What do we learn of turbulence when we look at a moving particle?

A new numerical study

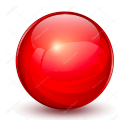
in collaboration with
Chao Sun (孙超) & Linfeng Jiang (蒋林峰)
Tsinghua University, Beijing, China

Navier-Stokes equations (NSE)



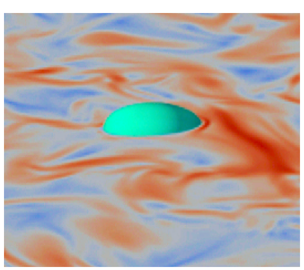
$$\partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} = -\rho^{-1} \nabla p + \nu \, \nabla^2 \mathbf{u} + \mathbf{f},$$
$$\nabla \cdot \mathbf{u} = 0,$$

+ Newton-Euler equations (NEE)



$$m_p \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \mathbf{F} \qquad \mathbf{F} = \oint_{S_p} \boldsymbol{\sigma} \cdot \mathbf{n} \, dS \qquad \boldsymbol{\sigma} = -p\boldsymbol{I} + \rho\nu(\nabla\mathbf{u} + \nabla\mathbf{u}^T)$$
$$\frac{\mathrm{d}\boldsymbol{\mathcal{I}\Omega}}{\mathrm{d}t} = \mathbf{T} \qquad \mathbf{T} = \oint_{S_p} (\mathbf{x} - \mathbf{r}) \times (\boldsymbol{\sigma} \cdot \mathbf{n}) \, dS$$

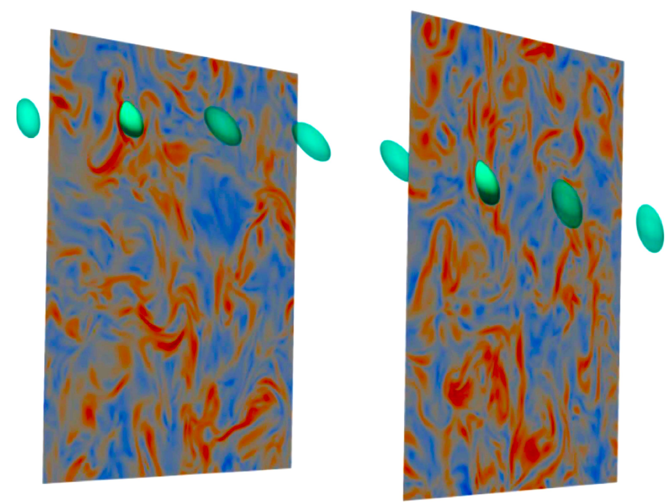
+ no-slip boundary conditions @fluid-particle interface



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

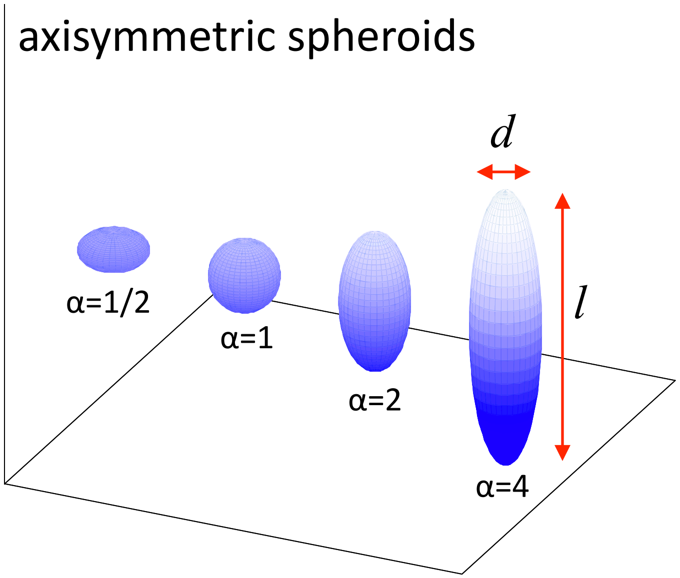
Methods:
- Lattice Boltzmann (fluid)
- Quaternions (rigid body)
- Immersed boundaries (interface)

Same methods as
K. Suzuki, T. Inamuro, Comput. & Fluids 49, 173-187 (2011)



Parameter space

axisymmetric spheroids



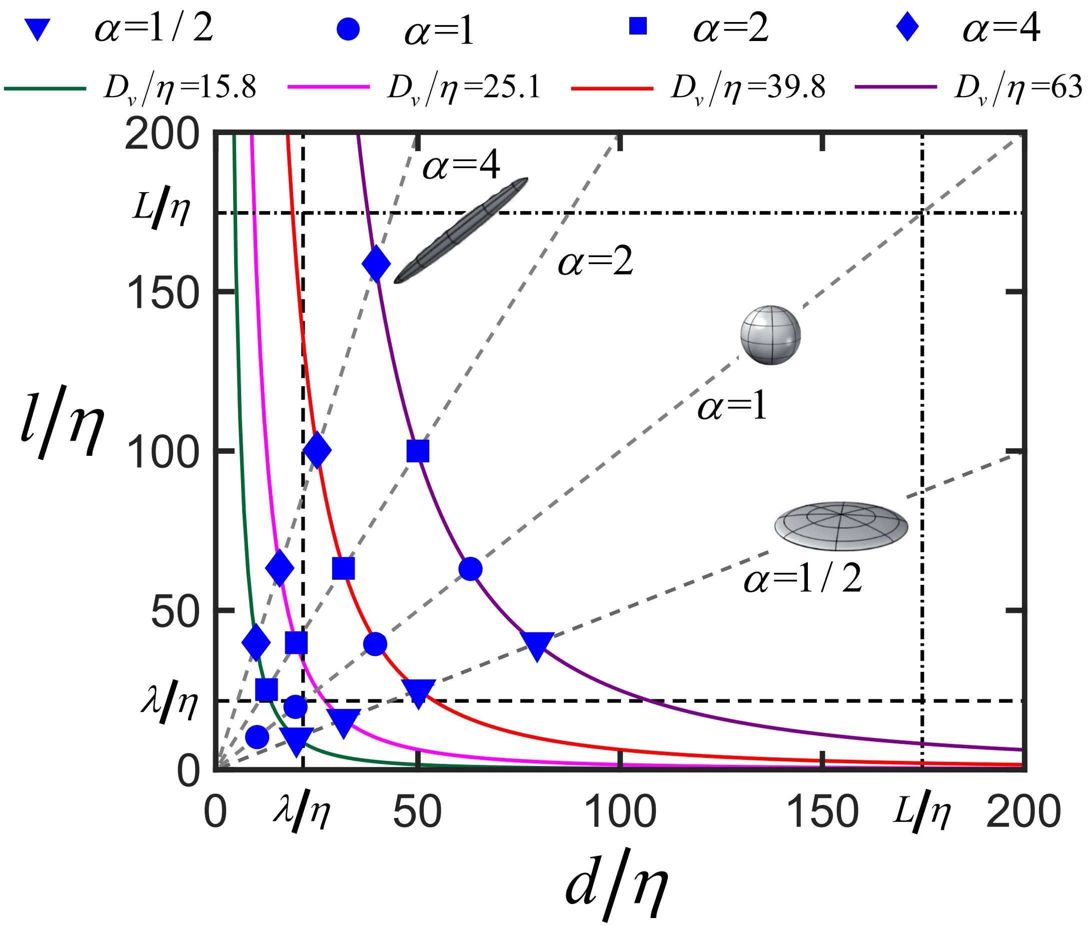
aspect ratio

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

Volume equivalent diameter

$$D_{\mathrm{v}} = (d^2 l)^{1/3} = d\alpha^{1/3}$$

$$Re_\lambda = 120$$

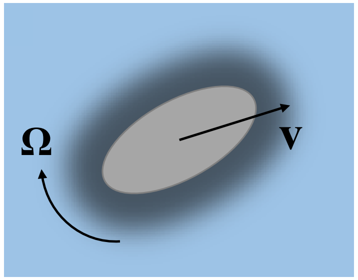


Auxiliary particle models

$$\mathbf{F} = \oint_{S_p} \boldsymbol{\sigma} \cdot \mathbf{n} \, dS$$

$$\mathbf{T} = \oint_{S_p} (\mathbf{x} - \mathbf{r}) \times (\boldsymbol{\sigma} \cdot \mathbf{n}) \, dS$$

Real Particles (RP)



