Fragmentation of small aggregates turbulent flows

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"Flowing Matter Across the Scales,"
COST/ERC Workshop, Rome, March 24-27, 2015

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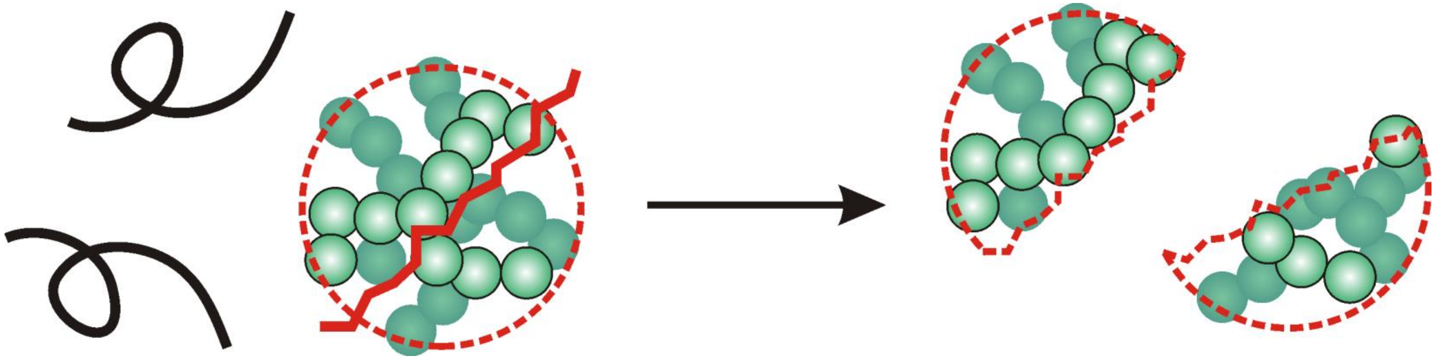
Breakup of aggregates



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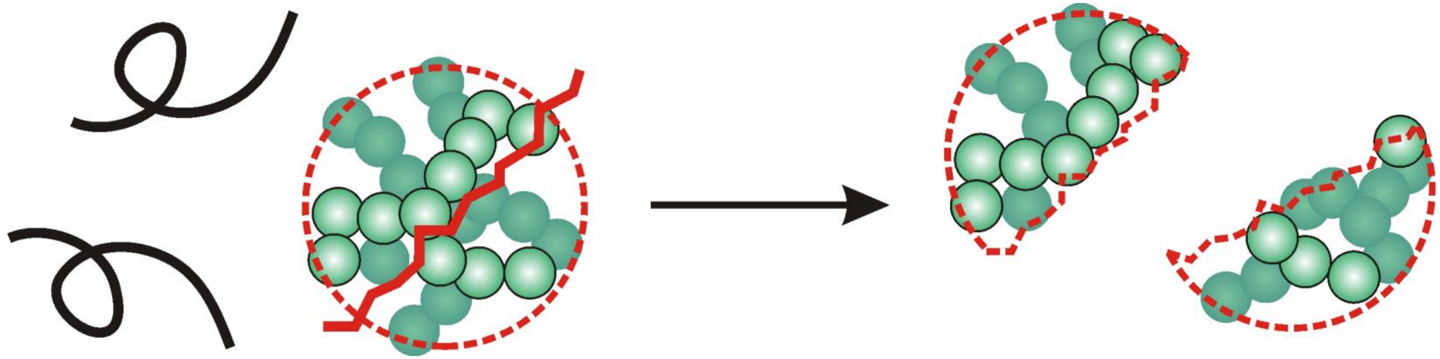

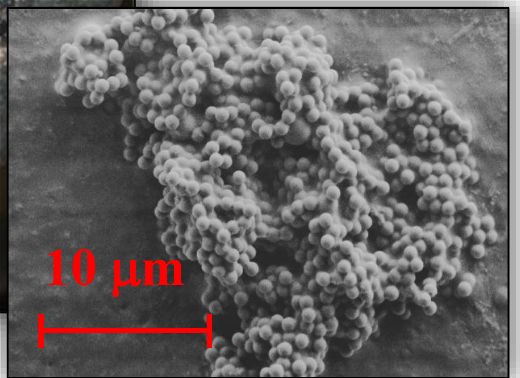

- Processing of industrial colloids (polymers, metal oxides, minerals)

