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OF TECHNOLOGY

Breakup of finite size colloidal aggregates in turbulent flow

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In collaboration with:

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W. Kinzelback (ETH Zurich)
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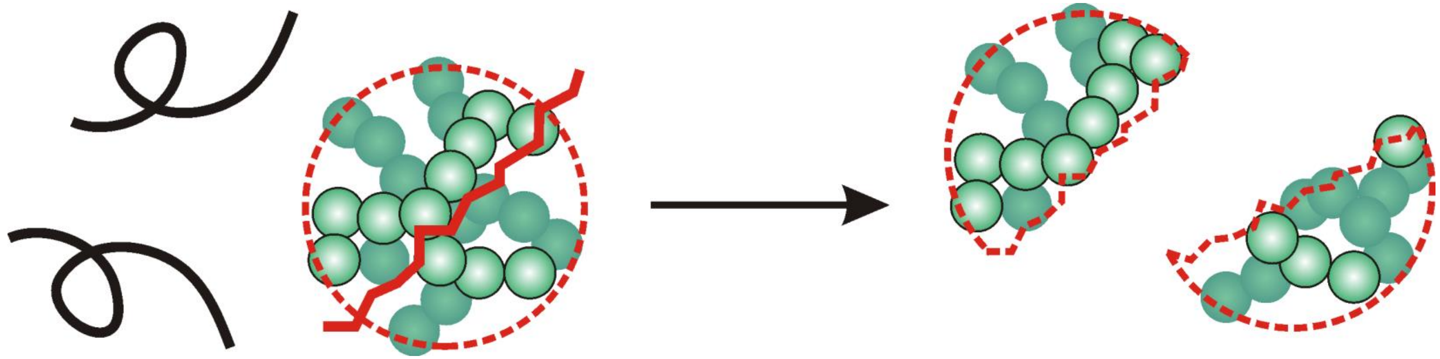
A.S. Lanotte (CNR Lecce)

COST Workshop – *Lagrangian transport: from complex flows to complex fluids,* Lecce, March 7-10, 2016

Breakup of aggregates



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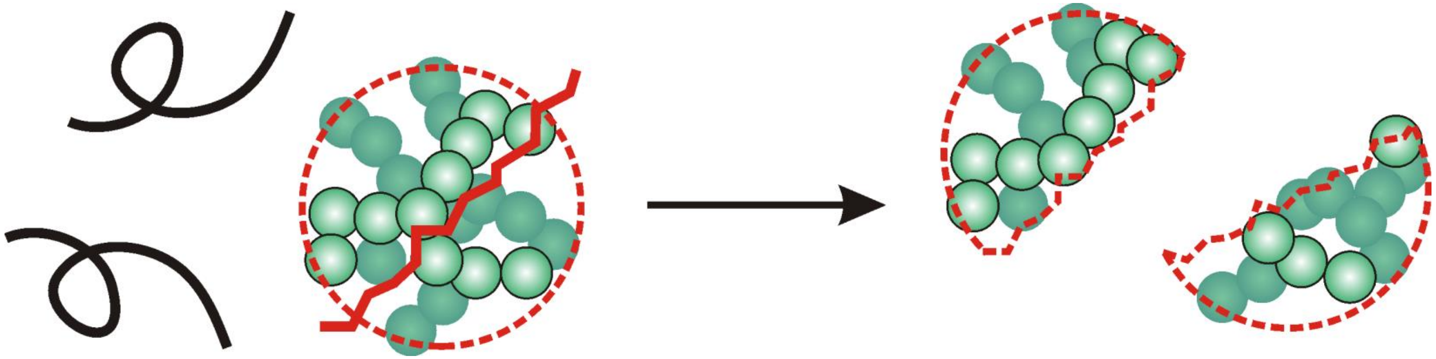
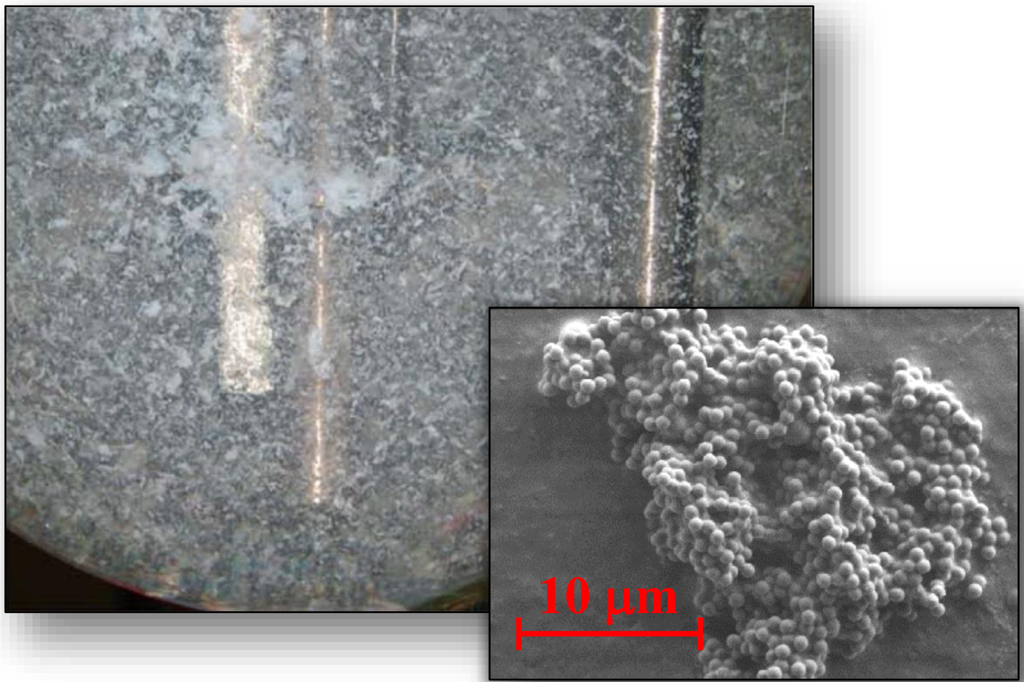
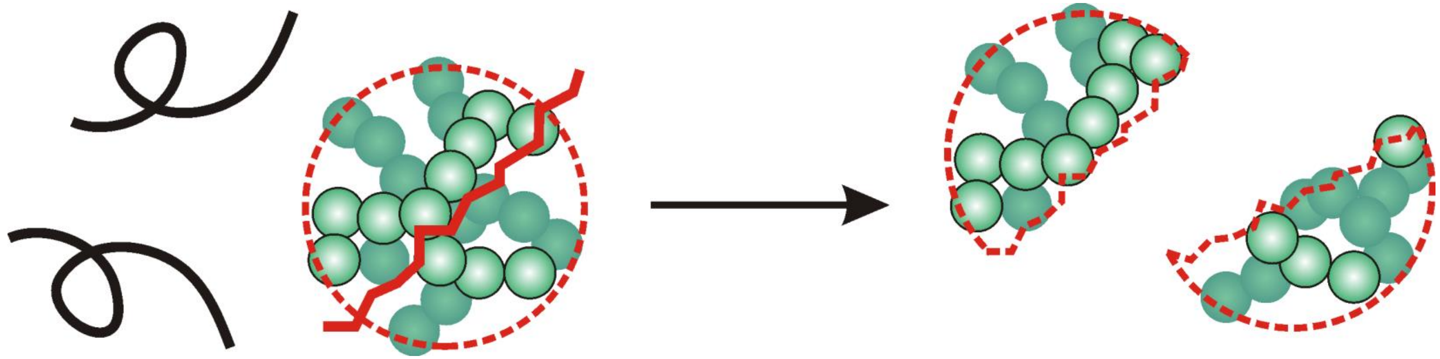


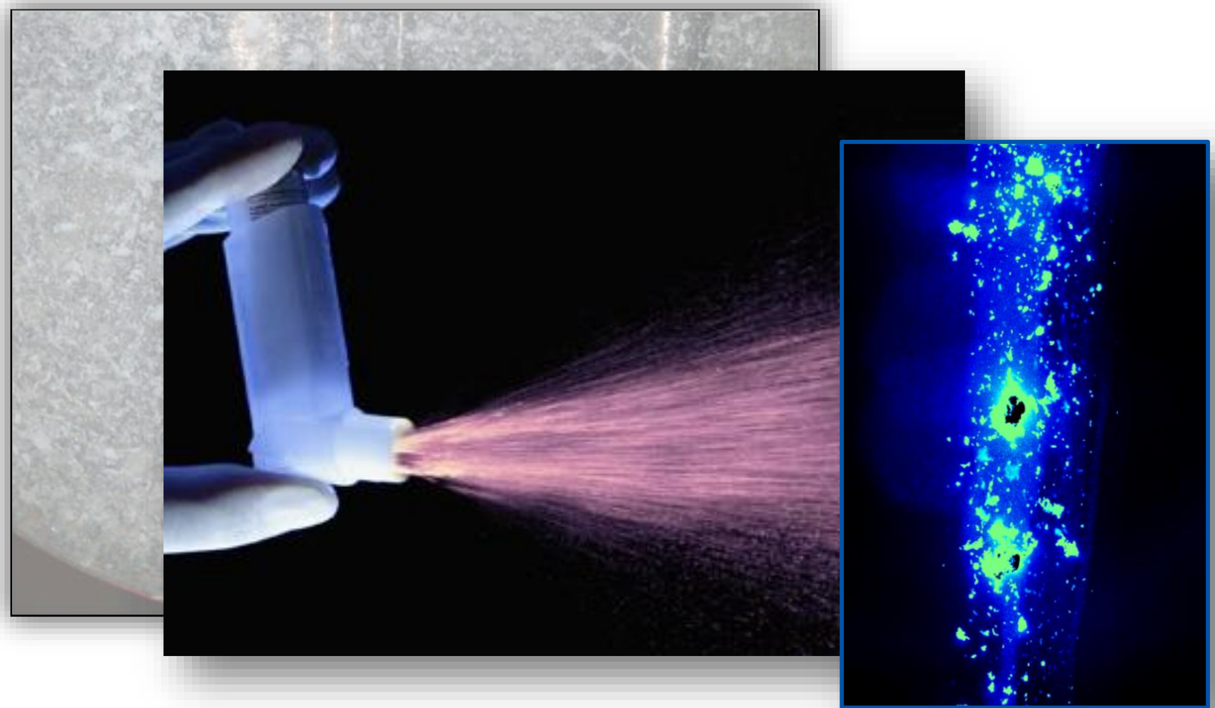


- Processing of industrial colloids, flocculation in (waste)water treatment

Pictures: M. Soos, D. Marchisio, J. Sefcik, *AIChE J.* (2013) and Soos, et al., *J. Colloid Interface Sci.* (2008)

Breakup of aggregates

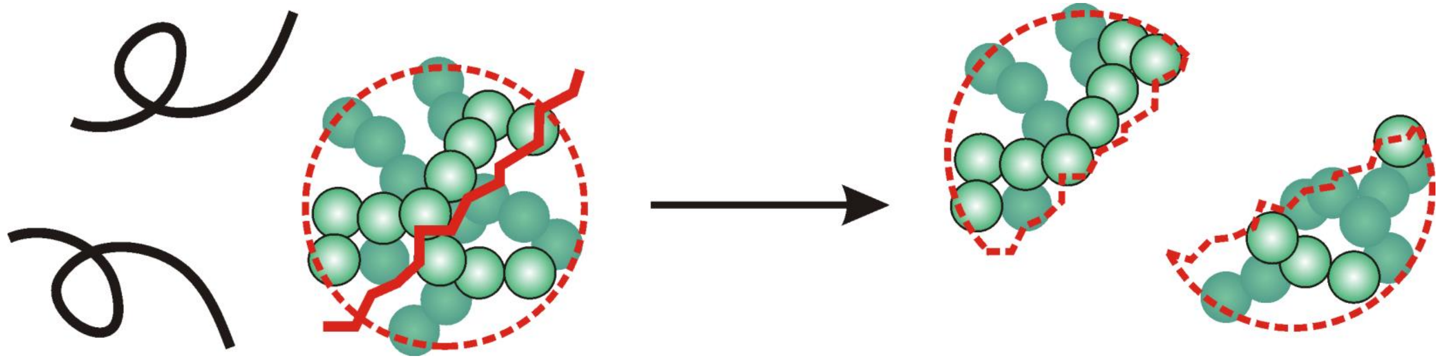




- Processing of industrial colloids, flocculation in (waste)water treatment
- Dispersion of powder agglomerates (inhalation drugs, powder burners)

Picture: Getty images (2015-03-22), Göktepe et al. *Fuel Process. Technol.* (2016)