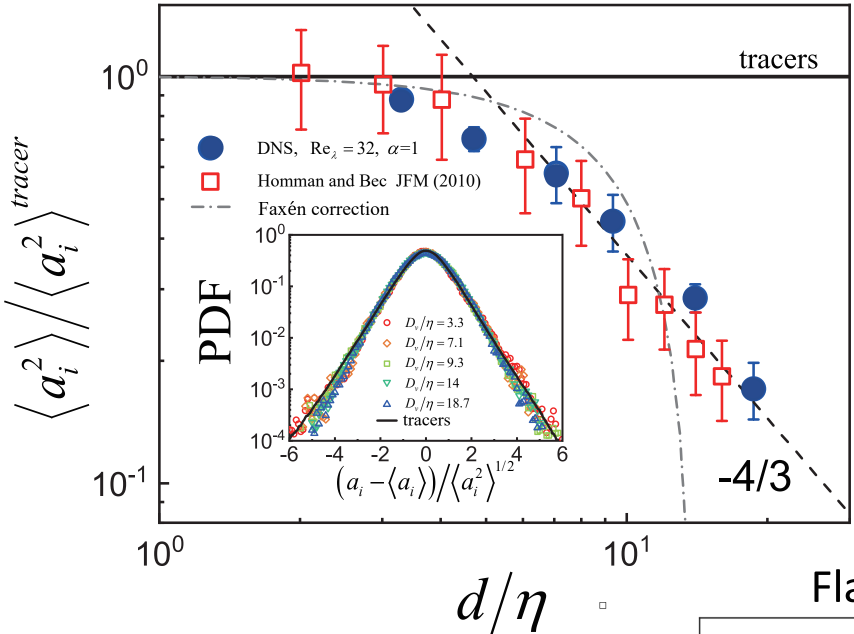
Numerical Experiments	Model Equations
Real Particles (RP)	NSE + NEE + IBM
Volume Averages (VA)	NSE
Virtual Particles (VP)	NSE + NEE
Real Particles with Fixed Locations (RPFL)	NSE + EE + IBM
Virtual Particles with Fixed Locations (VPFL)	NSE + EE
Jeffery Fluid Tracers (JFT)	NSE + tracer eq.+ Jeffery eq.