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

Matthäus Bäbler, babler@kth.se

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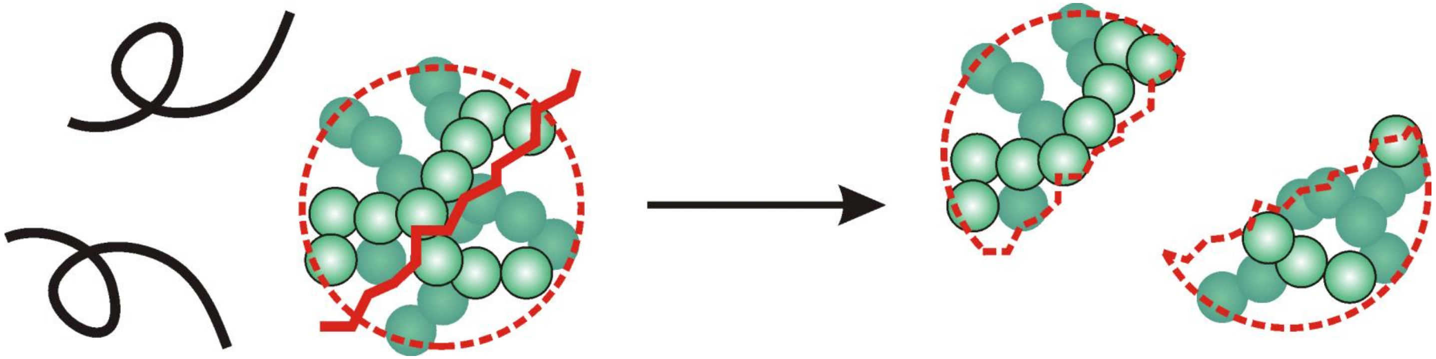
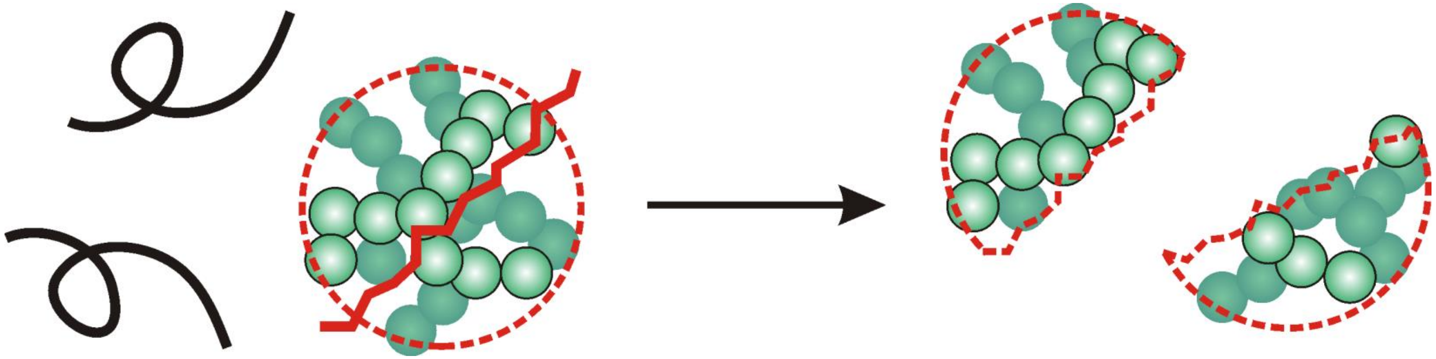


- Processing of industrial colloids (polymers, metal oxides, minerals)
- Evolution and transport of sediments and suspended mater in natural waters

Picture: Satelite image Rio de la Plata Estuary, March 10, 2010 (www.eosnap.com, retrieved 2014-03-12),