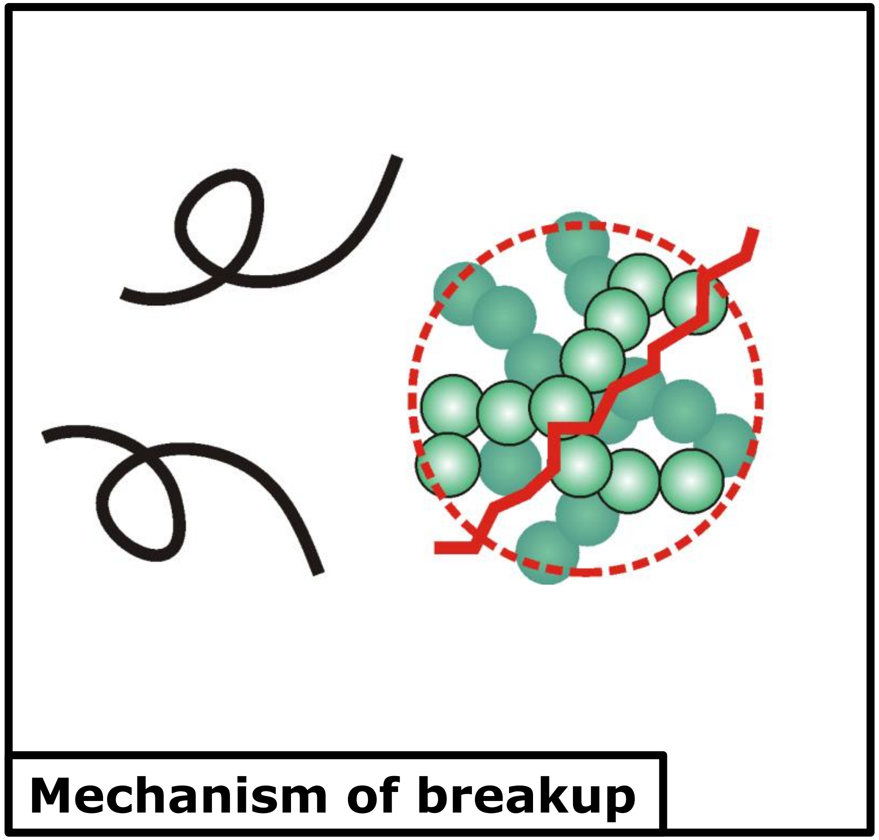
Breakup of aggregates

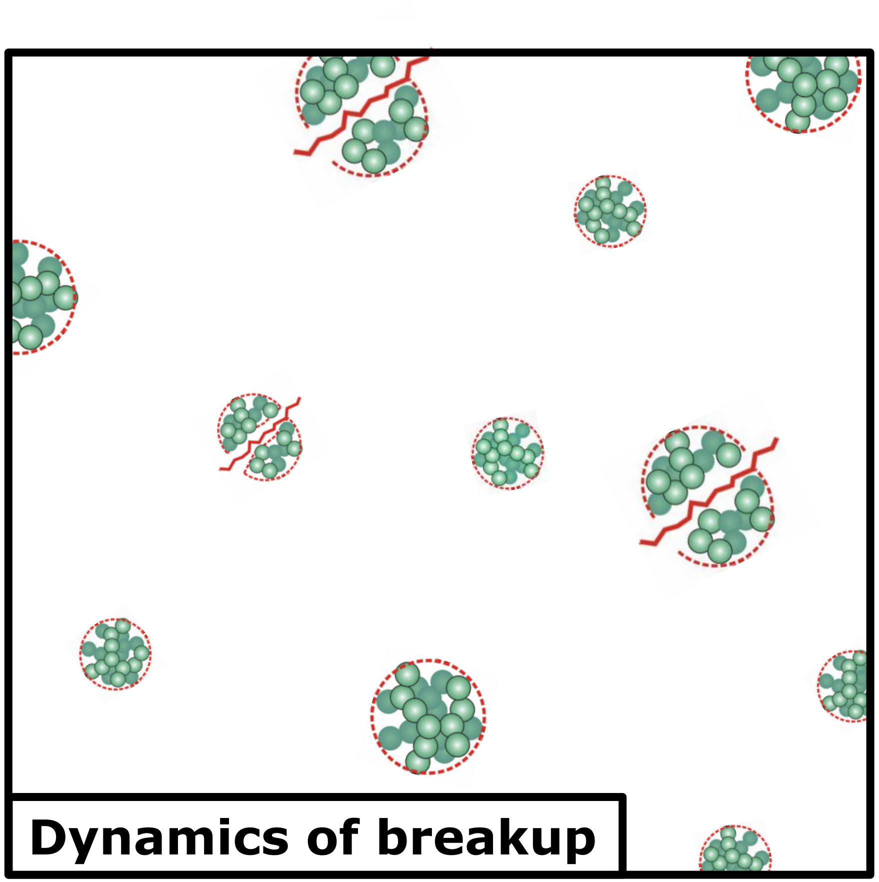


- Processing of industrial colloids, flocculation in (waste)water treatment
- Dispersion of powder agglomerates (inhalation drugs, powder burners)
- Evolution and transport of sediments and marine snow in natural waters

Picture: Satellite image River Plate Estuary, 2010-03-10 (www.eosnap.com, 2014-03-12)

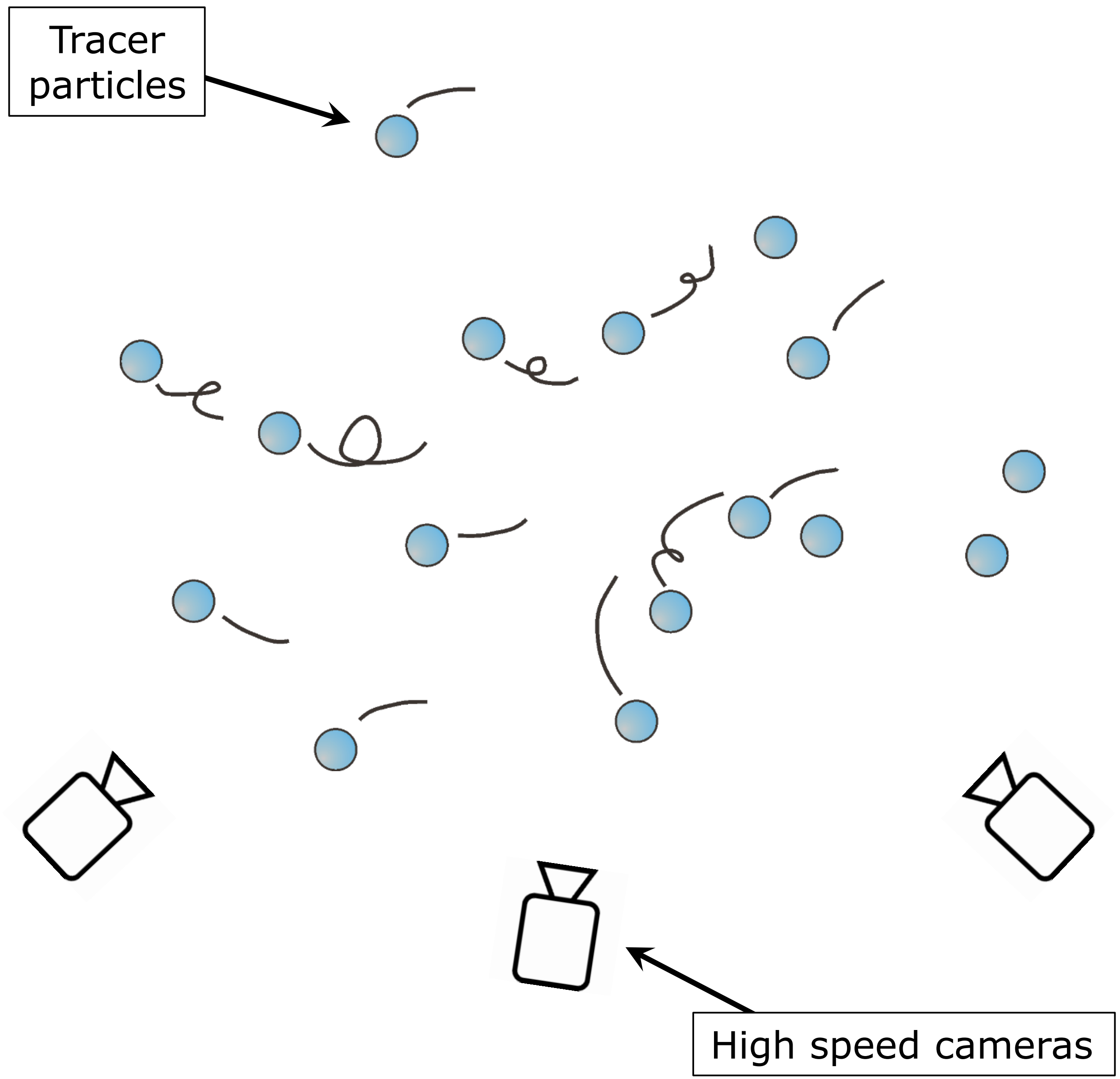
Aggregate breakup in turbulence





Experimental setup

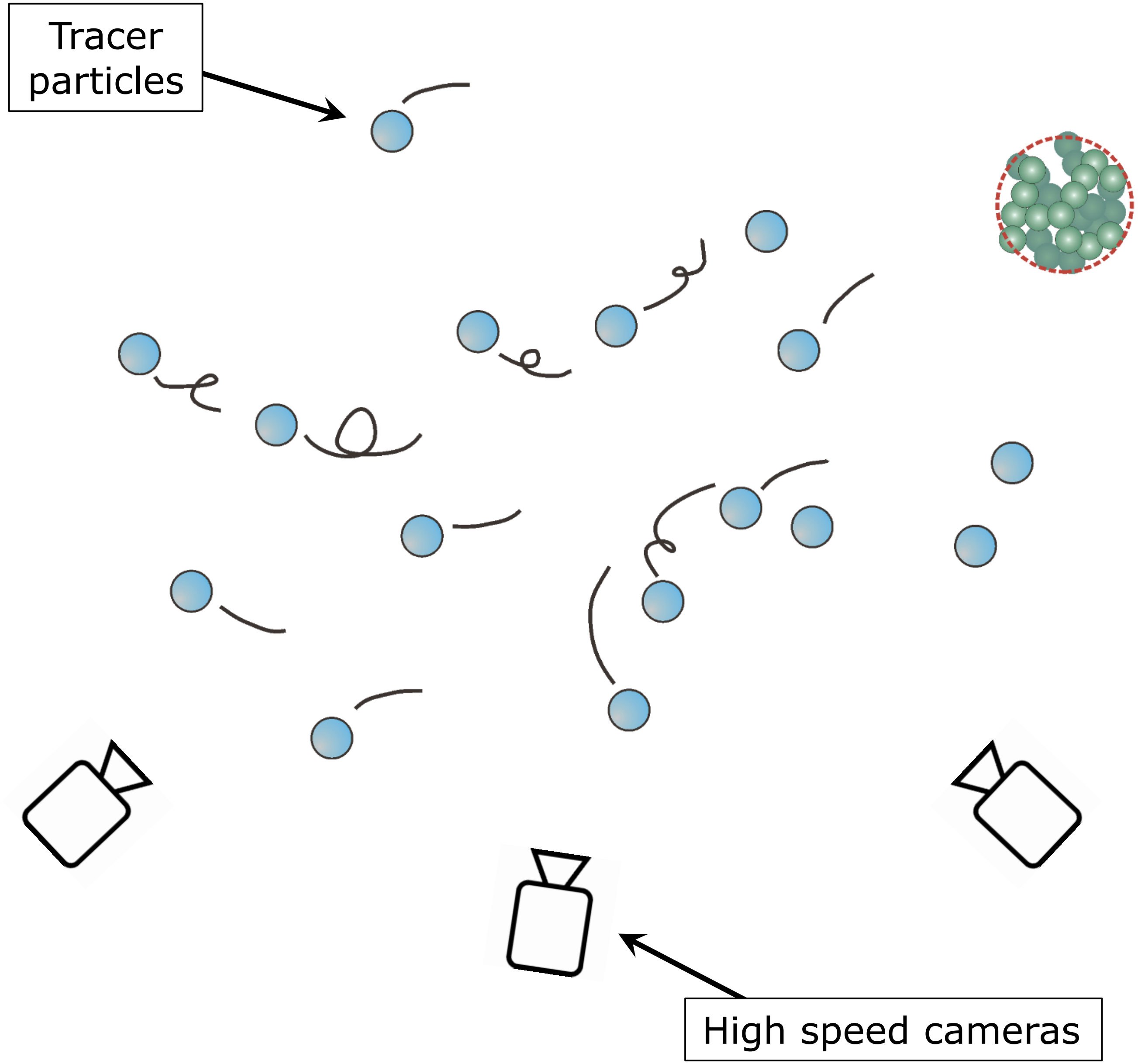
- Stationary turbulence, monitored by 3D PTV



Lüthi, Tsinober, Kinzelbach, *J. Fluid Mech.* **528** (2005) 87

Experimental setup

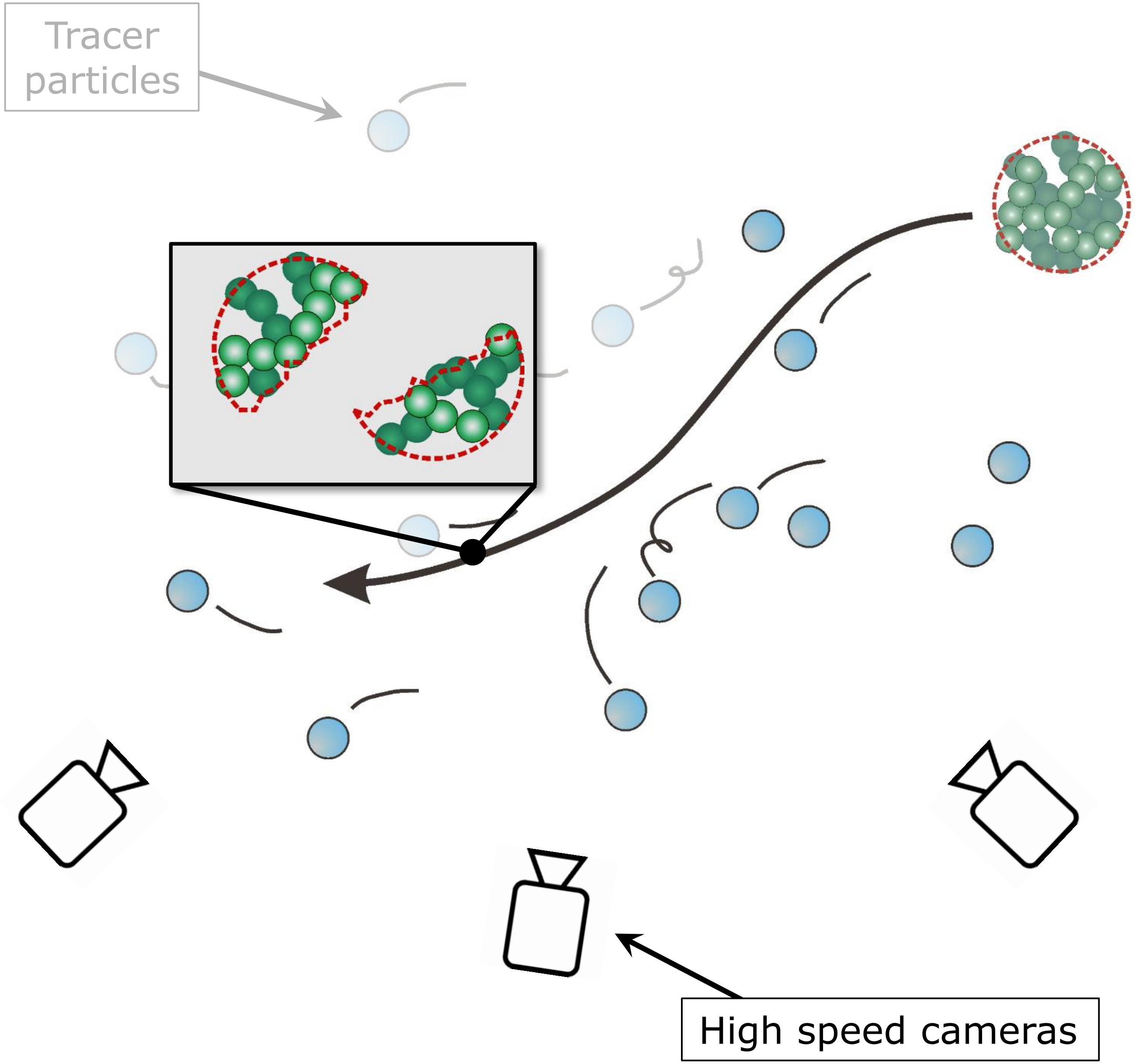
- Stationary turbulence, monitored by 3D PTV
- Inject a single pre-formed aggregate