Spheres: acceleration at low Re

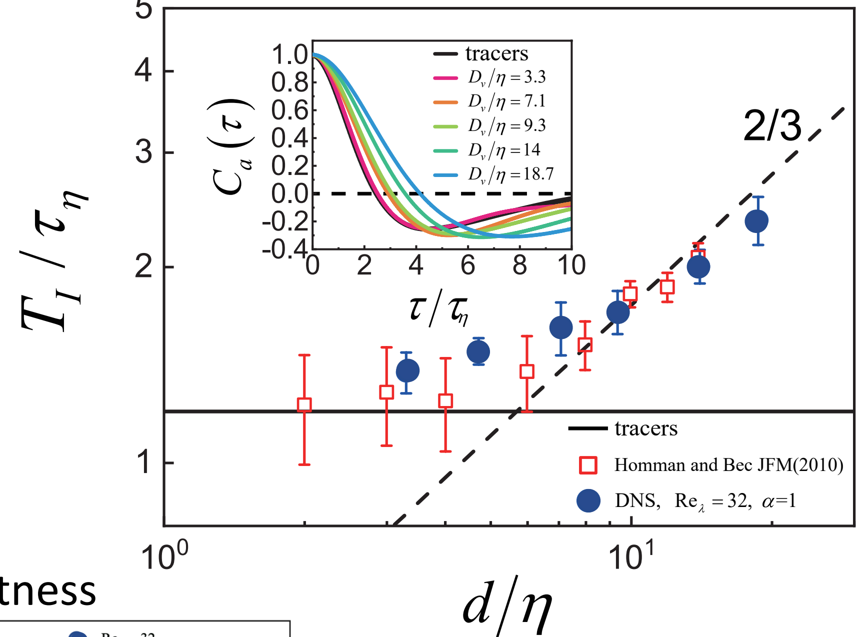
Comparison with Homann & Bec JFM 2010

$Re_\lambda = 32$

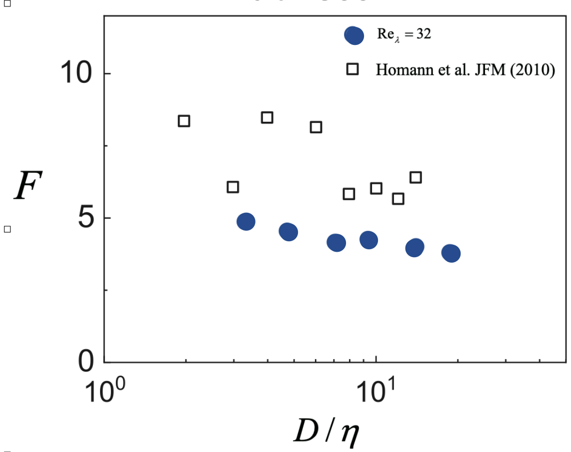
Variance



Correlation time



Flatness

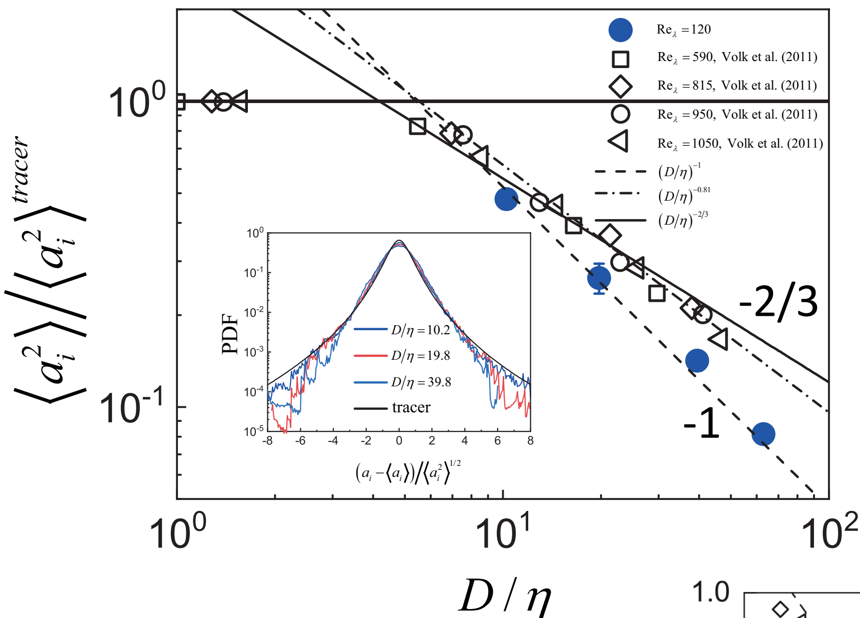


Spheres: acceleration at larger Re

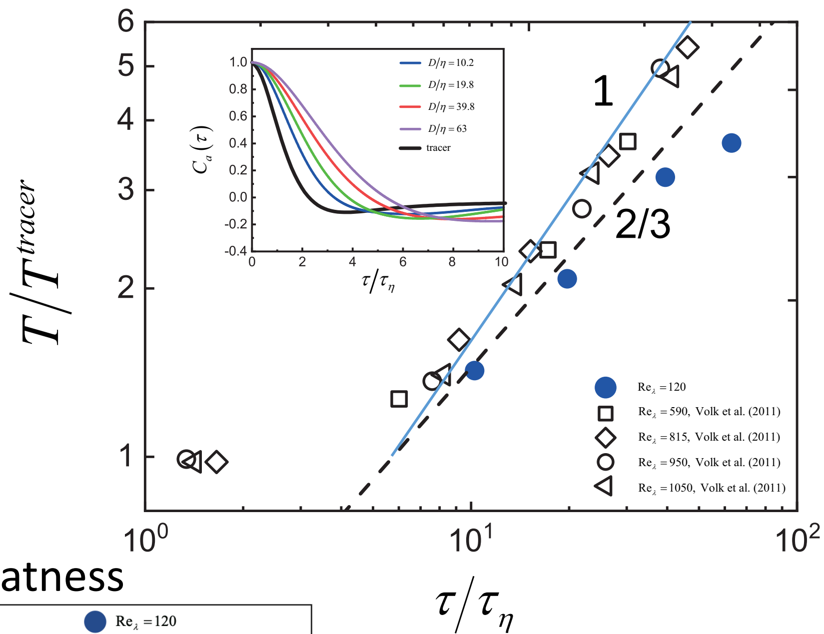
Comparison with Volk et al. JFM 2011

$Re_\lambda = 120$

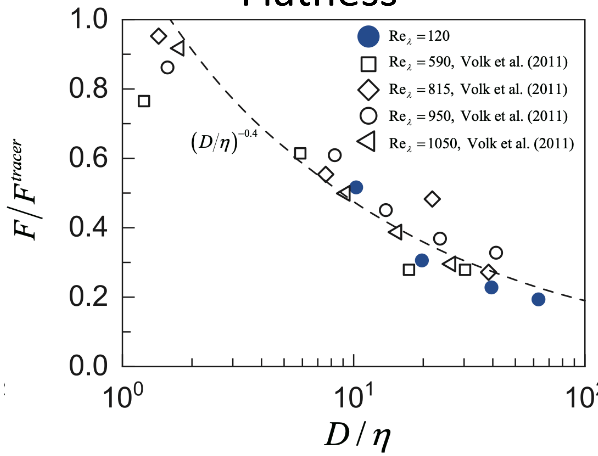
Variance



Correlation time

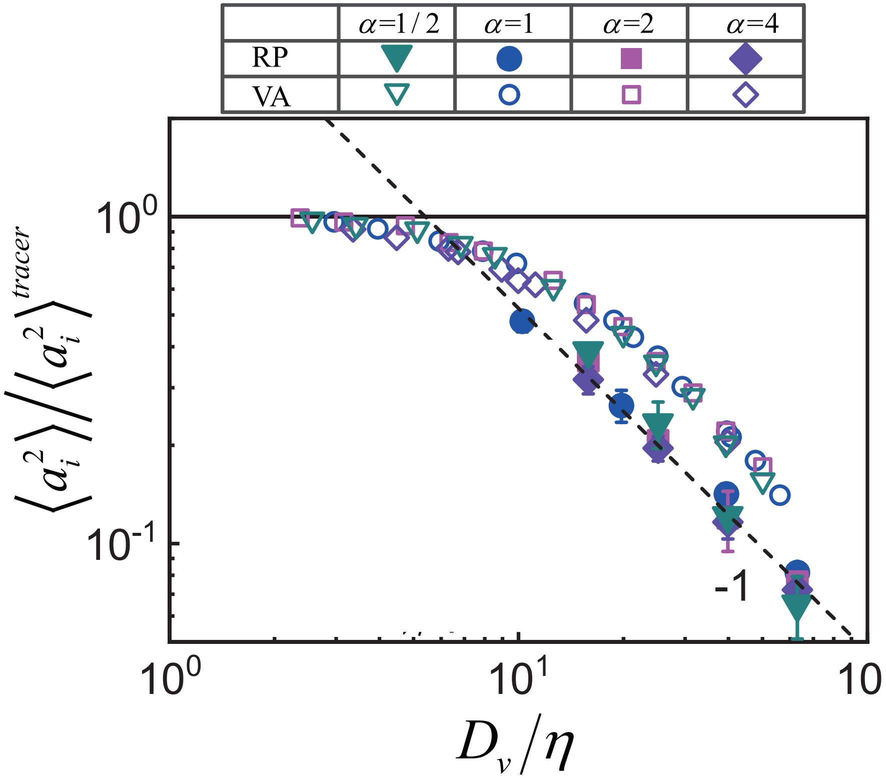


Flatness



Spheroids: Acceleration variance

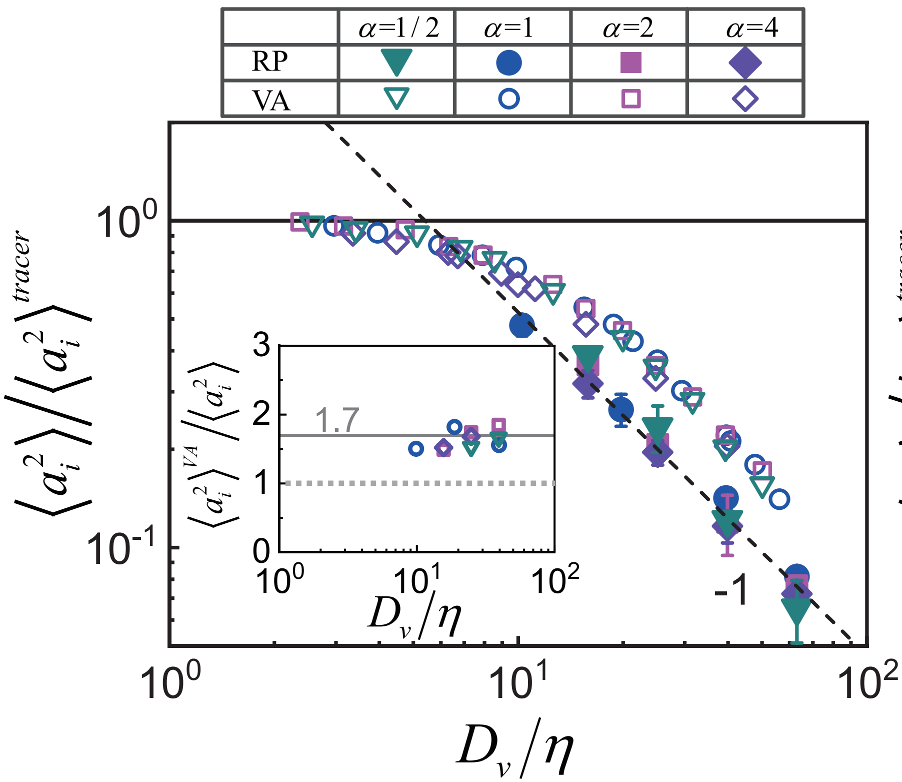
Real Particles vs Volume Averages



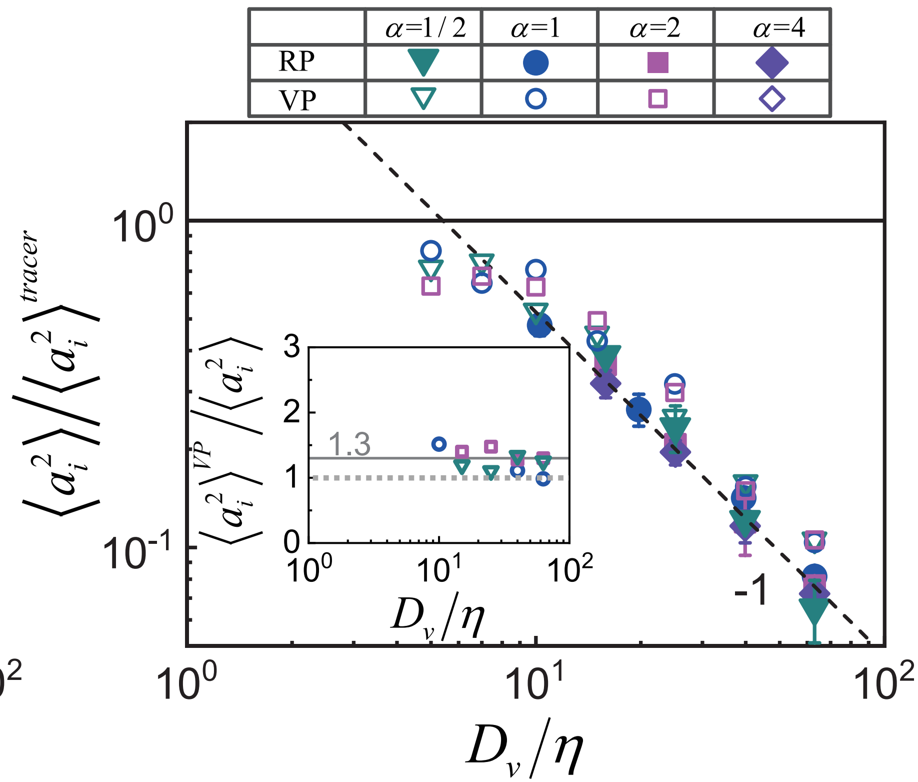
Same trend in D_v with an offset

Spheroids: Acceleration variance

Real Particles vs Volume Averages



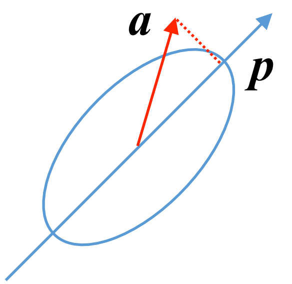
Real Particles vs Virtual Particles



Better overlap for VP particles

$$D_{\mathrm{v}} = (d^2 l)^{1/3} = d\alpha^{1/3}$$