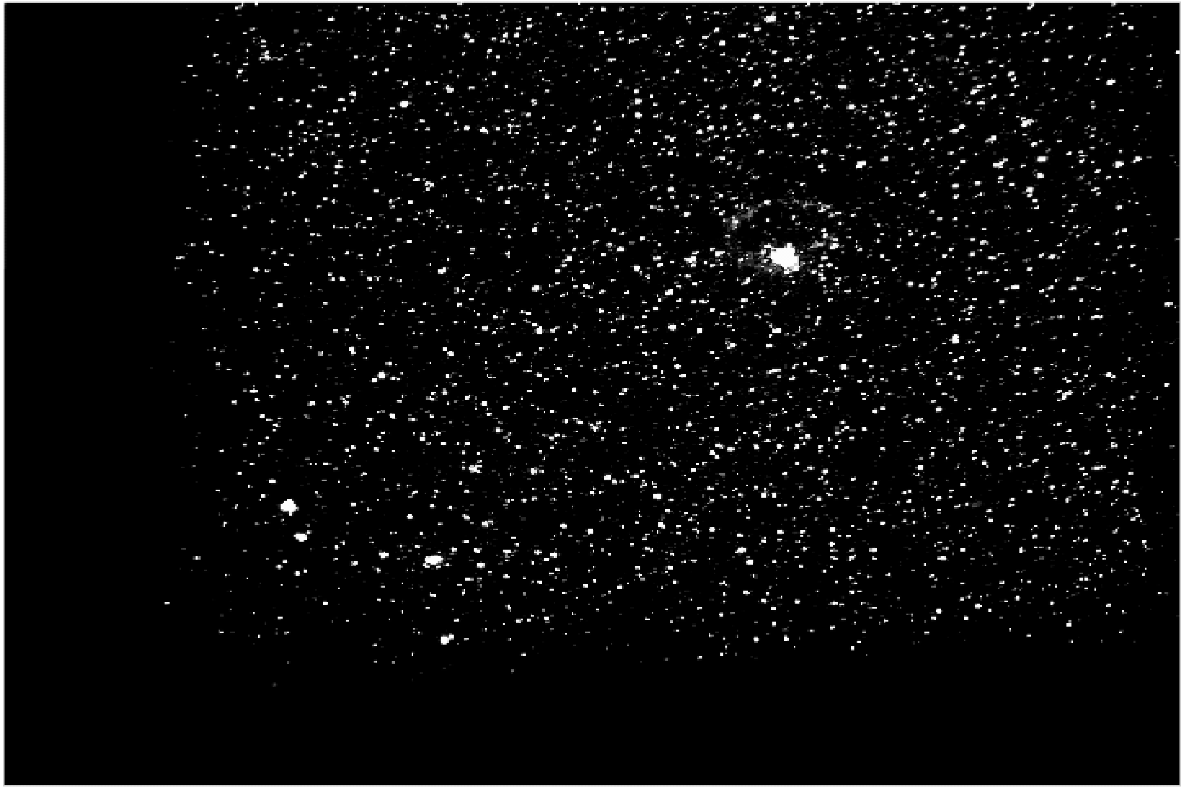
Breakup of aggregates



- Processing of industrial colloids (polymers, metal oxides, minerals)
- Evolution and transport of sediments and suspended mater in natural waters
- Dispersion of powder agglomerates for, e.g. inhalation drugs

Picture: Getty images (2015-03-22)

Breakup of aggregates



D. Saha, M.U.B., B. Lüthi, A. Liberzon, W. Kinzelback, M. Holzner, M. Soos, *in preparation* (2015)

Breakup of a polystyrene aggregate in a homogeneous and isotropic turbulent flow, monitored by PTV.