Lüthi, Tsinober, Kinzelbach, *J. Fluid Mech.* **528** (2005) 87

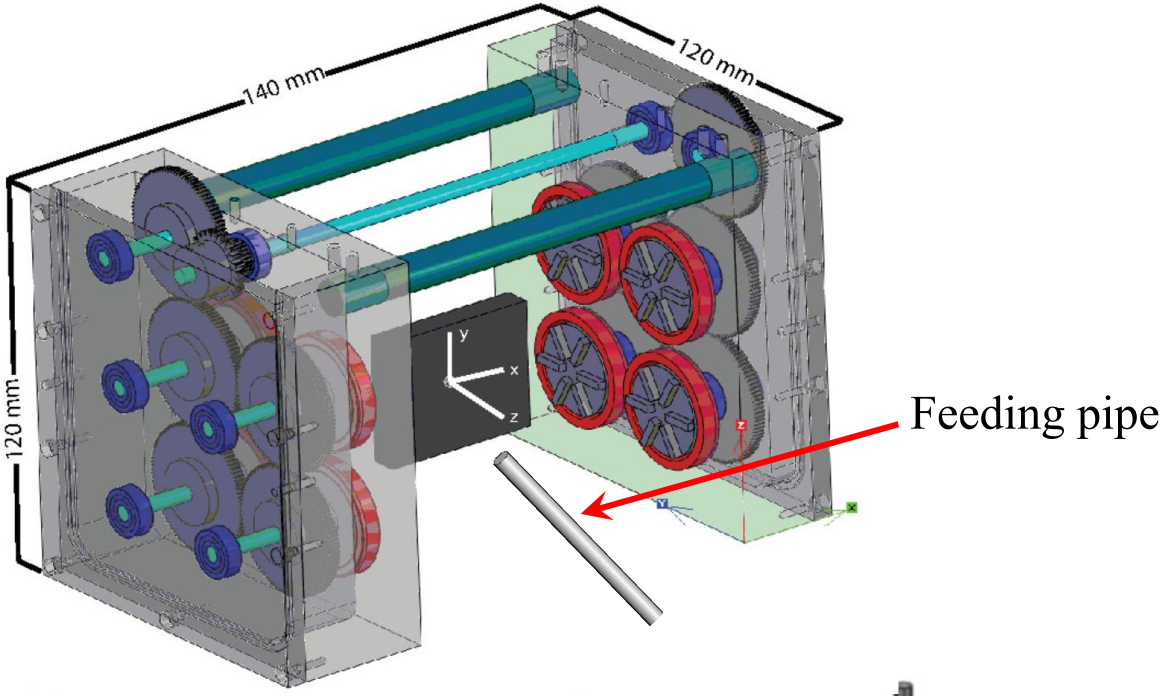
Experimental setup

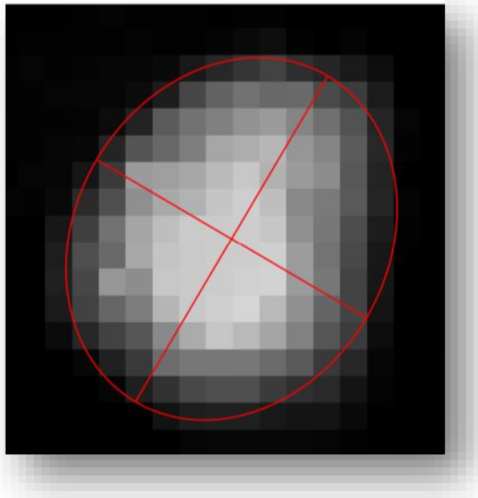
- Stationary turbulence, monitored by 3D PTV
- Inject a single pre-formed aggregate
- Follow the aggregate until (and beyond) breakup
- Determine local flow conditions that prevail at breakup



Lüthi, Tsinober, Kinzelbach, *J. Fluid Mech.* **528** (2005) 87

Experimental setup





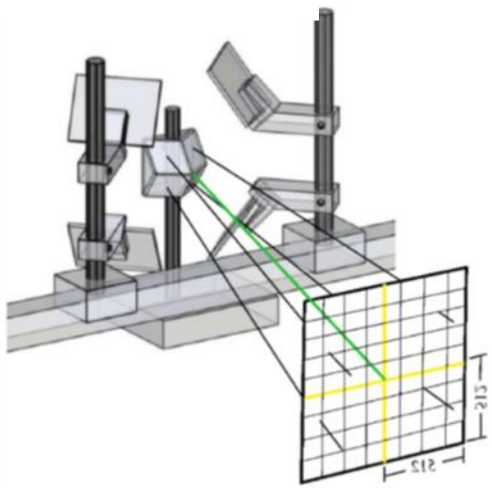
Aggregates

- Made out of polystyrene colloids, $d_p = 420$ nm
- Grown *in-situ* in the feed pipe, under oscillatory flow
- $d_{agg} = 1.4 \pm 0.4$ mm

Fractal dimension $d_f \sim 2.2$

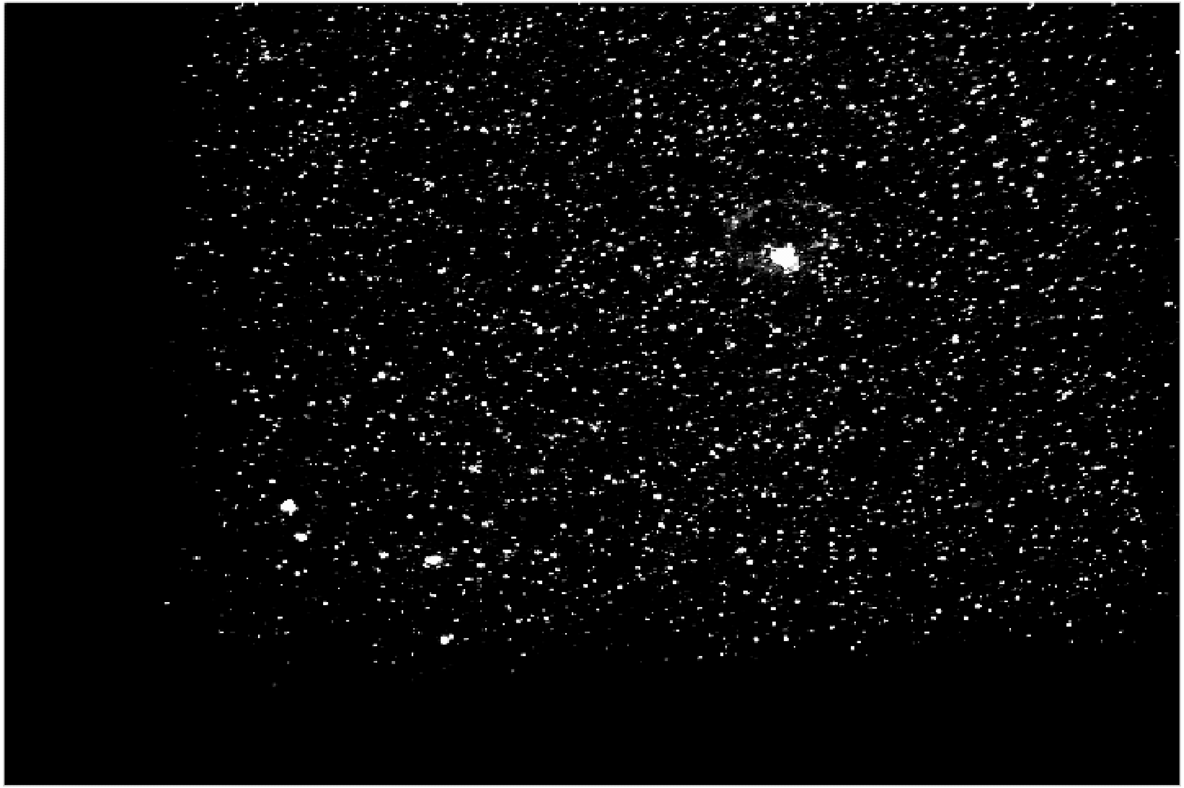
Flow device

- $R_\lambda \approx 117$
- $\langle \varepsilon \rangle \approx 19$ cm^2/s^3
- $\eta \approx 0.15$ mm



Liberzon, Guala, Lüthi, Kinzelbach, *Phys. Fluids* **17** (2015) 031707

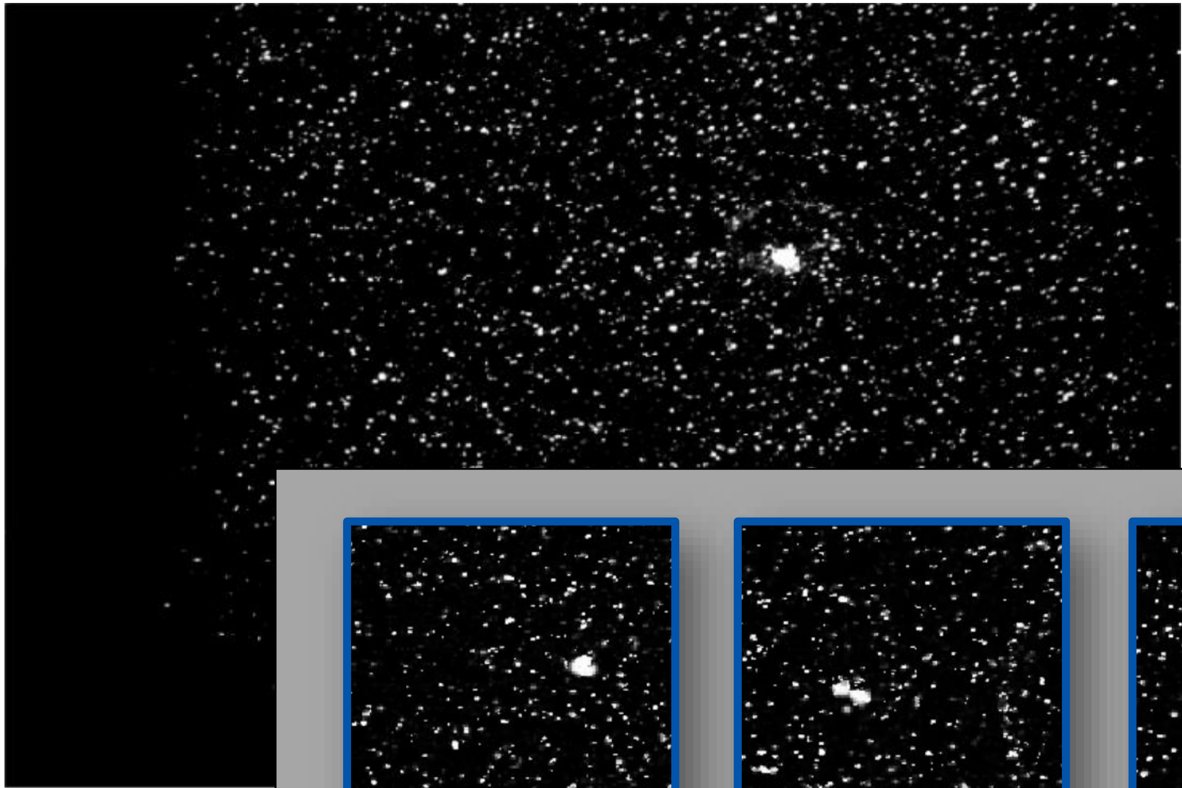
Breakup experiments



Example of a breakup experiment

- $R_\lambda \approx 117$
- $\langle \varepsilon \rangle \approx 19\ \mathrm{cm^2/s^3}$
- $\eta \approx 0.15\ \mathrm{mm}$
- $d_{\mathrm{agg}} \approx 1.4\ \mathrm{mm}$

Breakup experiments



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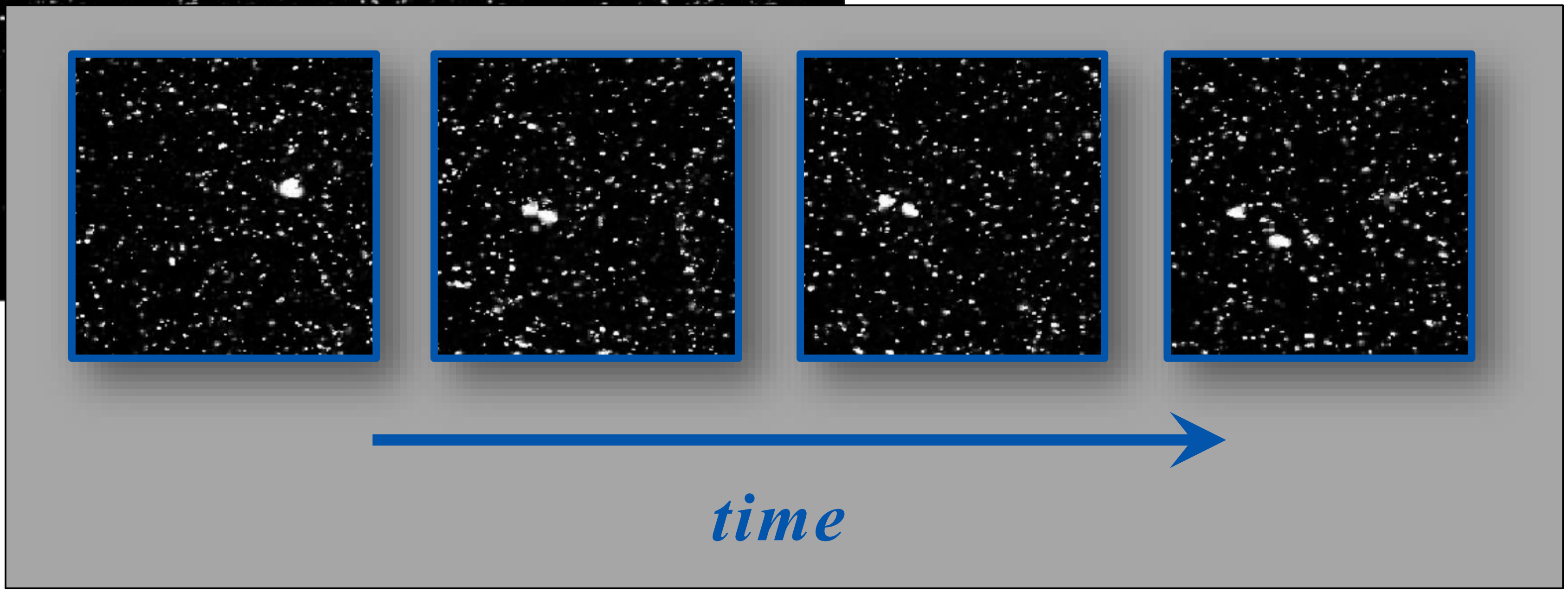