Spheroids: Acceleration alignment

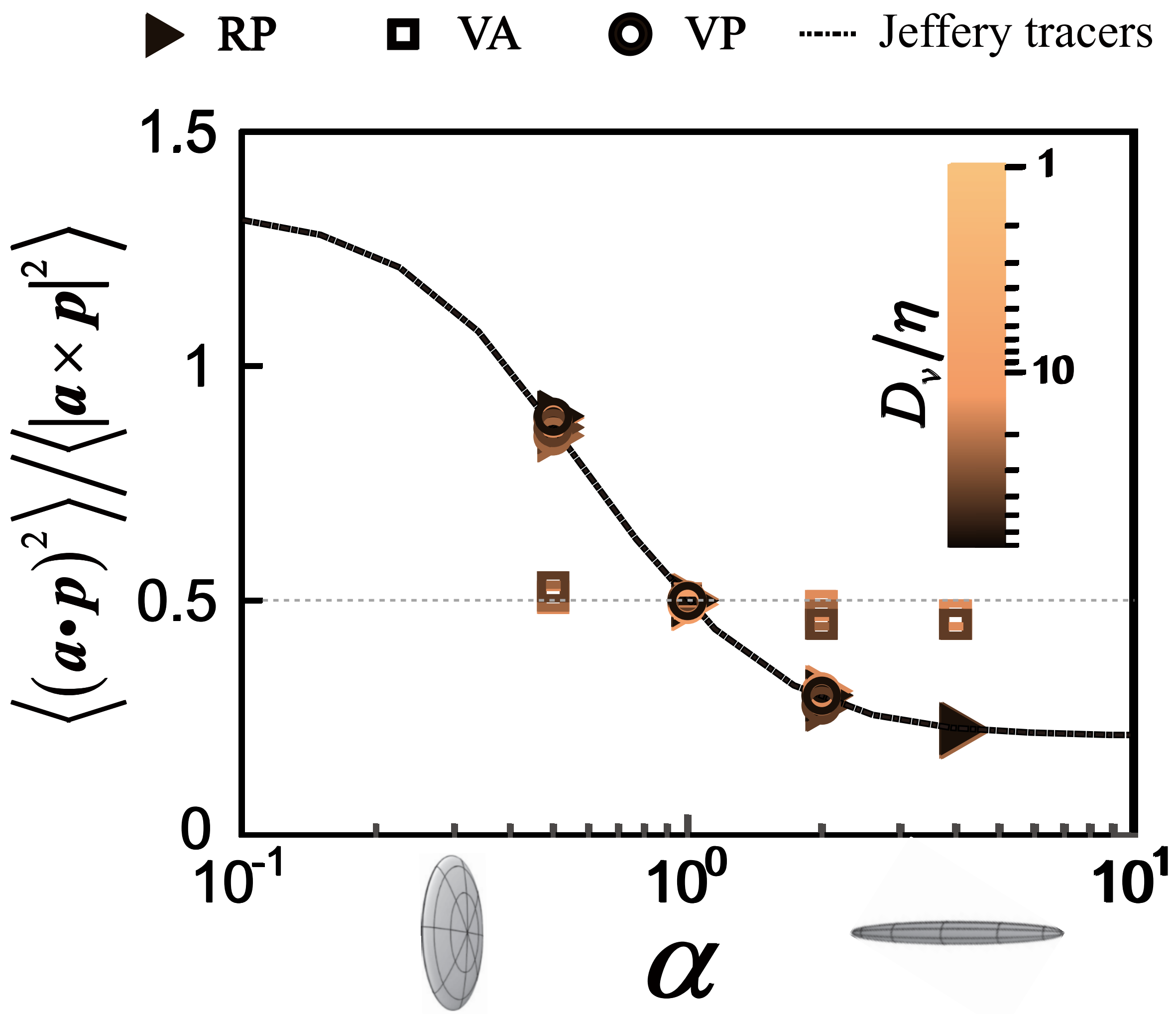


Axial acceleration

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

Transverse acc

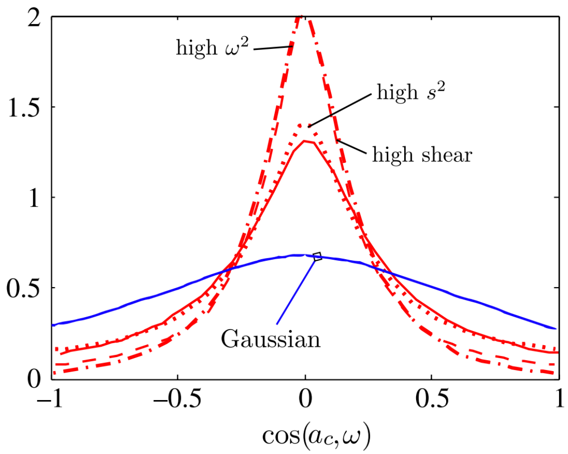
$$\boldsymbol{a}^{\perp} = \boldsymbol{a}\times\mathbf{p}$$



Spheroids: Acceleration alignment

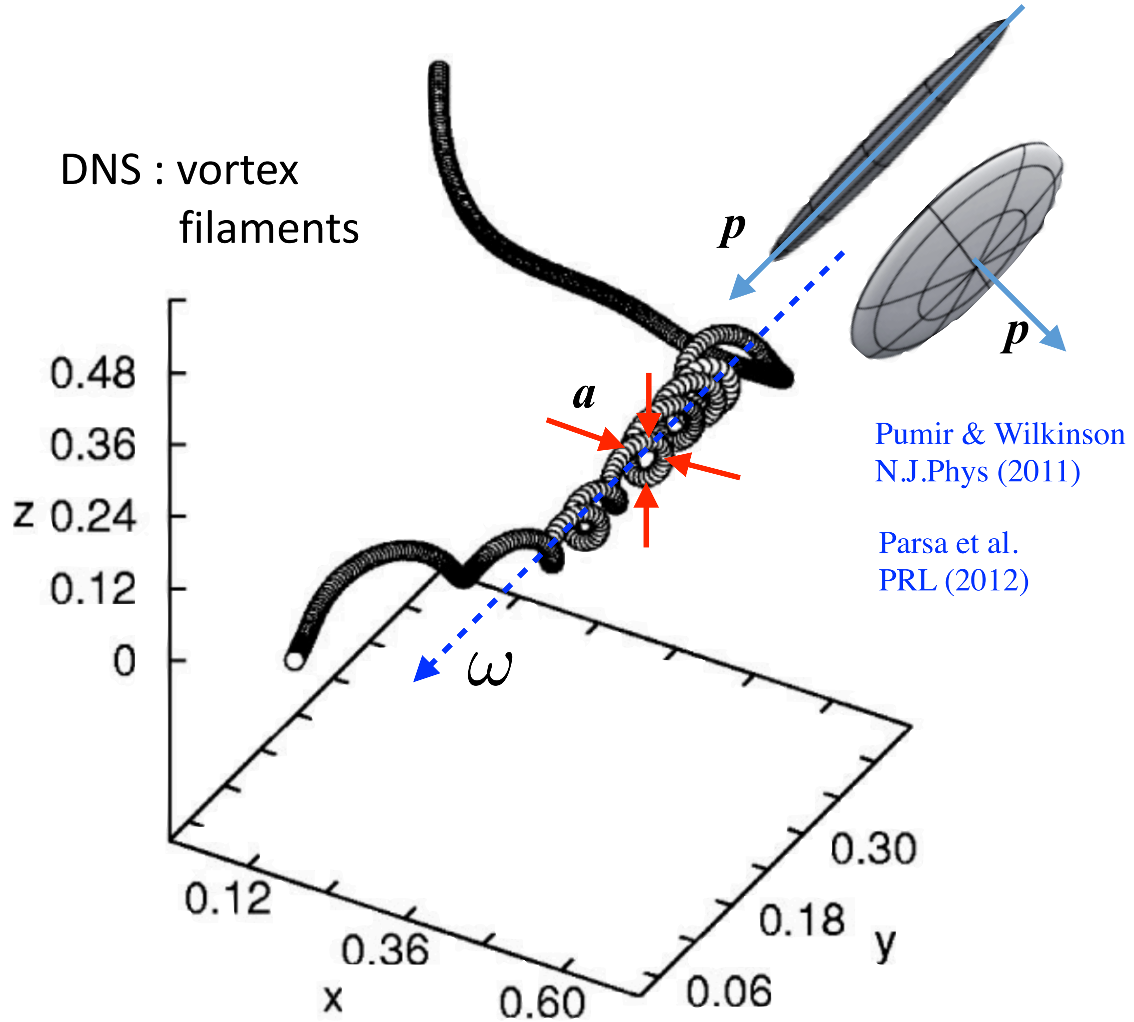
A qualitative explanation

EXP: $\mathbf{a} \perp \boldsymbol{\omega}$



A.Liberzon et al. Physics (2012)

DNS : vortex filaments



Pumir & Wilkinson N.J.Phys (2011)

Parsa et al. PRL (2012)

L.Biferale et al. Phys Fluids (2005)

Summary

Acceleration

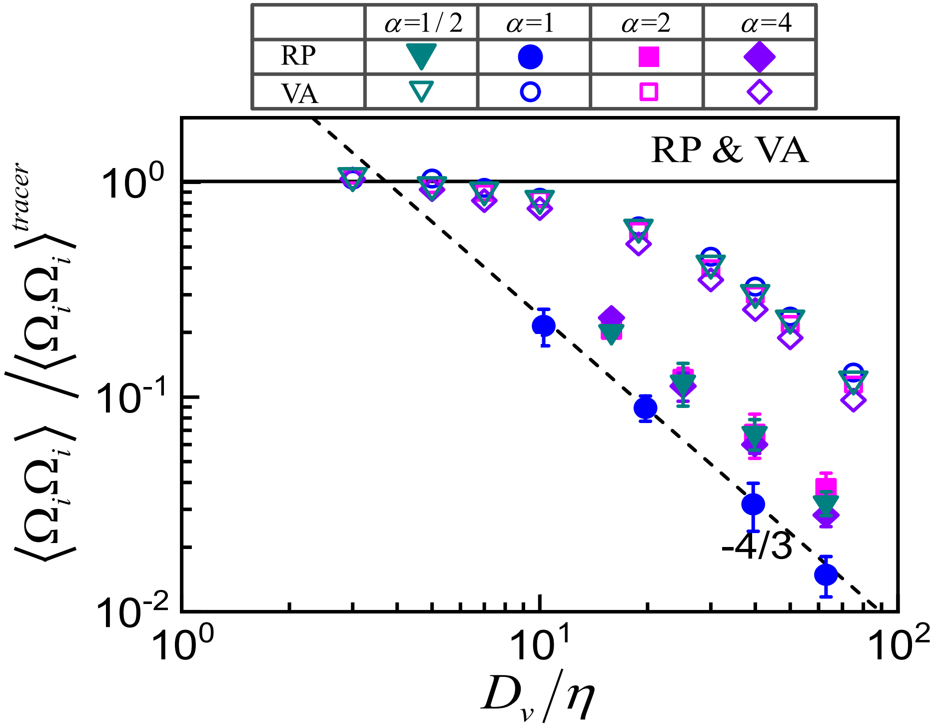
Size-dependence explained by **fluid acceleration volume averages** (VA or VP)
Amplitude better accounted for **dynamical** (Lagrangian) **volume averages** (VP)

Importance of **flow structures**: preferential alignment even for inertial-scale particles!