$Re_\lambda \approx 70$

$\eta = 0.33\,\mathrm{mm}$

$\tau_\eta = 0.1\,\mathrm{s}$

$\langle \varepsilon \rangle \approx 0.9\,\mathrm{cm}^2\,\mathrm{s}^{-3}$

$L/\eta = 120$

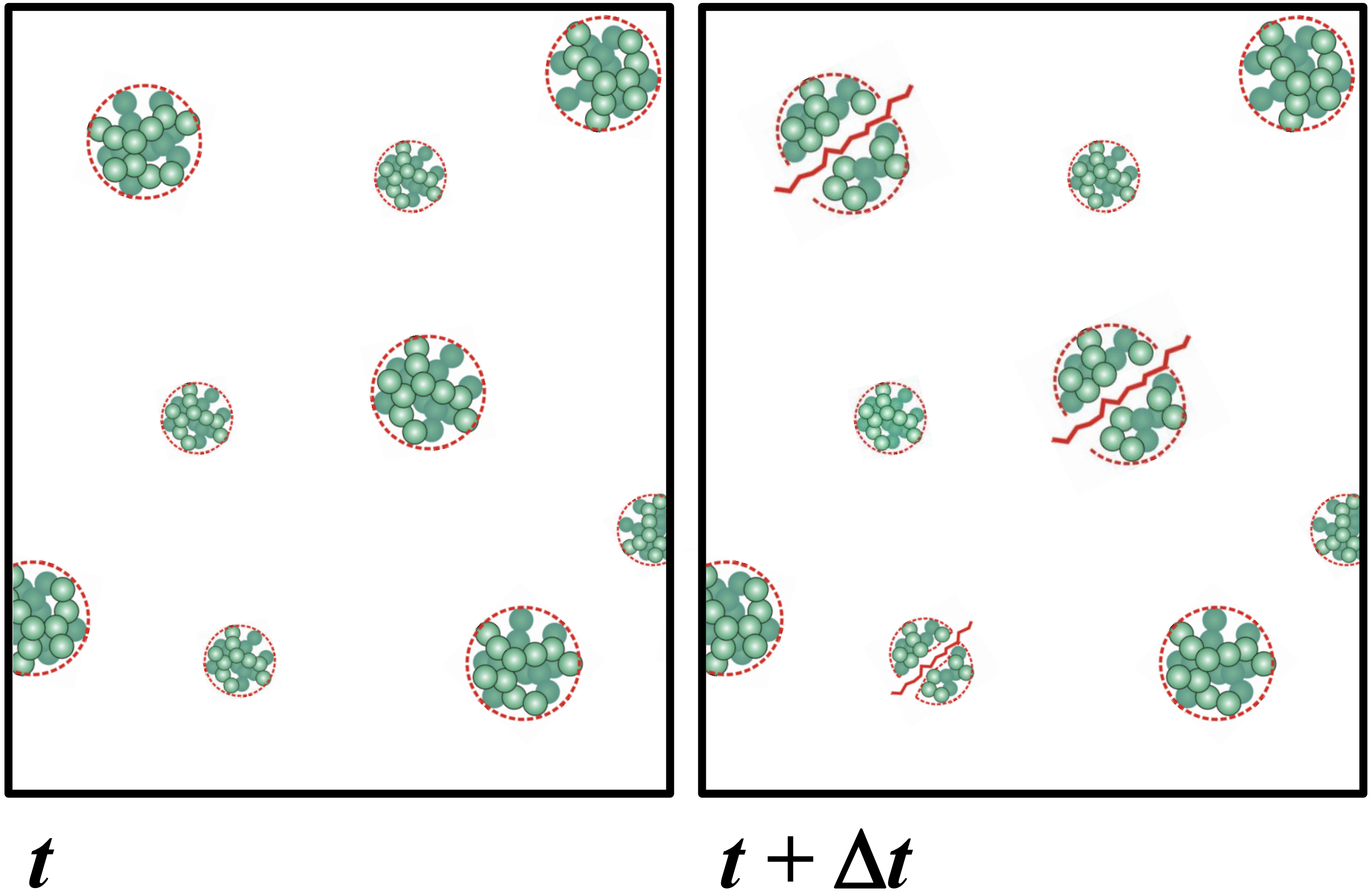
$G = 10\,\mathrm{s}^{-1}$

Breakup of aggregates

This work:

Dynamics of breakup of inertial aggregates caused by turbulent fluid motions

~ *How many breakup events per unit time*



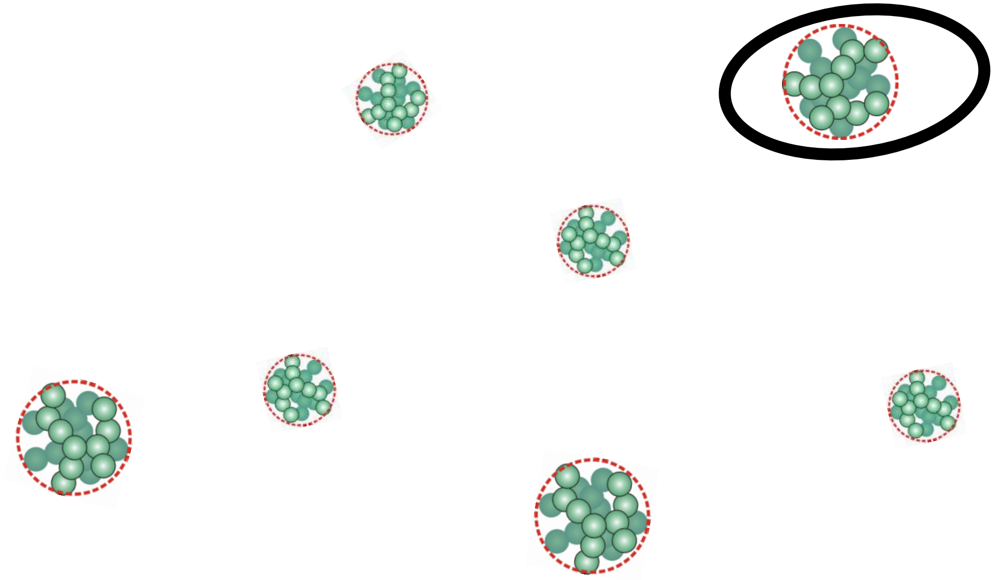
- Babler et al., *PRE* (2012): Tracer like aggregates
- Babler et al., *JFM* (2015): Tracers in non-homogeneous flows

Modeling framework

- Stationary homogeneous isotropic turbulent flow, loaded with few aggregates
- Small & heavy aggregates:
  - Aggregate size small with resect to η
  - Aggregate density large with respect to fluid density

$$R \ll \eta$$

$$\rho_a \gg \rho_f$$



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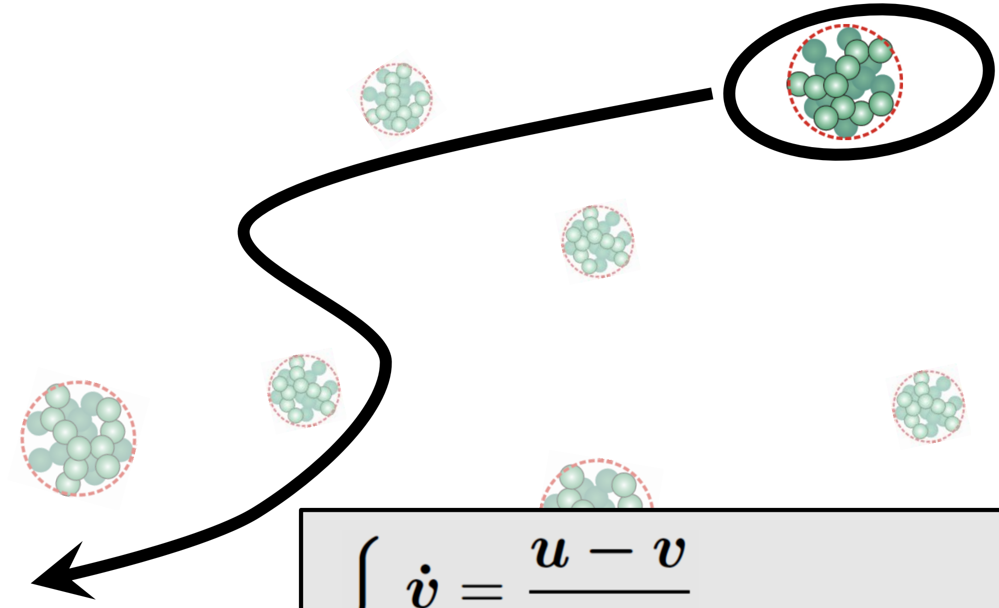


- Small & heavy aggregates:
  - Aggregate size small with resect to η
  - Aggregate density large with respect to fluid density