Hydrodynamic stress

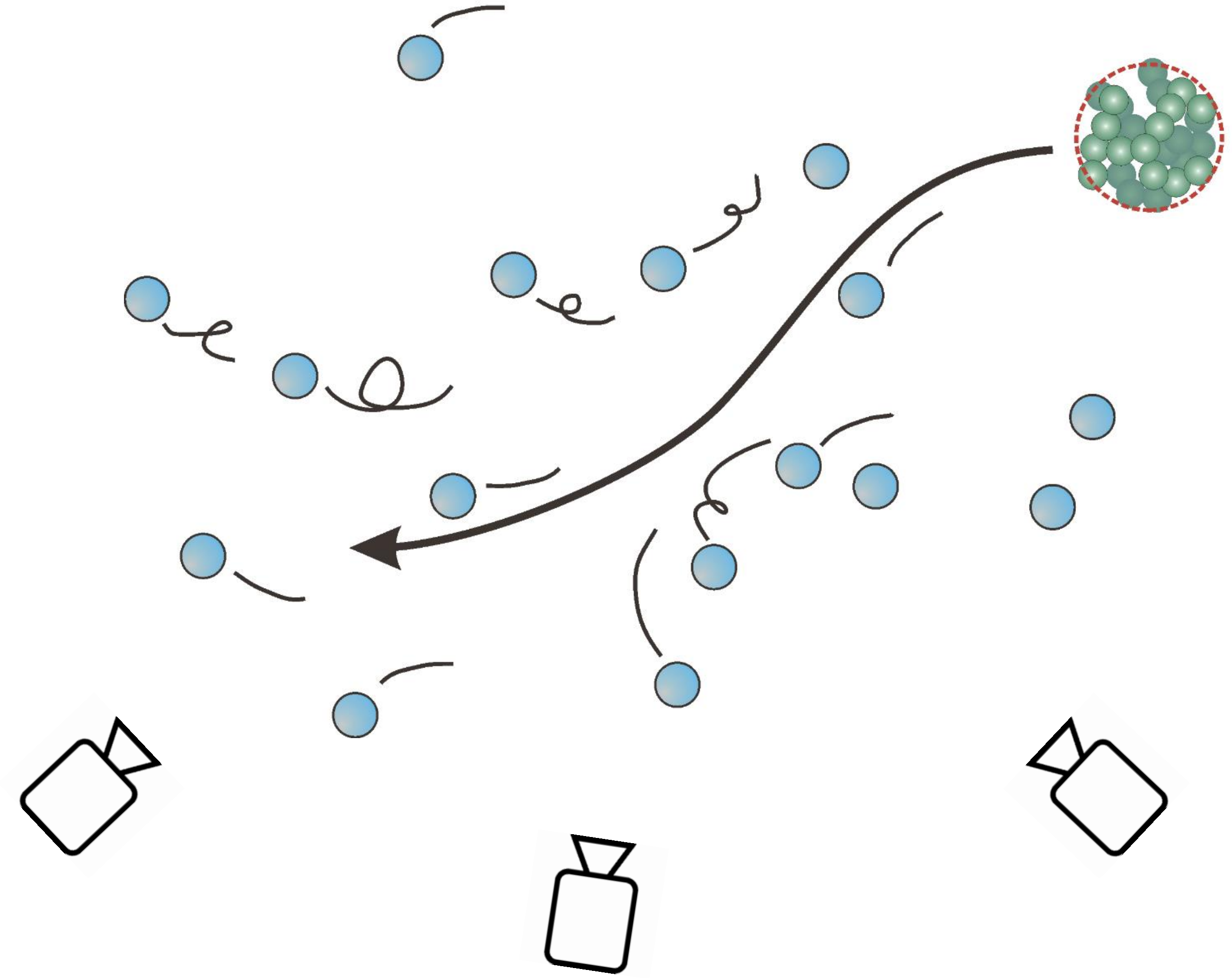
Aggregate motion

- $d_{agg} / \eta \approx 9 \pm 3$

- Aggregate Stokes number

$$St = \frac{1}{18} \frac{\rho_{agg}}{\rho_f} \left(\frac{d_{agg}}{\eta} \right)^{3/4}$$
$$= 0.3 \pm 0.1$$

⇨ Aggregate motion is influenced by inertia



Hydrodynamic stress

Filter size to estimate $\boldsymbol{u}$

Aggregate motion

- $d_{agg}/\eta \approx 9 \pm 3$
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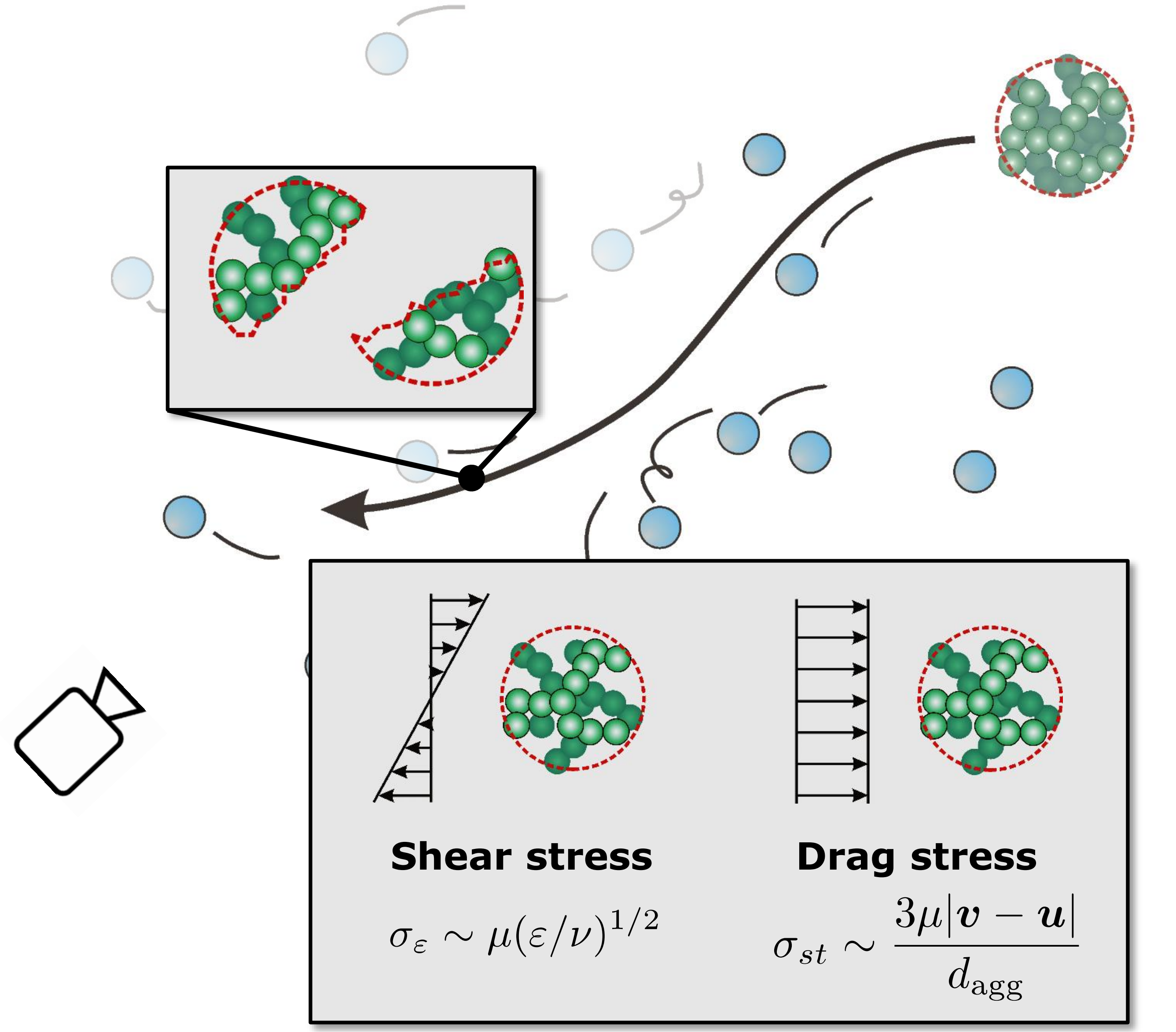

Breakup mechanism: limiting cases

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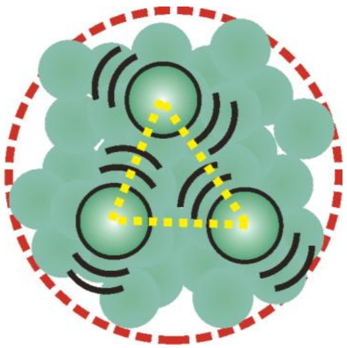
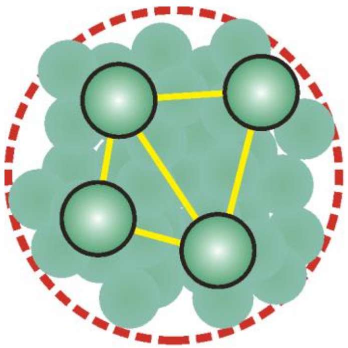
Soft aggregates (slow breakup)



Bond breakup due to thermal motion of the colloids [1].

- Depends on the duration the aggregate is subject to hydrodynamic stress.
- *If true:* weak aggregates (=large aggregates) break earlier than stronger ones.

Brittle aggregates (fast breakup)



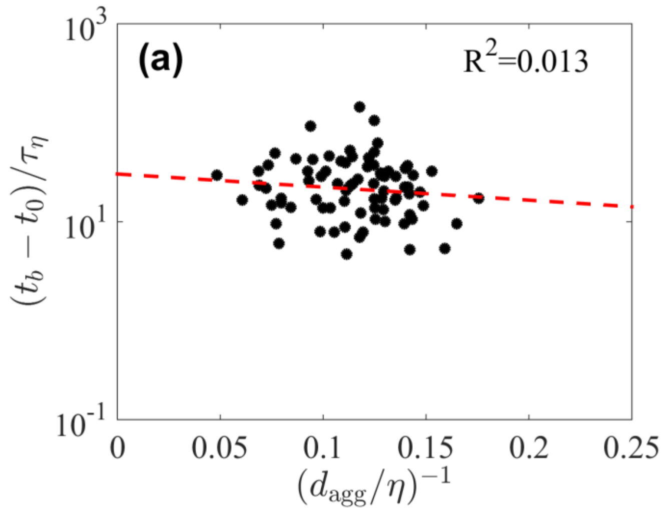
Breakup caused by an abrupt breakup of bonds [2].

- Occurs when the hydro-dynamic stress exceeds a critical threshold.
- *If true:* the hydrodynamic stress at breakup correlates with the aggregate size.

[1] B. O Conchuir, A. Zaccone, *PRE* **87** (2013) 032310 [2] M. Vanni, A. Gastaldi, *Langmuir* **27** (2011) 12822