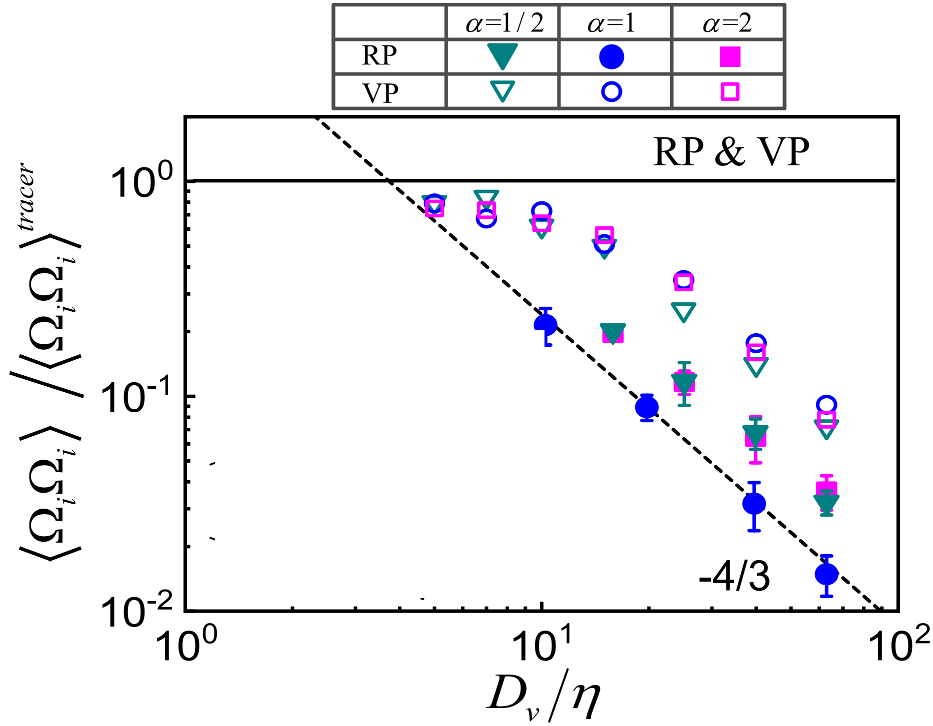
Rotation

Spheroids: Angular velocity

Real Particles vs Volume Averages



Real Particles vs Virtual Particles

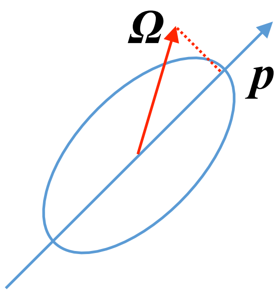


$$\Omega(D) \sim \frac{1}{\tau(D)} \sim \frac{\delta_D u}{D} \sim D^{-2/3}$$

Coarse grained scaling relation ok!

But no overlap of RP with VA or VP

Spheroids: spinning and tumbling



Two predictions:

1) Randomly oriented model in HIT flow

Parsa, EC, Voth, Toschi, PRL 2012

$$\langle \Omega_i^s \Omega_i^s \rangle = \frac{1}{12}\frac{1}{\tau_\eta^2}$$

$$\frac{\langle \Omega_i^s \Omega_i^s \rangle}{\langle \dot{p}_i \dot{p}_i \rangle} = \frac{\frac{1}{12}\langle \omega^2 \rangle}{\frac{1}{6}\langle \omega^2 \rangle + \frac{1}{5}\Lambda^2 \langle \mathcal{S} : \mathcal{S} \rangle} = \frac{5}{10 + 6\Lambda^2}$$

$$\langle \dot{p}_i \dot{p}_i \rangle = \left(\frac{1}{6} + \frac{1}{10}\Lambda^2\right)\frac{1}{\tau_\eta^2}$$

$$\Lambda = \frac{\alpha^2 - 1}{\alpha^2 + 1}$$

Axial rotation rate (spin)

$$\boldsymbol{\Omega}^s = (\boldsymbol{\Omega} \cdot \mathbf{p})\mathbf{p}$$

Transverse rotation (tumbling)

$$\dot{\mathbf{p}} = \boldsymbol{\Omega} \times \mathbf{p}$$

2) CGH prediction

Oehmke et al., PRF 2021

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

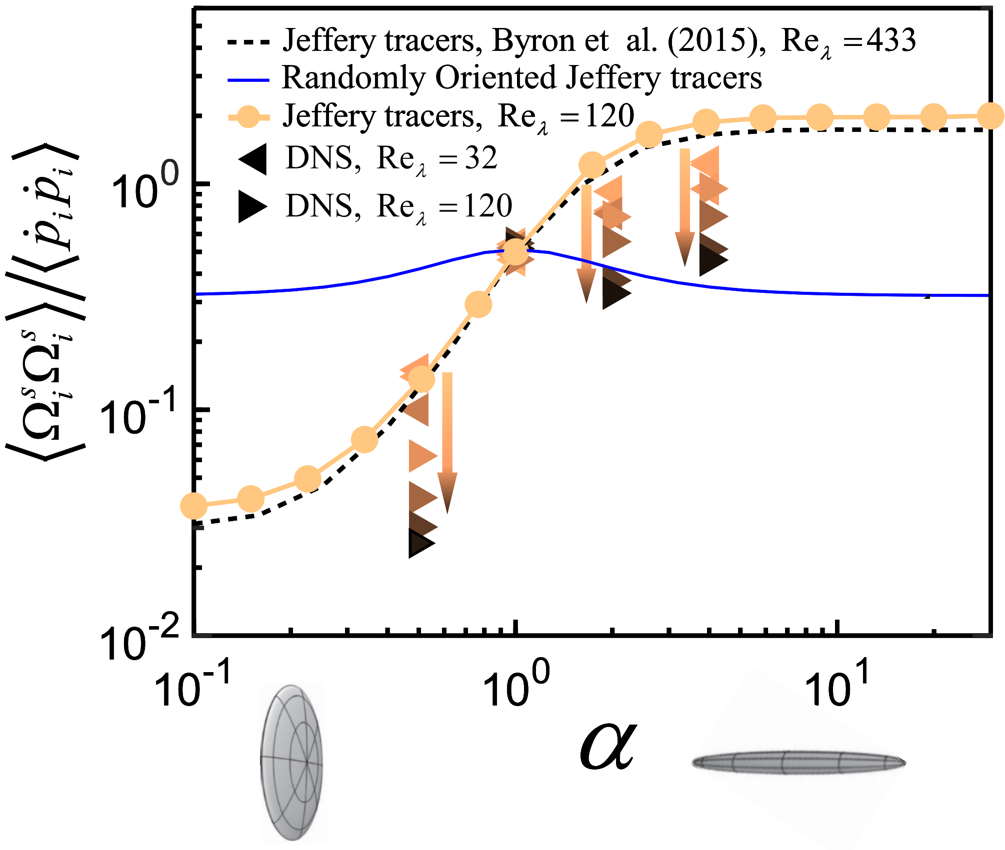
$$\langle \dot{p}_i \dot{p}_i \rangle \sim l^{-4/3}$$

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

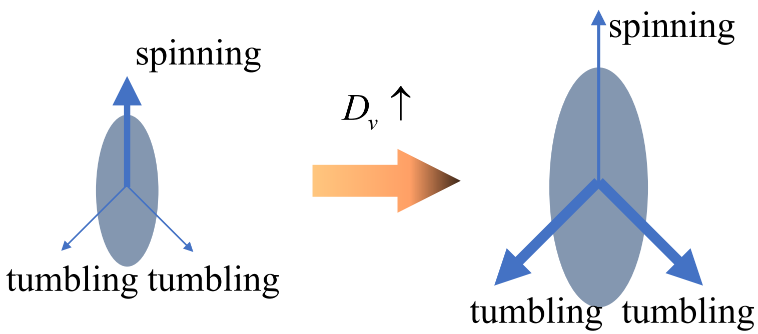
Always no size dependence!