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

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

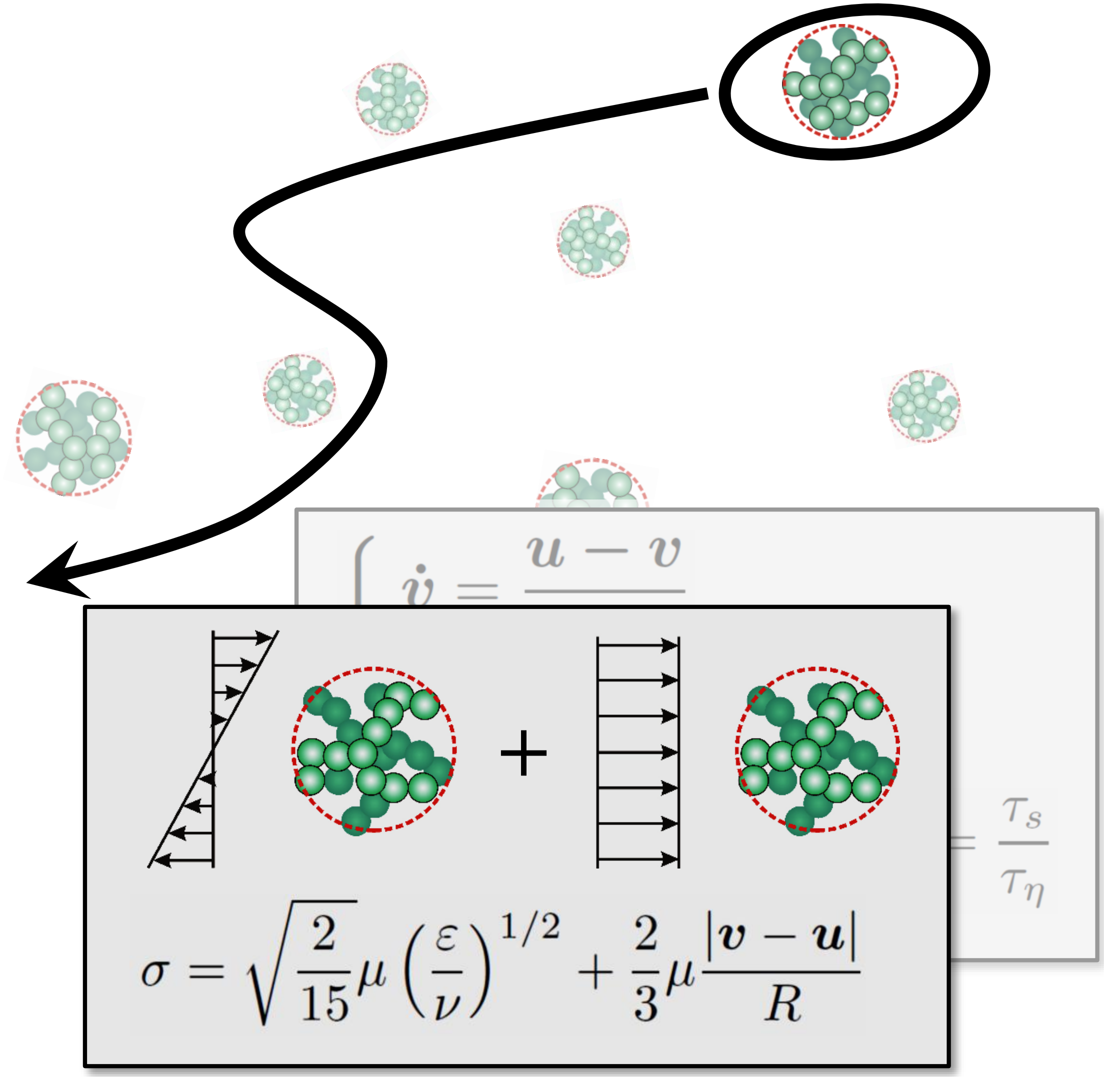
Modeling framework

$R \ll \eta$

$\rho_a \gg \rho_f$

- Aggregates are broken due to due hydrodynamic stress acting on them

- *Brittle limit*: Aggregate break up when the hydrodynamic stress exceeds a critical value σ_{cr}



K.A. Kusters (1991)