Experimental results

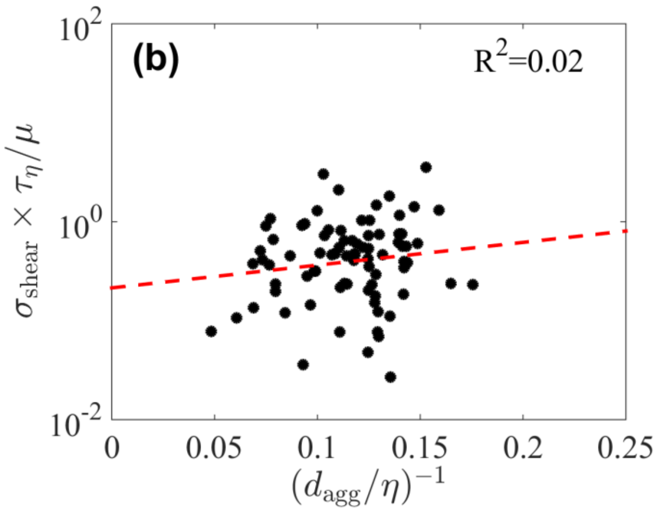
Time lag from release to breakup



weak → **strong**

Aggregate strength

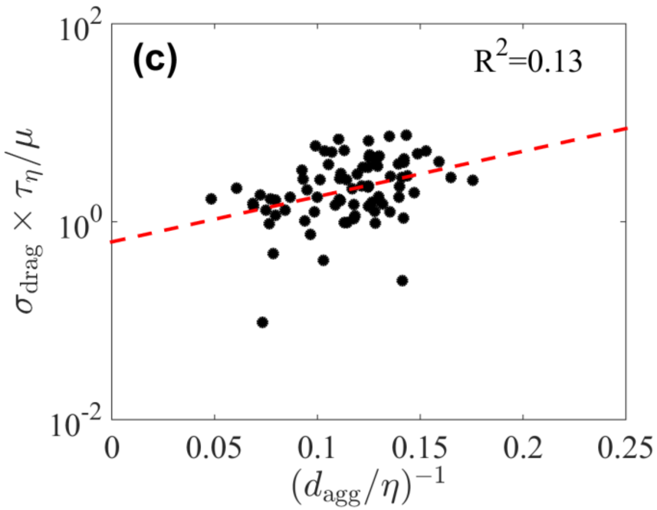
Shear stress at breakup



weak → **strong**

Aggregate strength

Drag stress at breakup

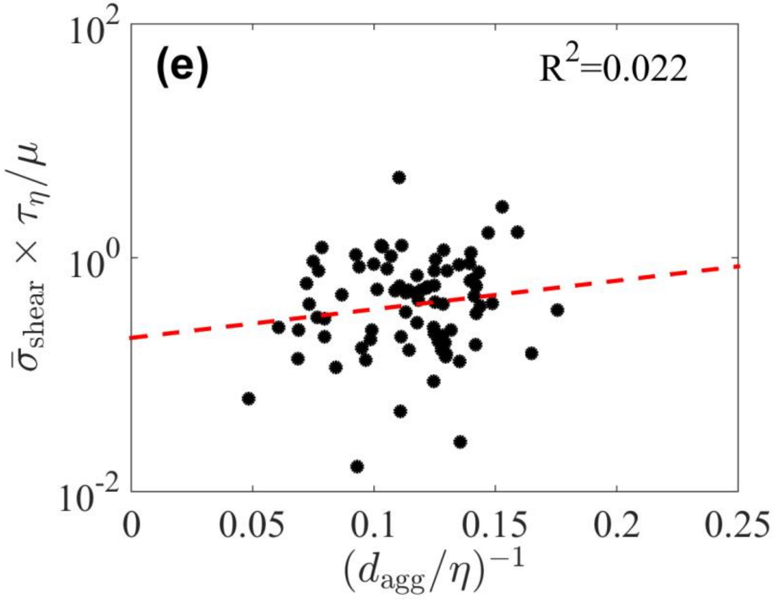


weak → **strong**

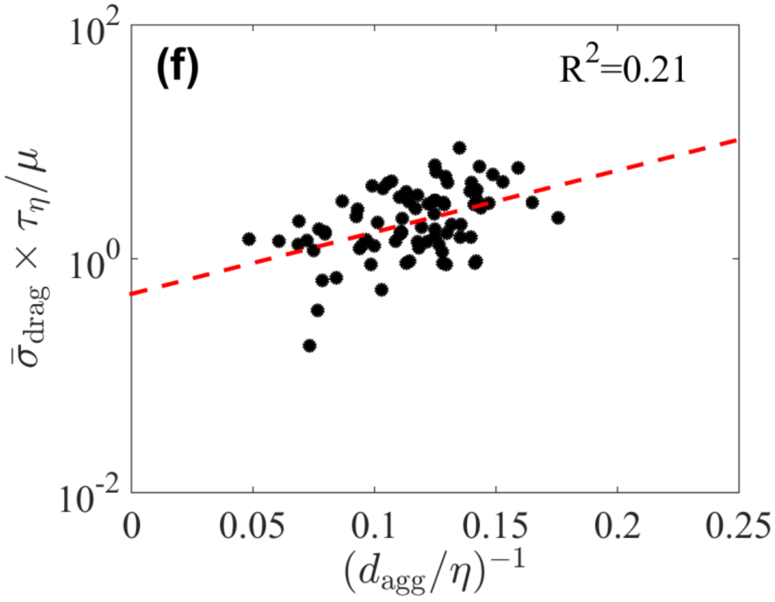
Aggregate strength

Experimental results

Accumulation of shear stress



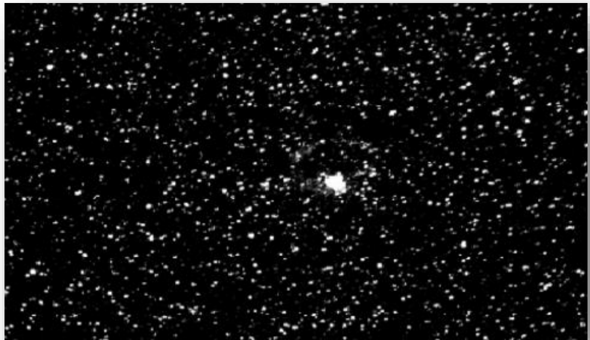
Accumulation of drag stress



$$\bar{\sigma}_i = \frac{1}{\Delta t}\int_{t_b-\Delta t}^{t_b} \sigma_i \, dt \qquad \Delta t \sim \tau_\eta$$

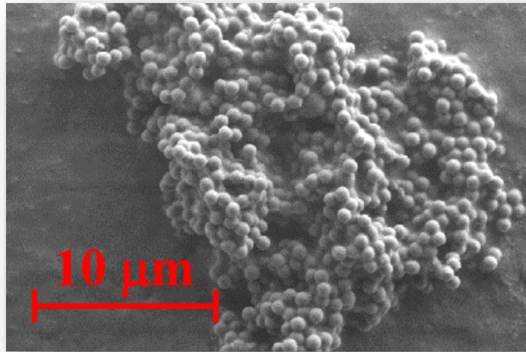
Breakup mechanism

3D PTV with large aggregates



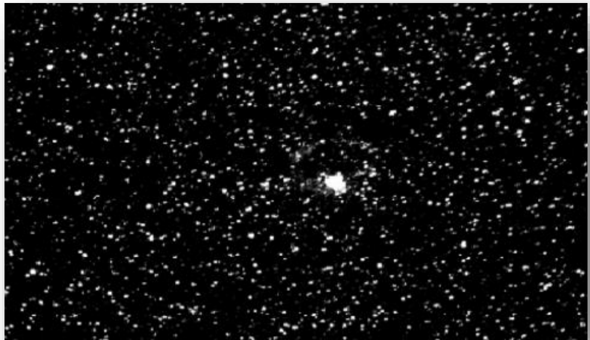
- Hydrodynamic stress dominated by drag
- Breakup is caused by weak accumulation of stress

Sub-Kolmogorov aggregates



Breakup mechanism

3D PTV with large aggregates



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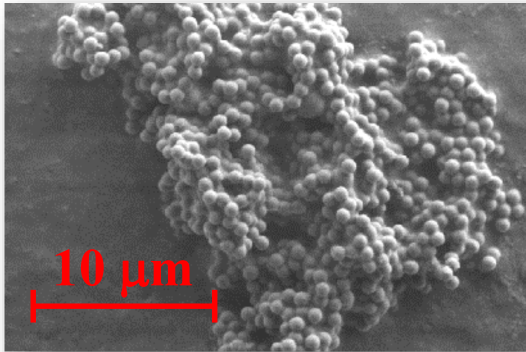
Drag originates from the finite aggregate size

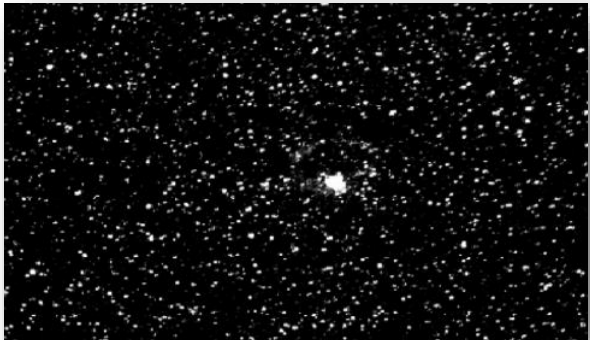
Sub-Kolmogorov aggregates



- Stress on small aggregates (in liquid) dominated by shear

Breakup mechanism

3D PTV with large aggregates



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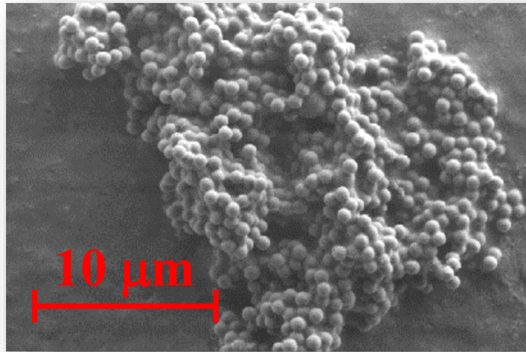


- Hydrodynamic stress dominated by drag

Drag originates from the finite aggregate size →

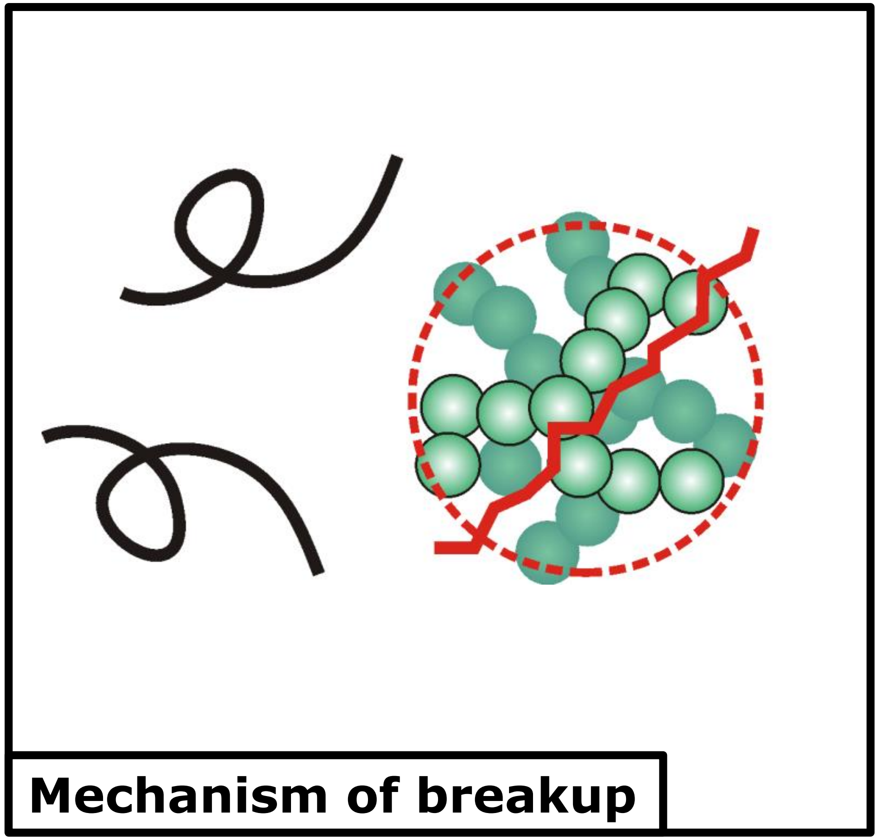
- Stress on small aggregates (in liquid) dominated by shear

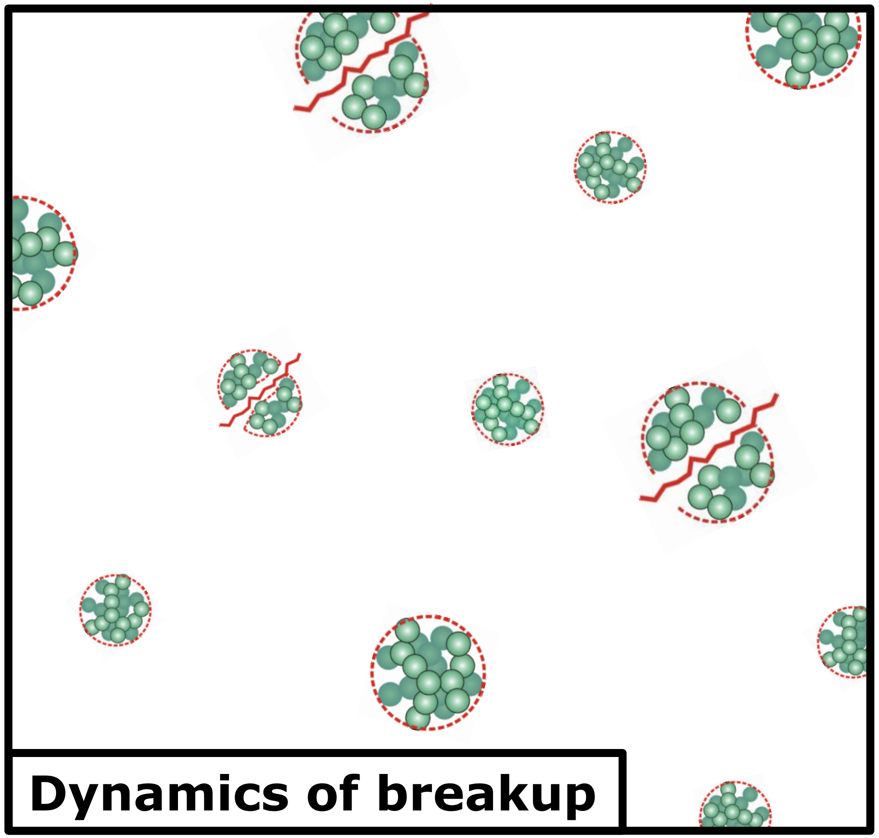
- Breakup is caused by weak accumulation of stress

Bonds within the aggregate store elastic energy →

- Small aggregates exhibit faster response

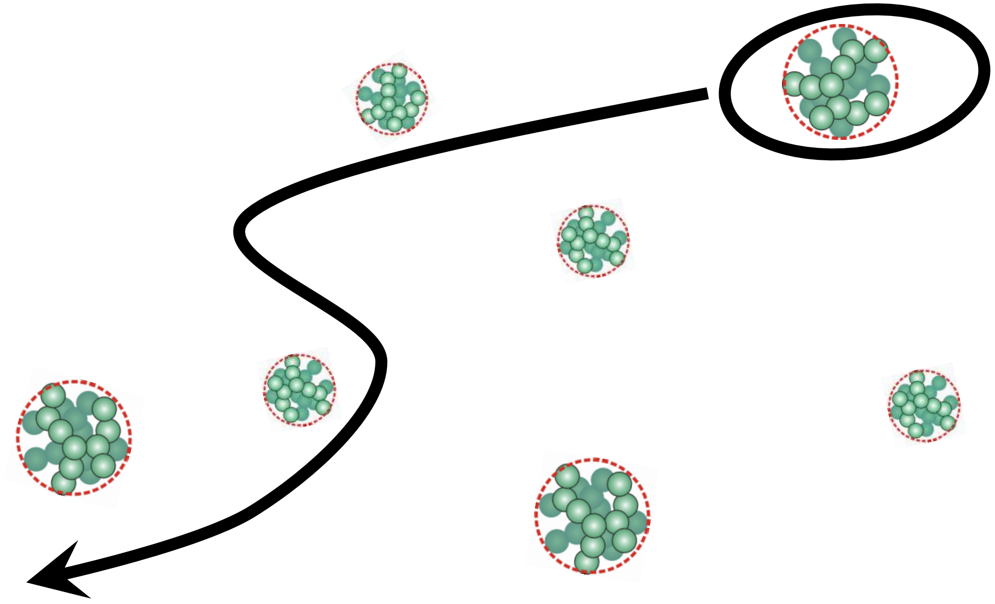
Aggregate breakup in turbulence





Numerical experiments

- Stationary turbulent flow, release of few pre-formed aggregates

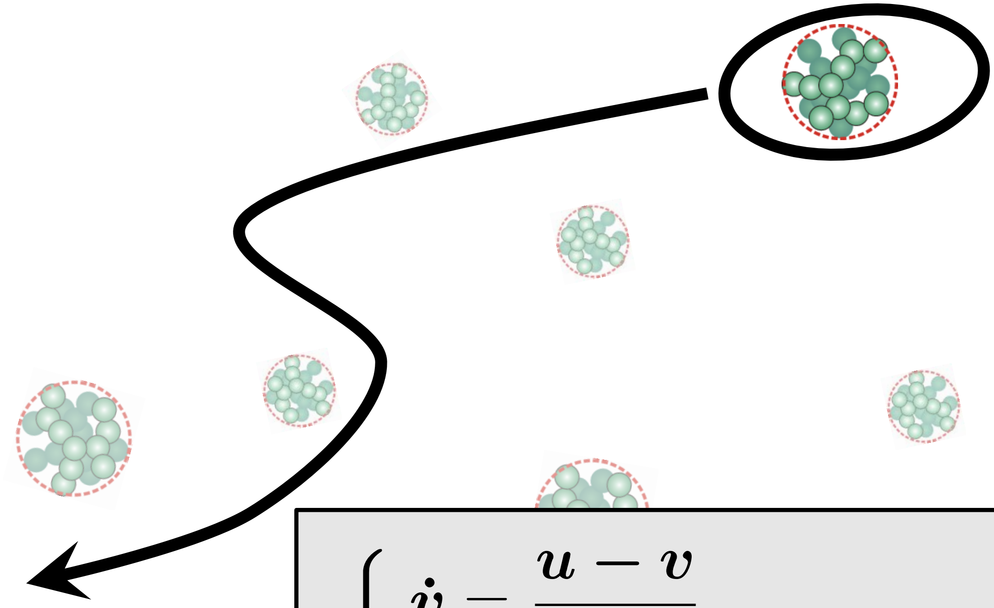


Numerical experiments

- Stationary turbulent flow, release of few pre-formed aggregates
- Aggregates are small and heavy
  - Move as if they were heavy point particles

$$R < \eta$$

$$\rho_a \gg \rho_f$$



$$\begin{cases} \dot{\boldsymbol{v}} = \dfrac{\boldsymbol{u} - \boldsymbol{v}}{\tau_s} \\ \dot{\boldsymbol{x}} = \boldsymbol{v} \end{cases}$$

$$\tau_s = \frac{(2\rho_a + \rho_f)R^2}{9\rho_f \nu} \qquad St = \frac{\tau_s}{\tau_\eta}$$