Review:
Voth & Soldati, Ann Rev Fluid Mech 2017

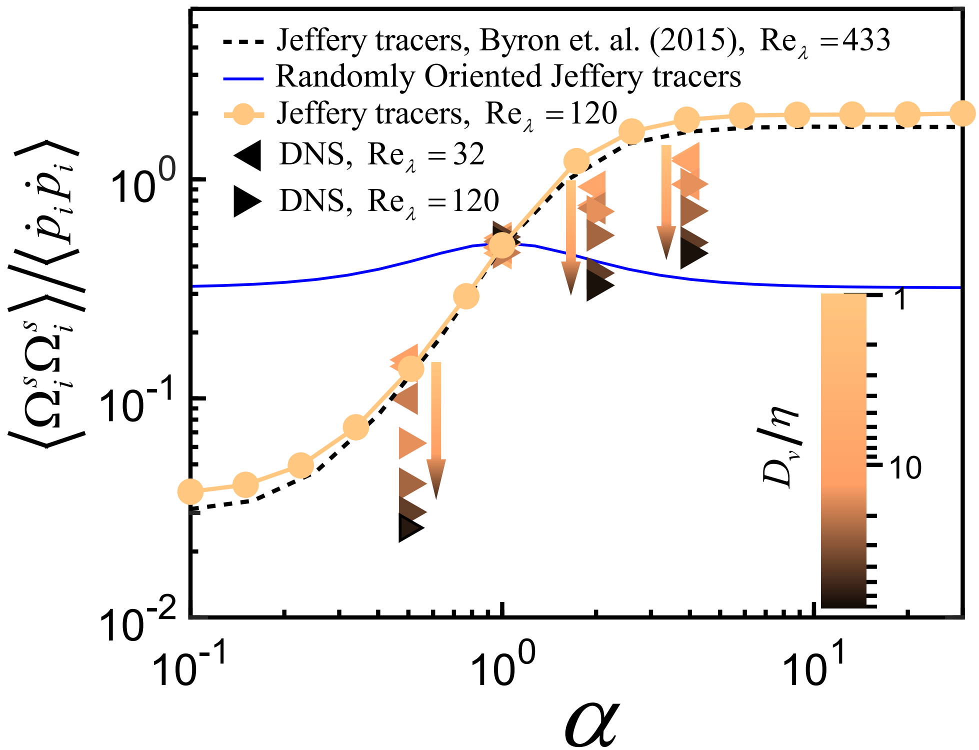
Spinning - tumbling variance ratio



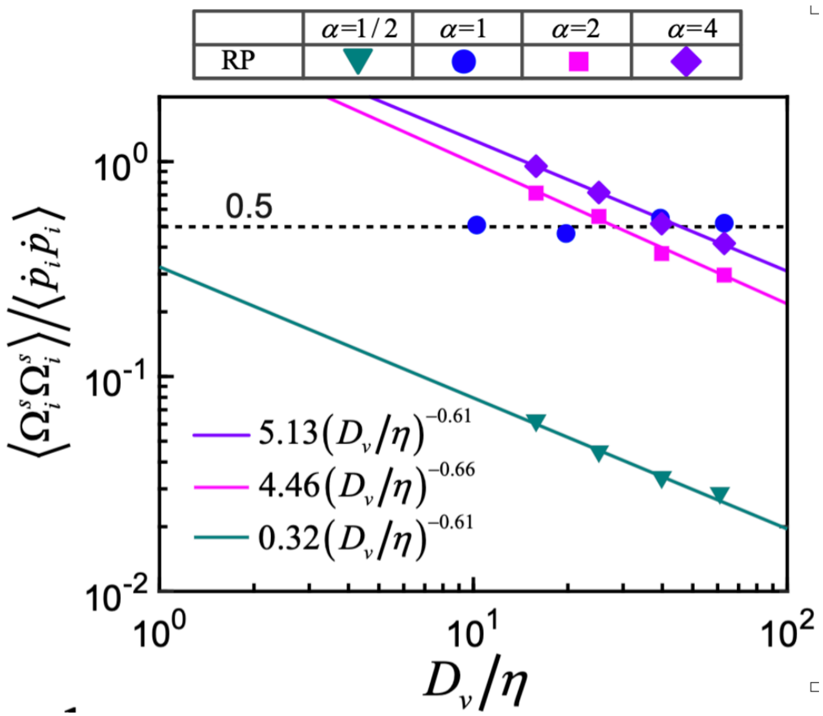
Large particles
spin less and tumble more



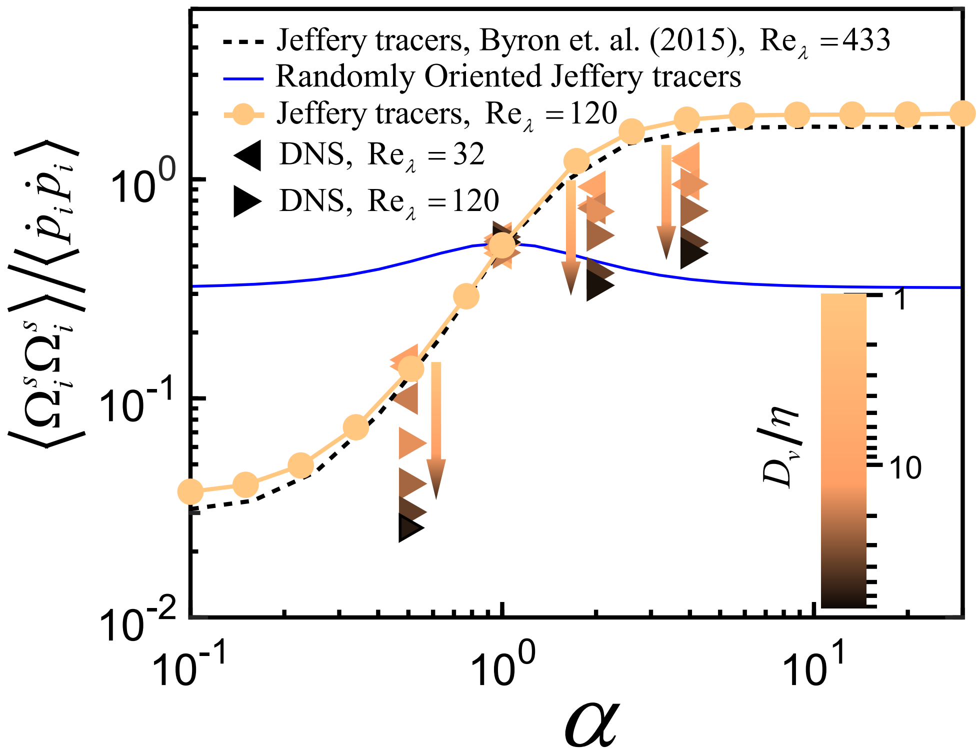
Spinning - tumbling variance ratio



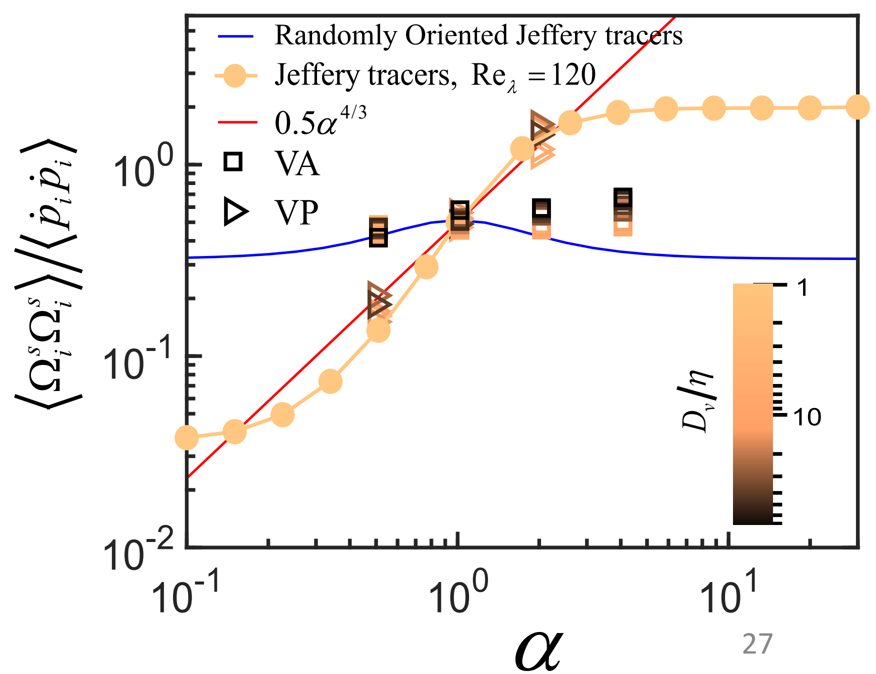
$$\frac{\langle \Omega_i^s \Omega_i^s \rangle}{\langle \dot{p}_i \dot{p}_i \rangle} \sim D_v^{-0.6}$$