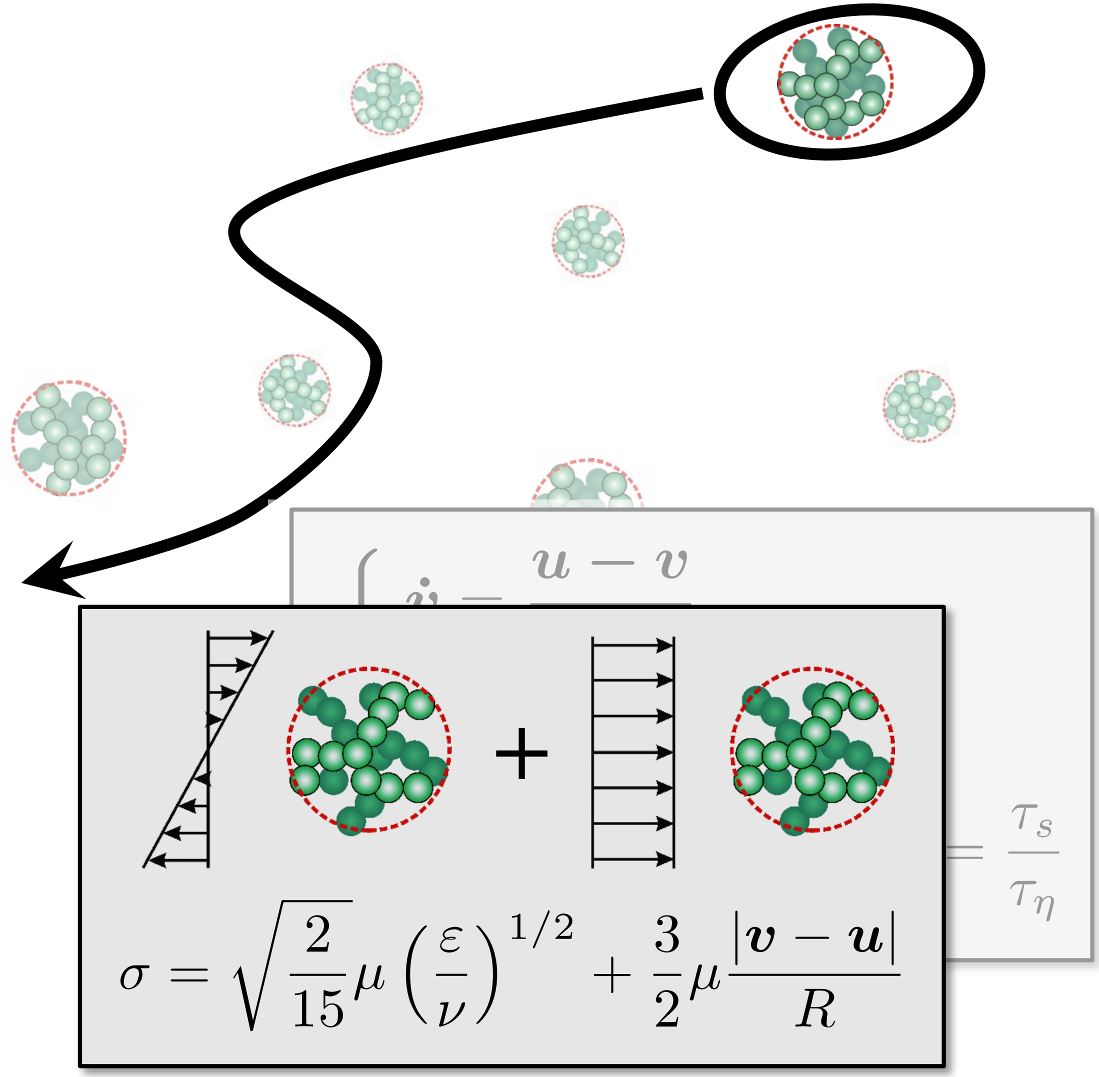
Numerical experiments

$$R < \eta$$

$$\rho_a \gg \rho_f$$

- Stationary turbulent flow, release of few pre-formed aggregates

- Aggregates are small and heavy
  - Move as if they were heavy point particles
  - Subject to shear and drag stress



K.A. Kusters (1991), Bagster and Tomi, *Chem. Eng. Sci.* (1974)

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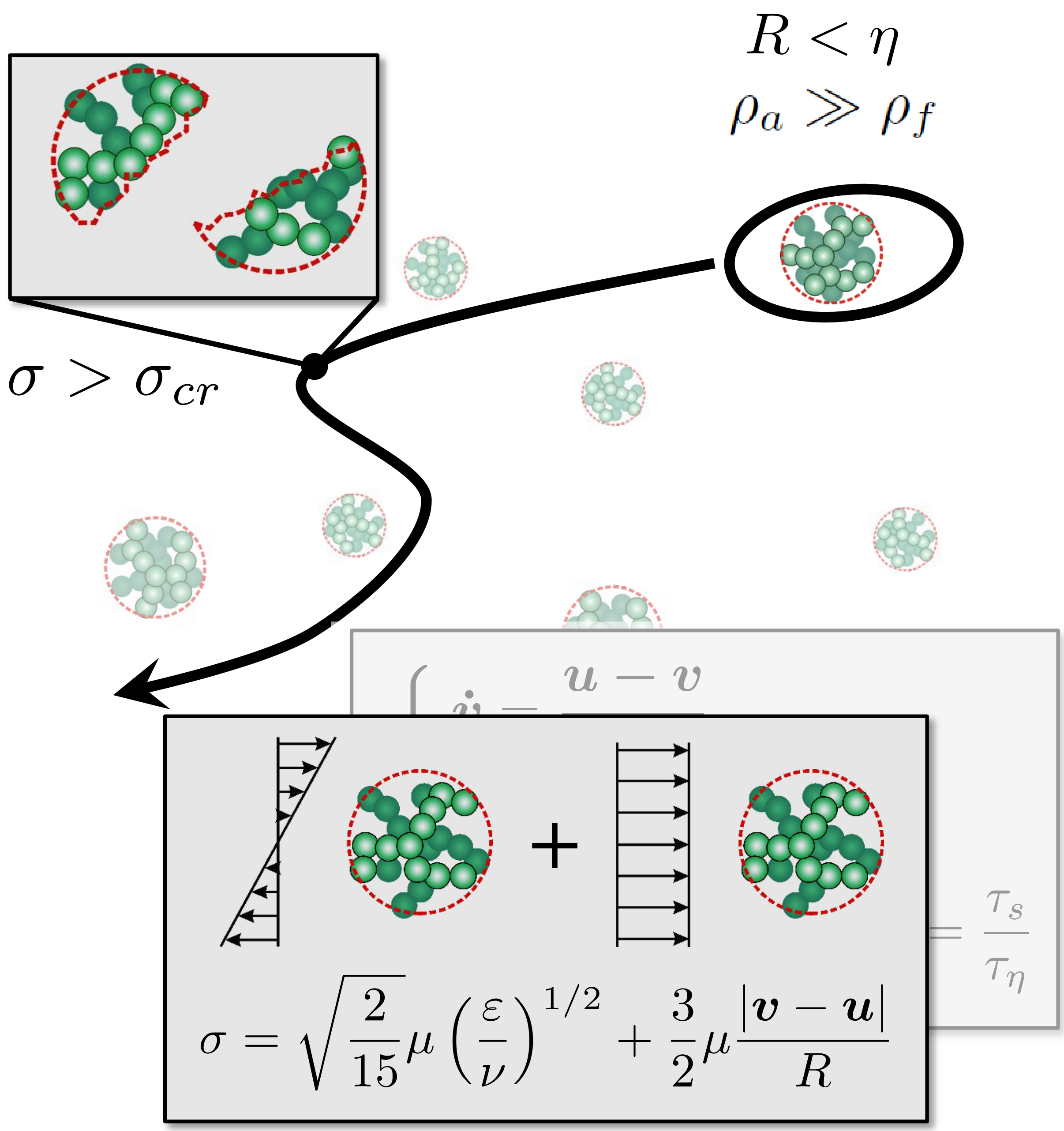
Numerical experiments

- Stationary turbulent flow, release of few pre-formed aggregates
- Aggregates are small and heavy
  - Move as if they were heavy point particles
  - Subject to shear and drag stress
- Predefined rule for breakup



Babler, Biferale, Lanotte (2012)

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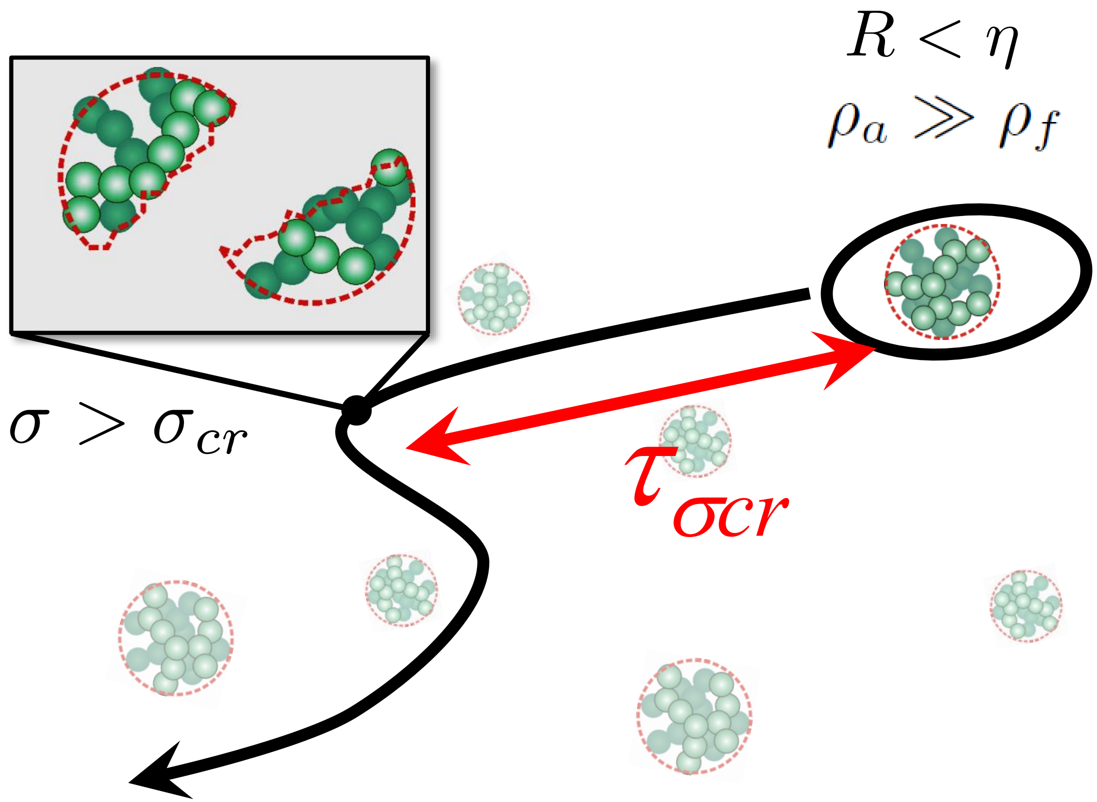


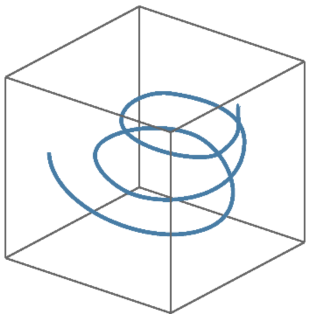
Aggregate breakup rate

$$f_{\sigma_{\mathrm{cr}}} = \frac{1}{\langle \tau_{\sigma_{\mathrm{cr}}} \rangle}$$

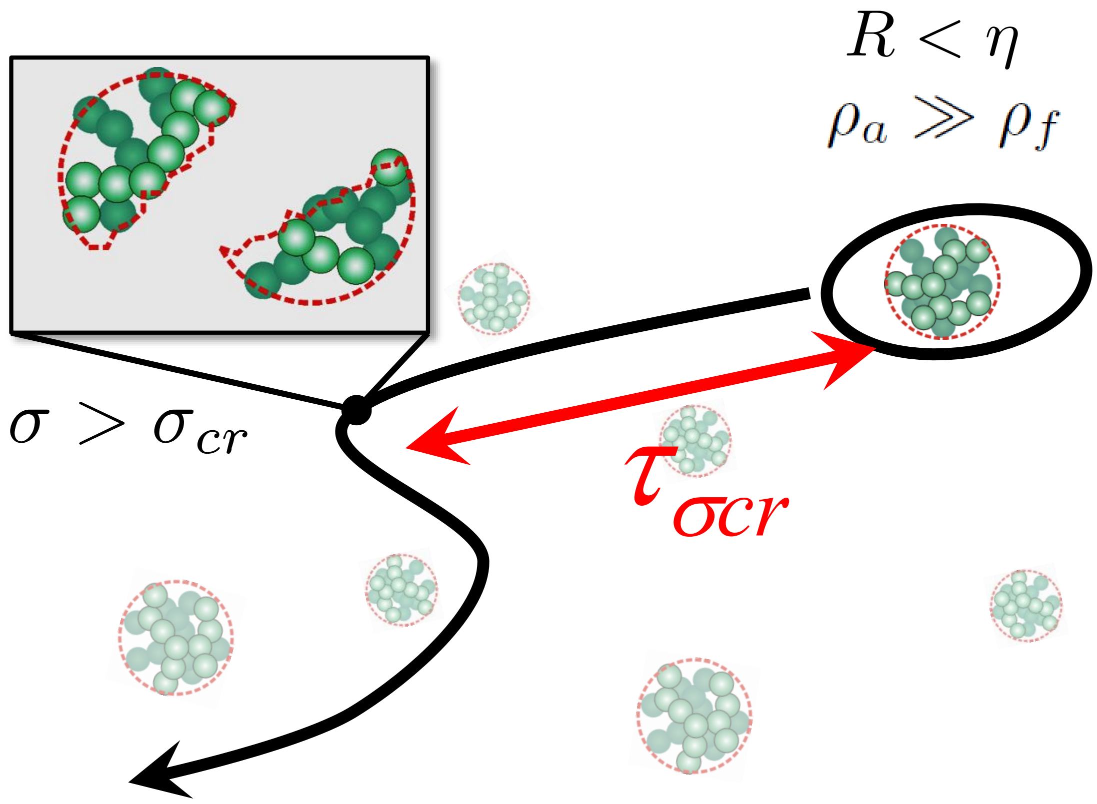
Babler, Biferale, Lanotte (2012)