Spinning - tumbling variance ratio



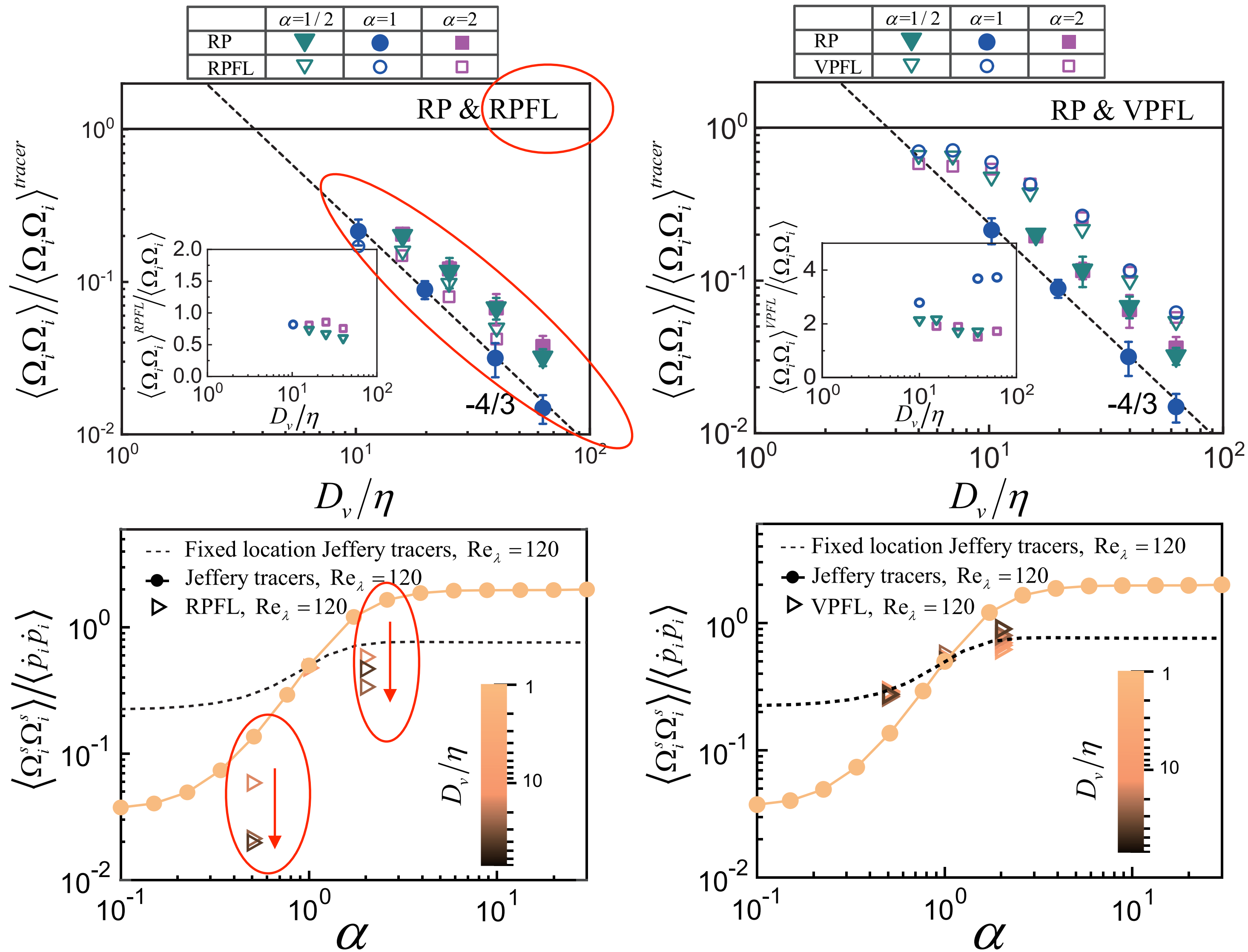
VA and VP do not explain the trends



Spinning - tumbling variance ratio

Real Particles Fixed Location

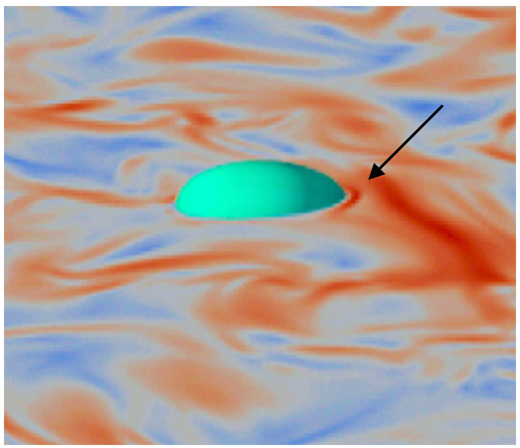
Virtual Particles Fixed Location



Spinning - tumbling variance ratio

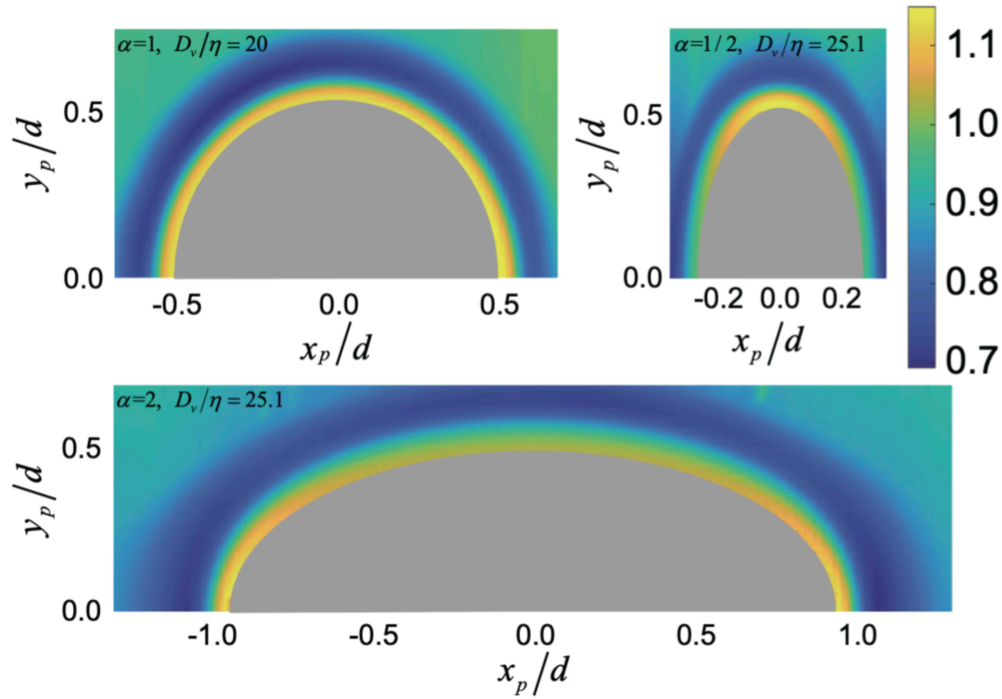
A boundary layer effect?

$$Re_p = \frac{|\mathbf{u}-\mathbf{v}|D_v}{\nu} \simeq \frac{D_v}{\lambda} Re_\lambda \sim O(10^2)$$



Dissipation field surrounding a fully resolved particle

$$\frac{1}{4}\overline{\boldsymbol{\omega}^2}/\overline{S:S}$$



Overall increase in strain-rate as compared to vorticity —> this promote tumbling

Cisse, Homann & Bec JFM 2013

Summary / conclusion

Acceleration

Size-dependence explained by **fluid acceleration volume averages** (VA or VP)
Amplitude better accounted for by **dynamical** (Lagrangian) **volume averages** (VP)

Importance of **flow structures**: preferential alignment even for inertial-scale particles!

Rotation

Size-dependence explained in terms of volume averages but not its **amplitude**

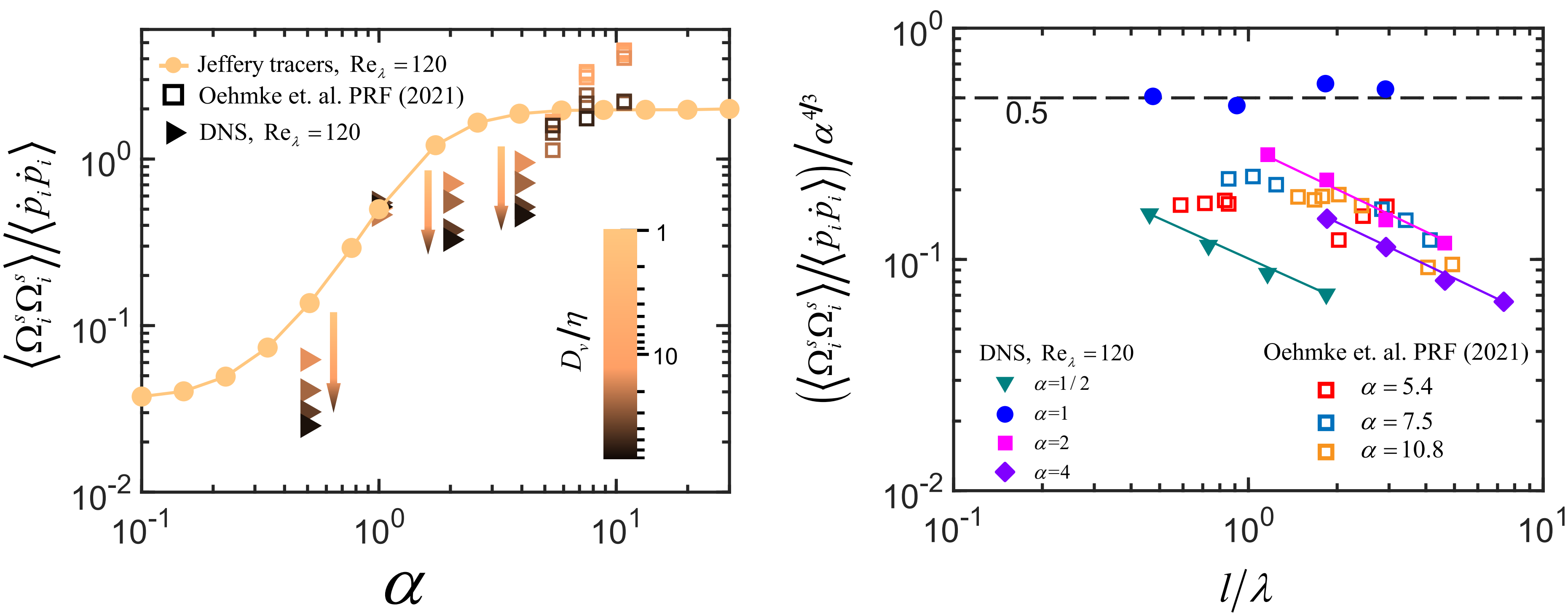
Importance of **two-way coupling** and **boundary layers**: decrease of spinning vs. tumbling!