Numerical experiments

- Turbulent trajectories for heavy point particles in HIT are available on http://turbase.cineca.it (as part of *EuHIT* program)



- Resolution 2048^3
- $Re_\lambda = 400$



Aggregate breakup rate

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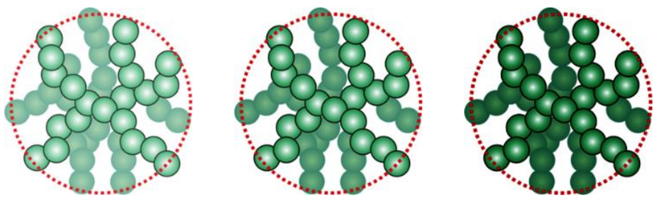
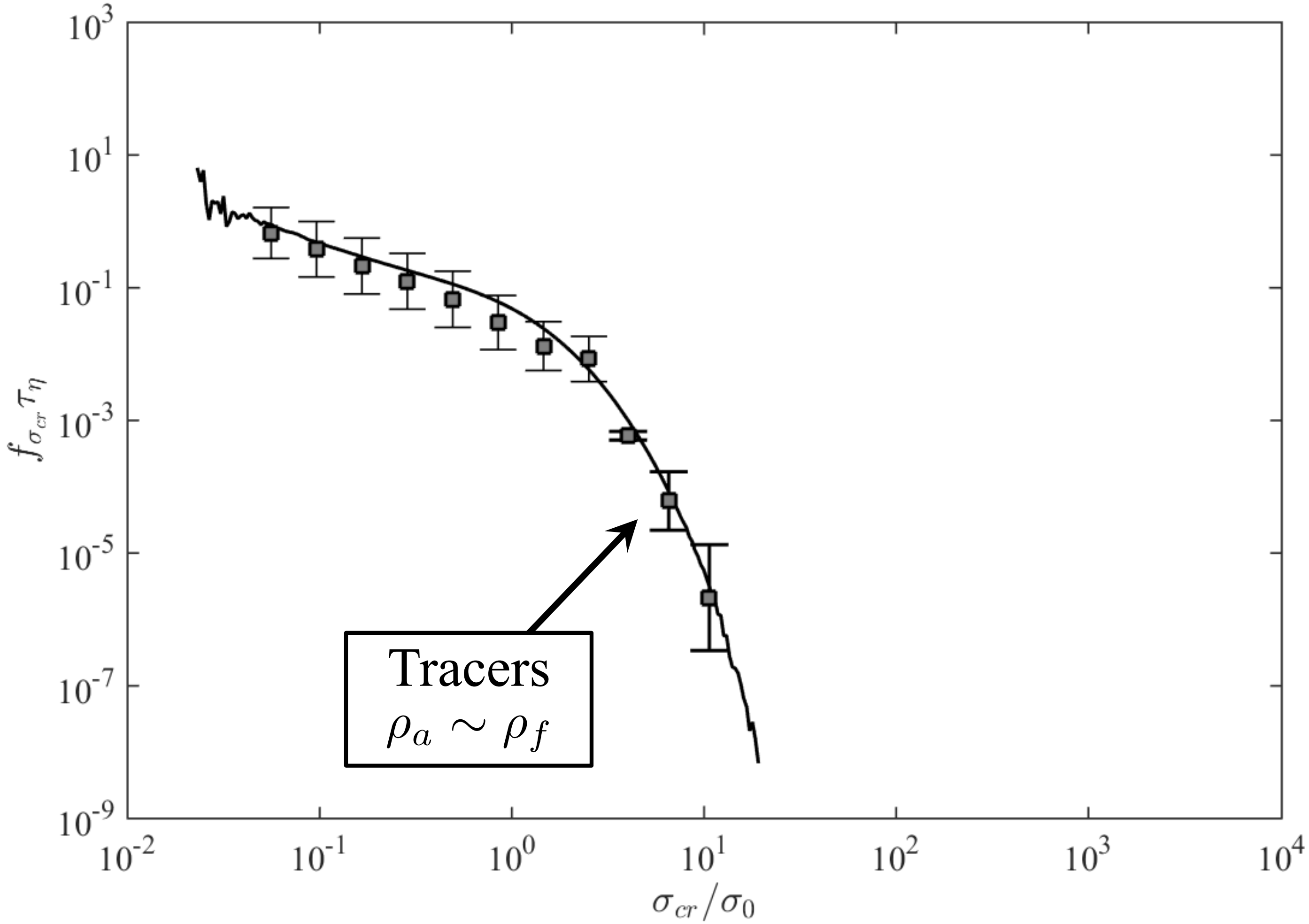
Aerosols aggregates in HIT

- Aggregates of size $R/\eta = 0.1$ and varying density





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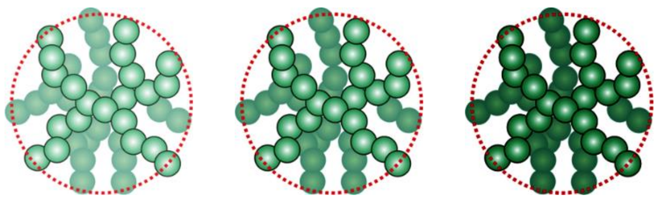

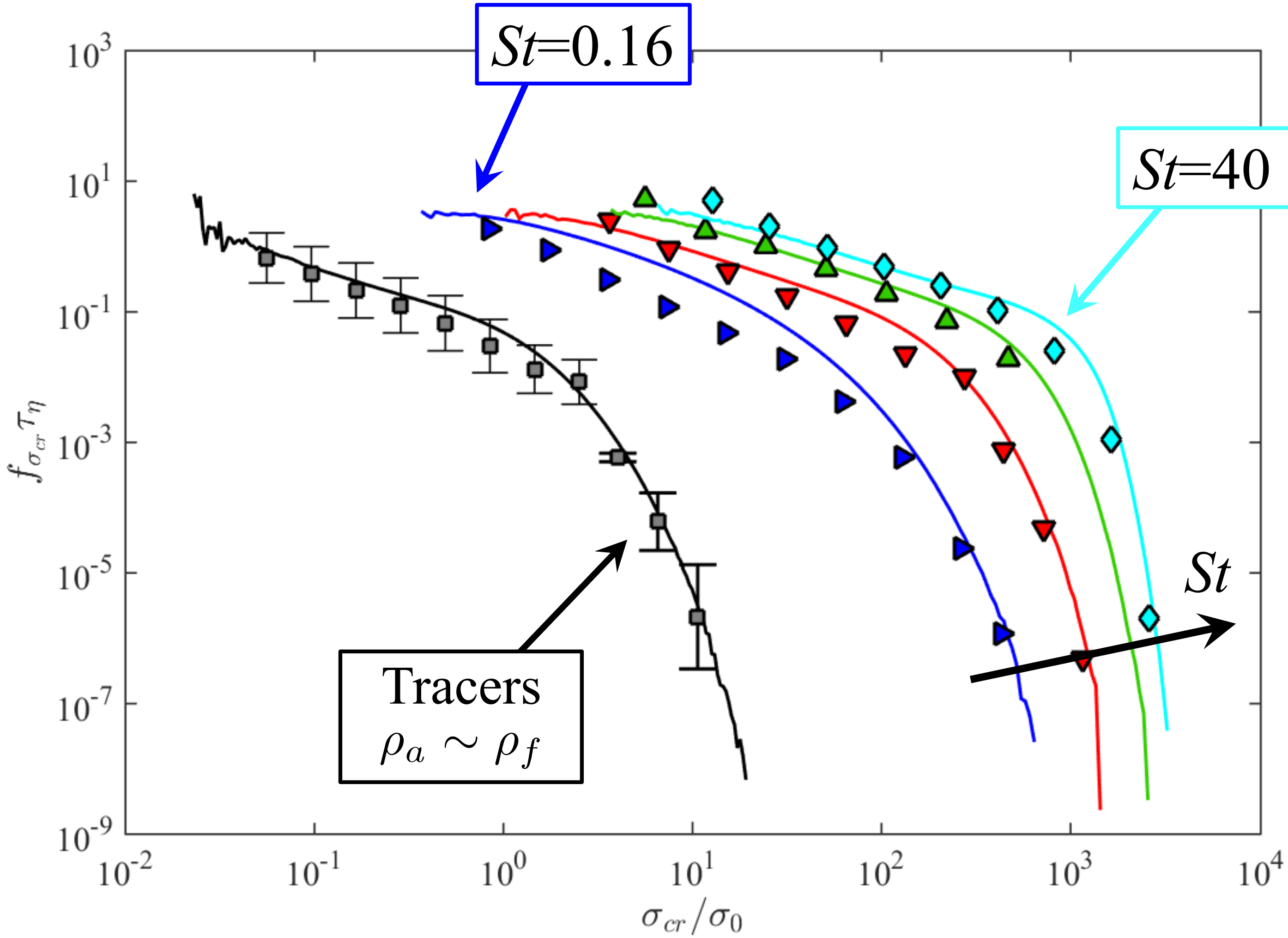

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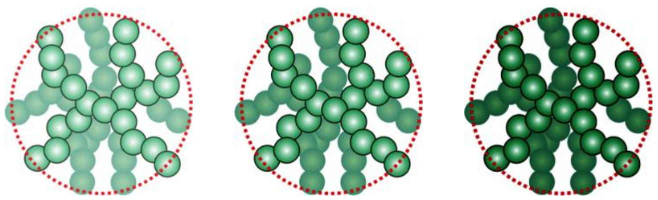

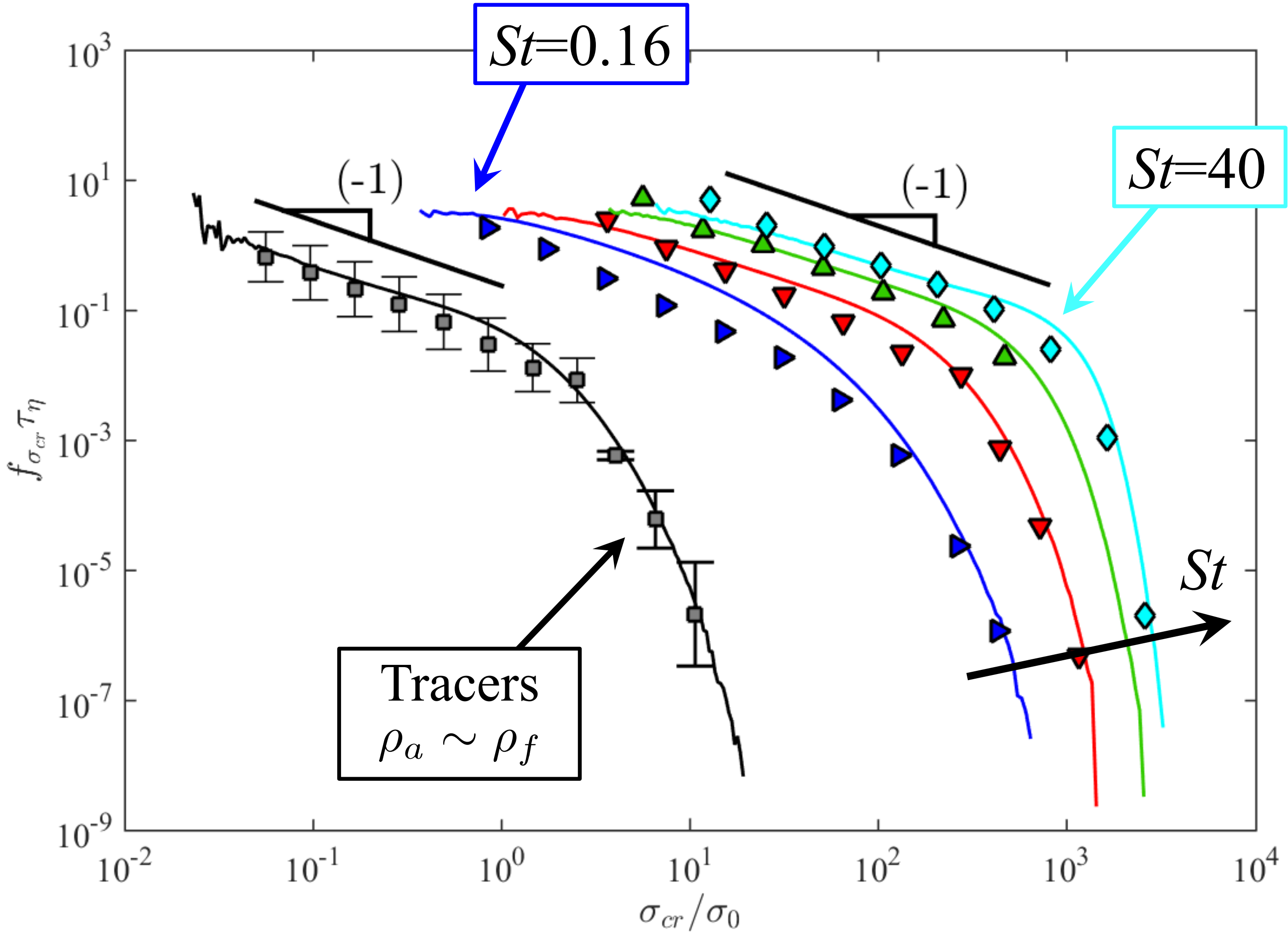

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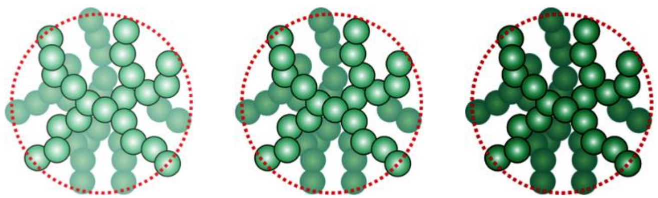
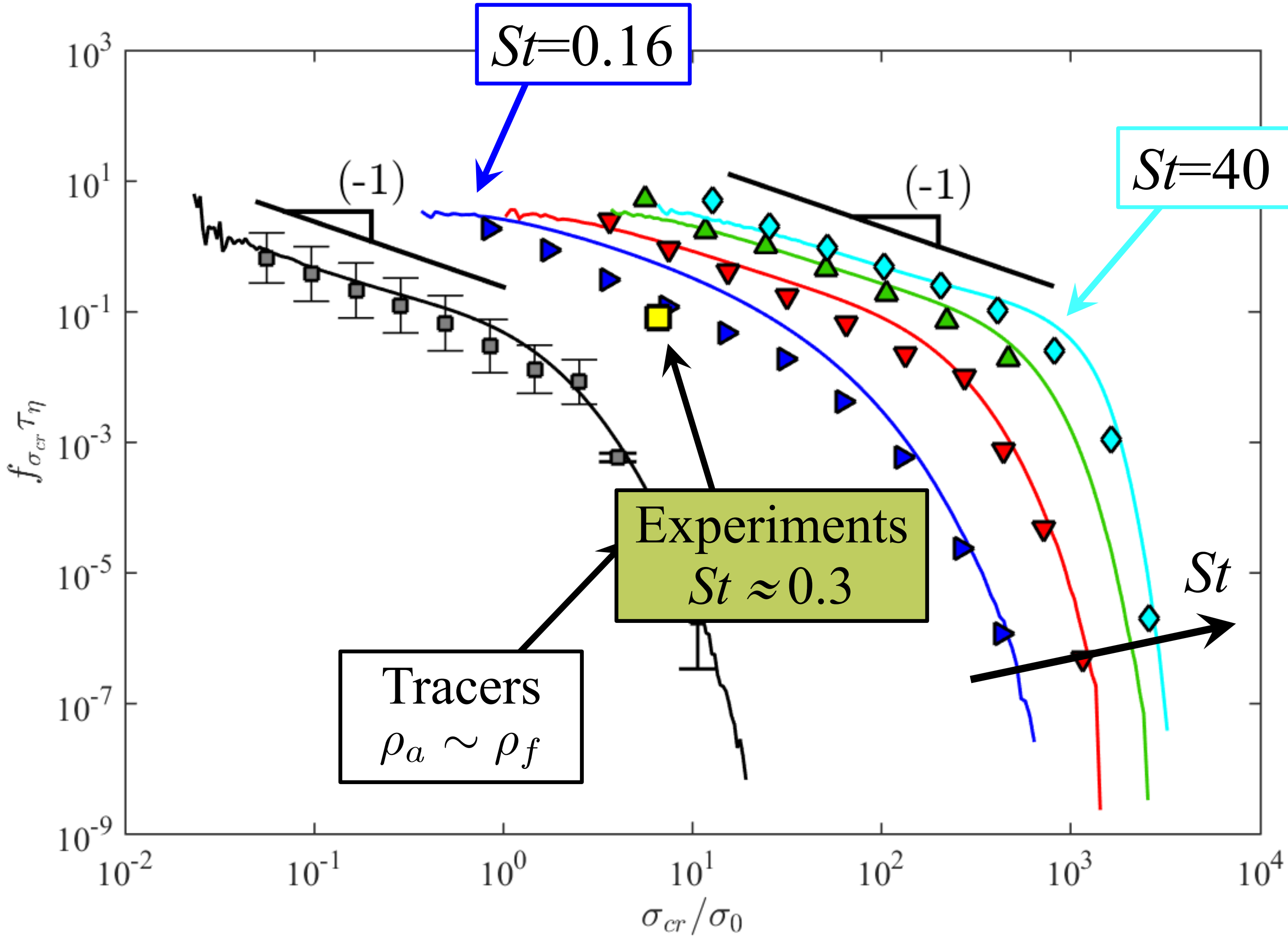


- 3D-PTV Experiments
  $R/\eta = 18$, $St \approx 0.3$



Conclusions

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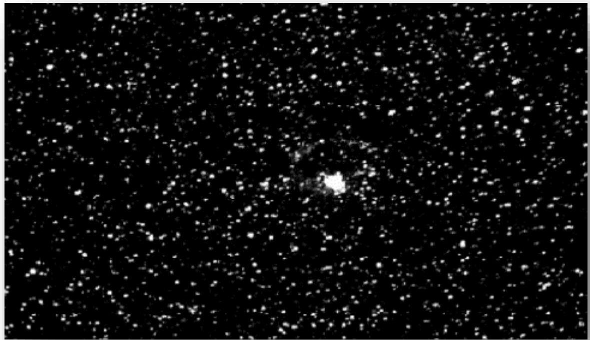


We studied the breakup of finite size aggregates made out of fully destabilized polystyrene colloids in homogeneous isotropic turbulence by means of 3D-PTV.

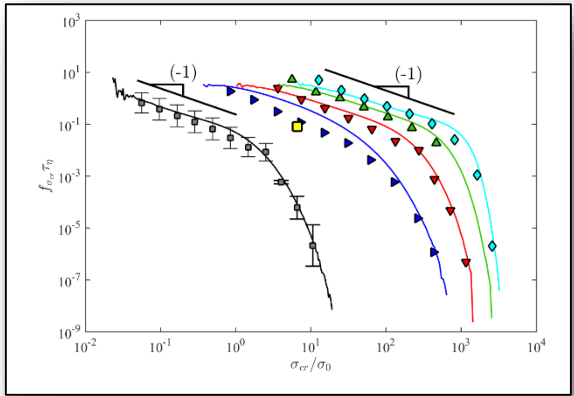
Major findings are:

- Hydrodynamic stress is dominated by drag.
- Breakup is caused by weak accumulation of stress.

Both these findings are an effect of the large aggregate size.

Ref. D. Saha, **M.U.B.**, M. Holzner, M. Soos, B. Lüthi, A. Liberzon, W. Kinzelbach, *Langmuir* (2016) doi:10.1021/acs.langmuir.5b03804

Conclusions



Numerical simulations of small and brittle aggregates show that the breakup rate as a function of aggregate strength exhibits power law behavior for weak aggregates, followed by a sharp cut-off as the aggregate strength increases.

- Power law is controlled by the smooth part of the flow whose statistics are close to Gaussian.
- The sharp cut-off is causes by rare intermittent turbulent events.

Acknowledgements

- Swedish Research Council VR, grant nr 2012-6216
- EU-COST Action MP1305 *Flowing Matter*

Backup slide

Breakup mechanism

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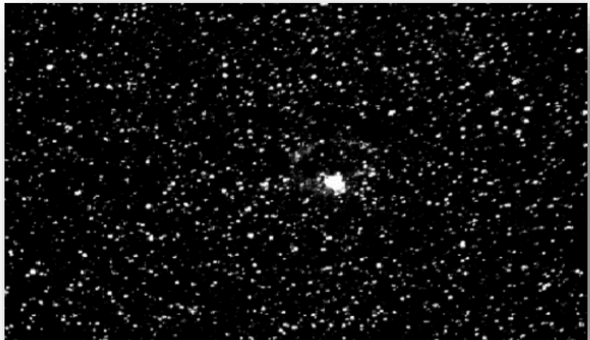
3D PTV with large aggregates

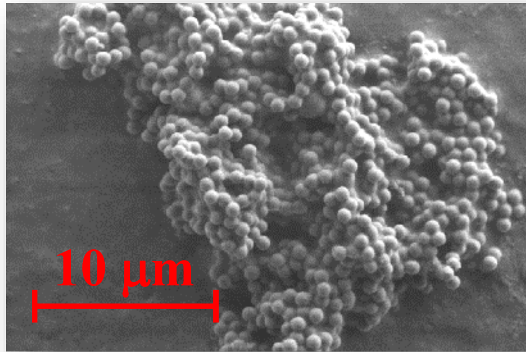


- Hydrodynamic stress dominated by drag
- Breakup is caused by weak accumulation of stress

Drag originates from the finite aggregate size →

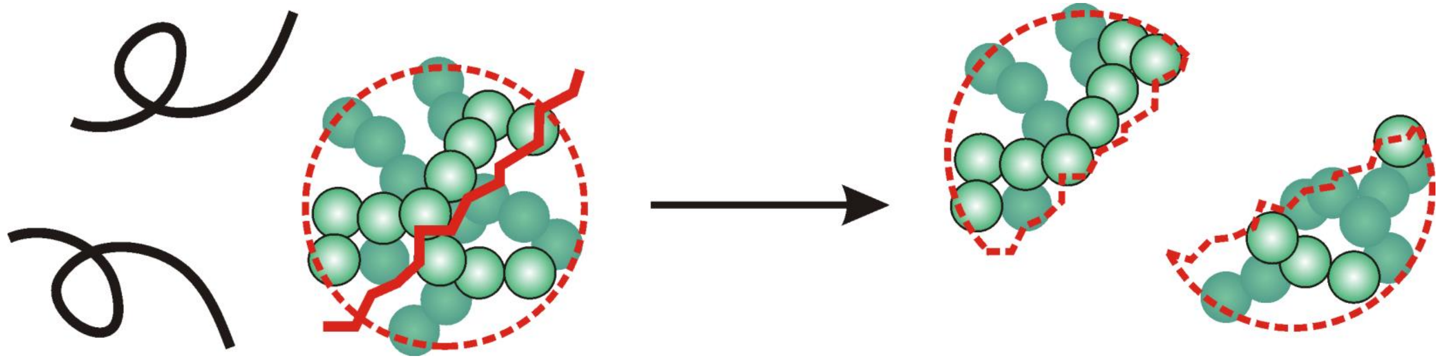
Finite stress propagation inside the aggregate →

Sub-Kolmogorov aggregates



- Stress on small aggregates (in liquid) dominated by shear
- Small aggregates exhibit faster response

Breakup of aggregates



***Aim*: Investigating the mechanism of breakup in turbulence by monitoring individual breakup events in well controlled experiments**

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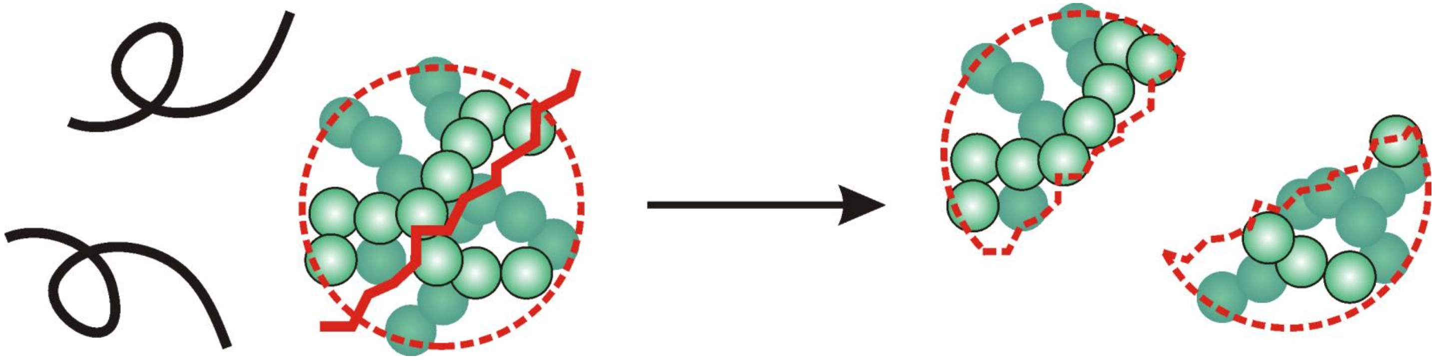
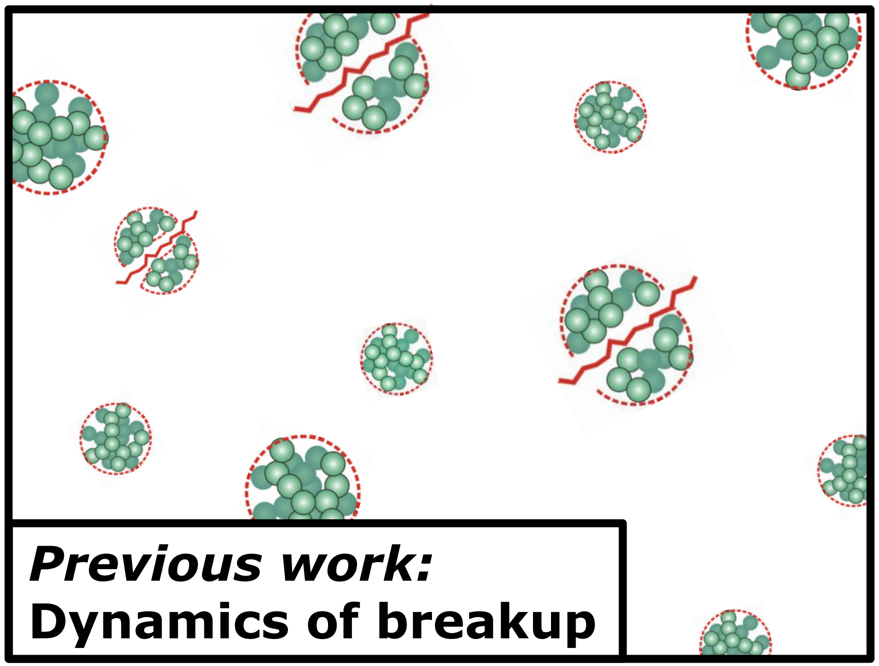
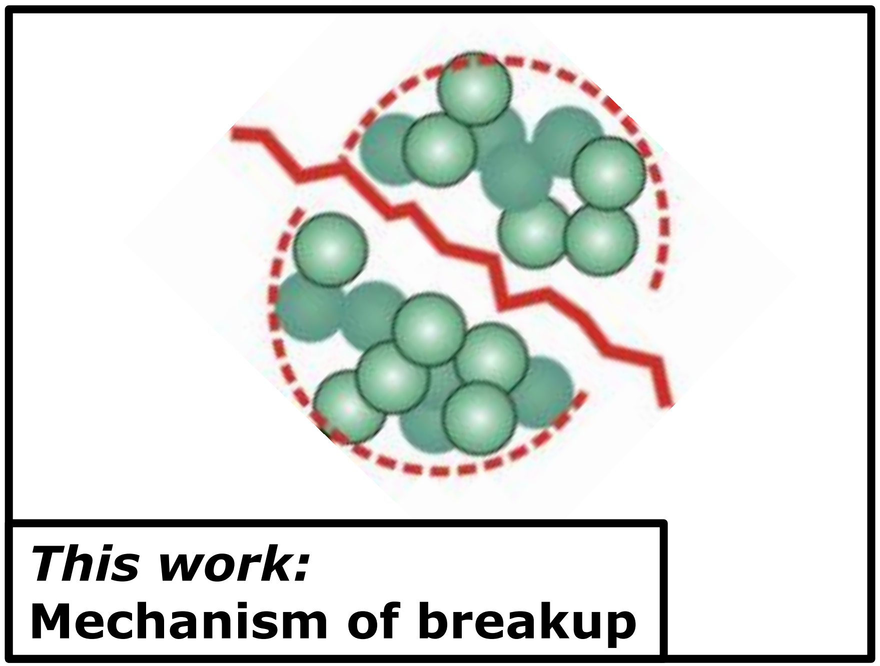
Aim of this work







Aim of this work