Experimental verifications and high-resolution DNS are still (very much) needed!

Dynamics of finite-size spheroids in turbulent flow: the roles of flow structures and particle boundary layers,
L. Jiang, C. Wang, S. Liu, C. Sun, E. Calzavarini, [http://arxiv.org/abs/2202.03937] **J. Fluid Mech** (2022)

Spinning - tumbling variance ratio

Comparison with Oehmke, Bordoloi, Variano, Verhille PRF (2021)



More experimental measures of tumbling & spinning needed.

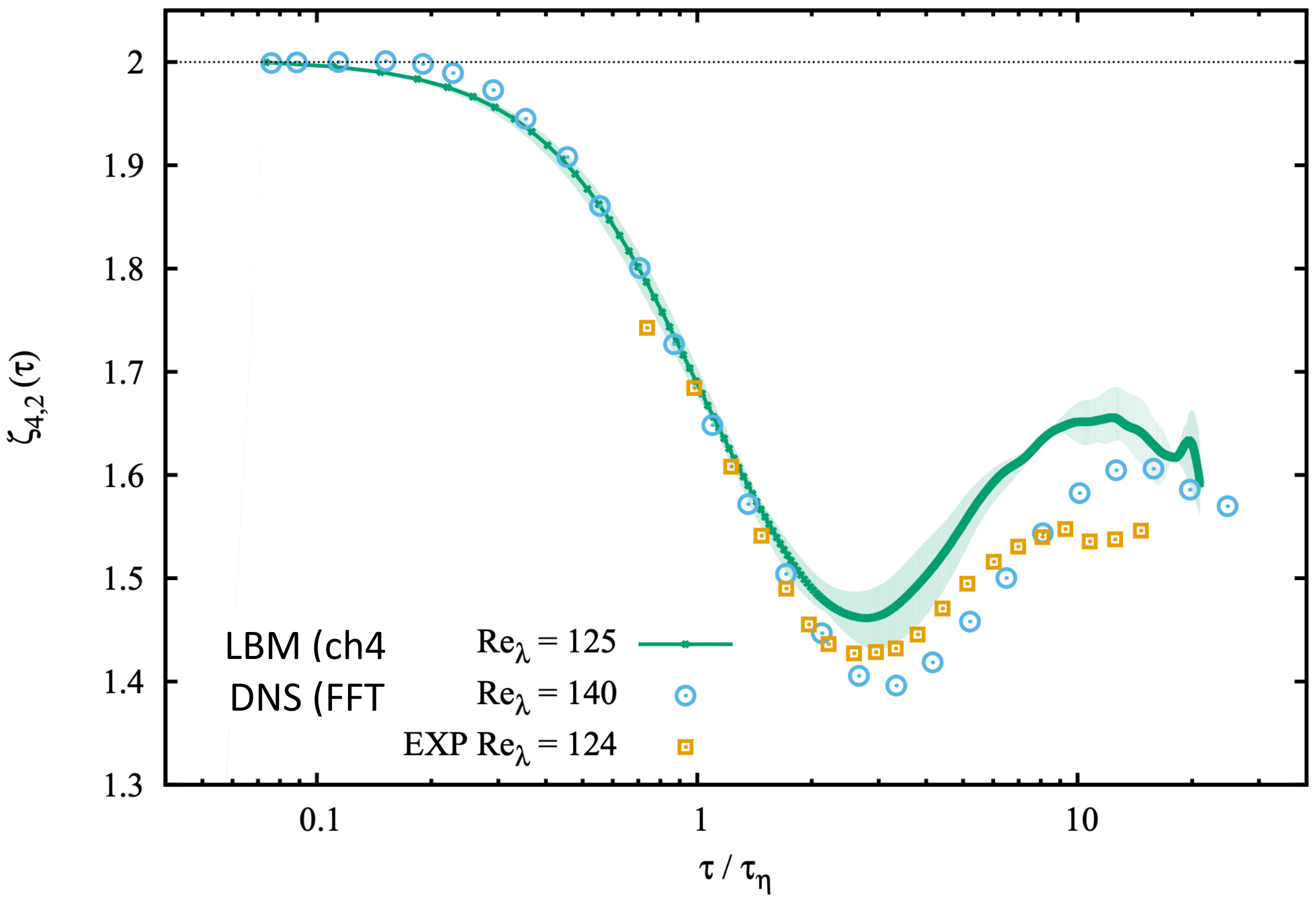
Perspectives

- How to reach a more quantitative understanding? Modelling needed.

- Numerical results must be extended to higher Re numbers and to non-neutrally buoyant particles

Code validation: Lagrangian tracer statistics

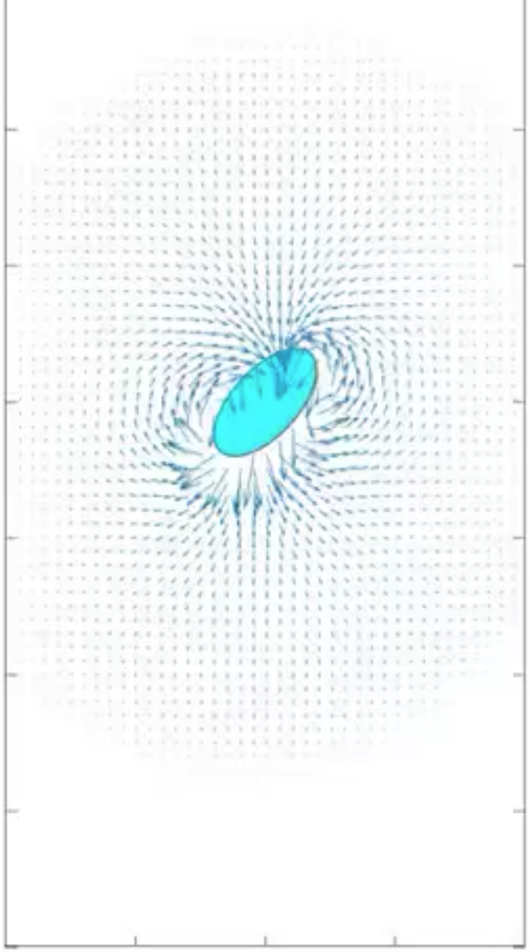
Calz....PRF (2021)



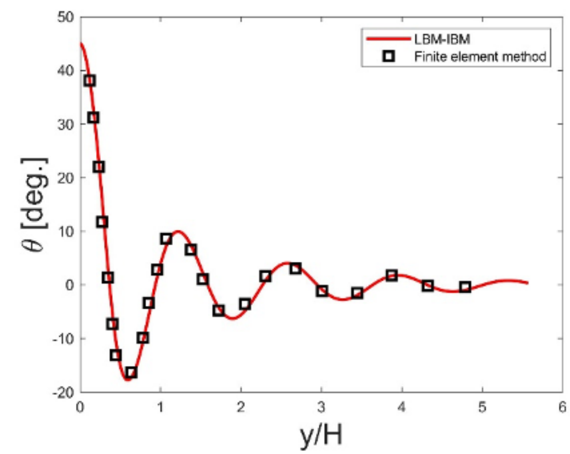
$$\zeta_{4,2}(\tau) = \frac{d \log \langle (\delta_\tau \dot{x}_{s,i})^4 \rangle}{d \log \langle (\delta_\tau \dot{x}_{s,i})^2 \rangle},$$

Code validation: particle sedimentation

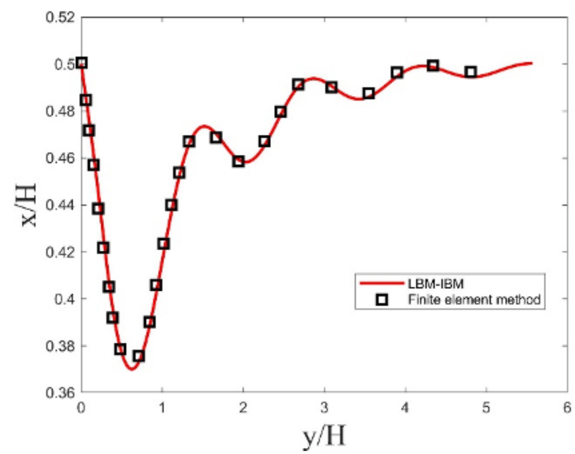
Settling of an elliptic finite-sized particle



Orientation angle vs. vertical displacement



Horizontal vs. vertical displacement



Z. Gia, K. W. Connington, S. Rapaka, P. Yiue, J.J. Feng & S. Chen, JFM 625,249-272 (2009)
K. Suzuki & T. Inamuro, Comput. & Fluids 49, 173-187 (2011)