Modeling framework

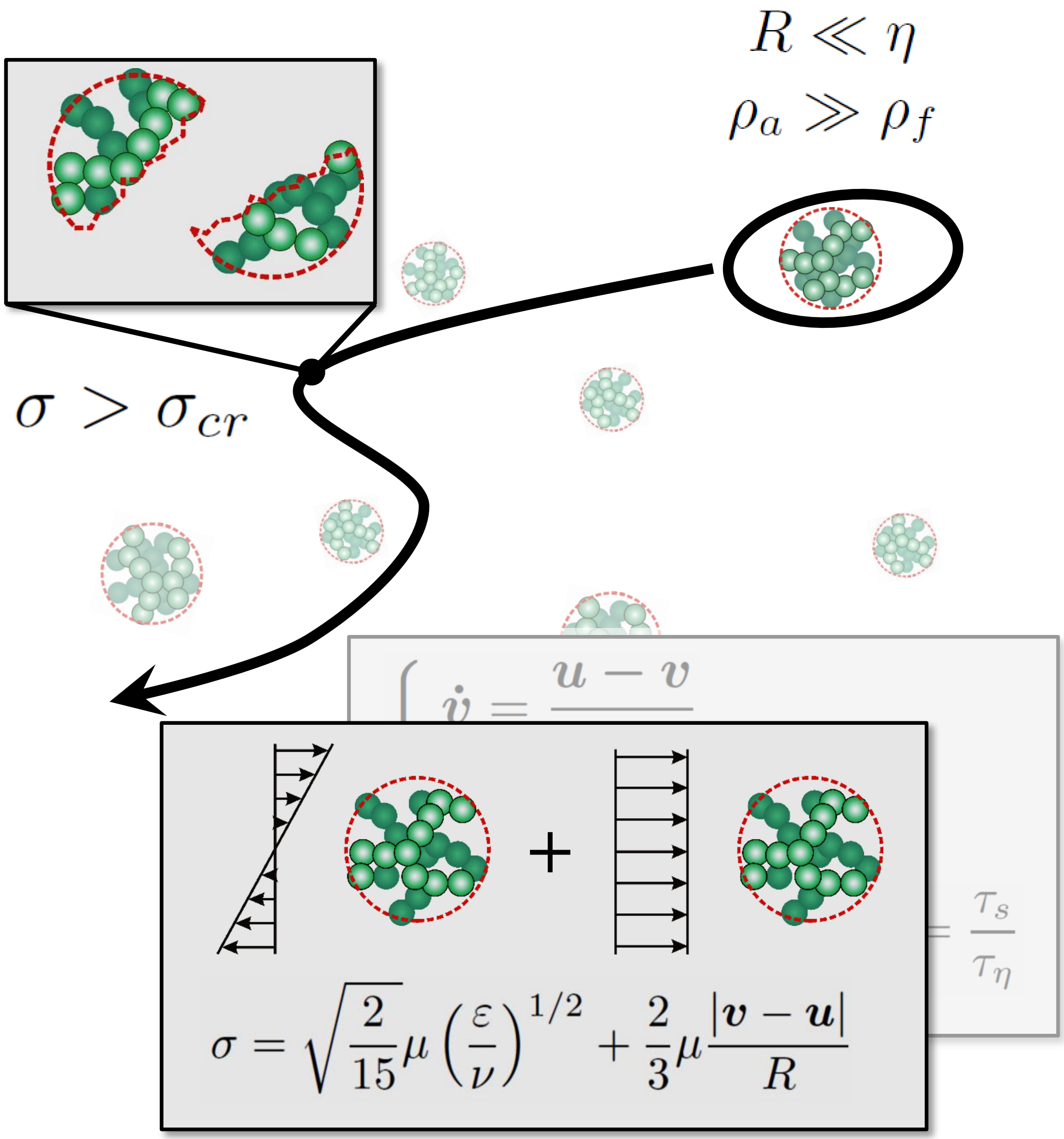
- Aggregates are broken due to due hydrodynamic stress acting on them

- *Brittle limit*: Aggregate break up when the hydrodynamic stress exceeds a critical value σ_{cr}

- σ_{cr} is a characteristic for a given type of aggregates

$$\sigma_{\mathrm{cr}} \sim R^{-q}$$

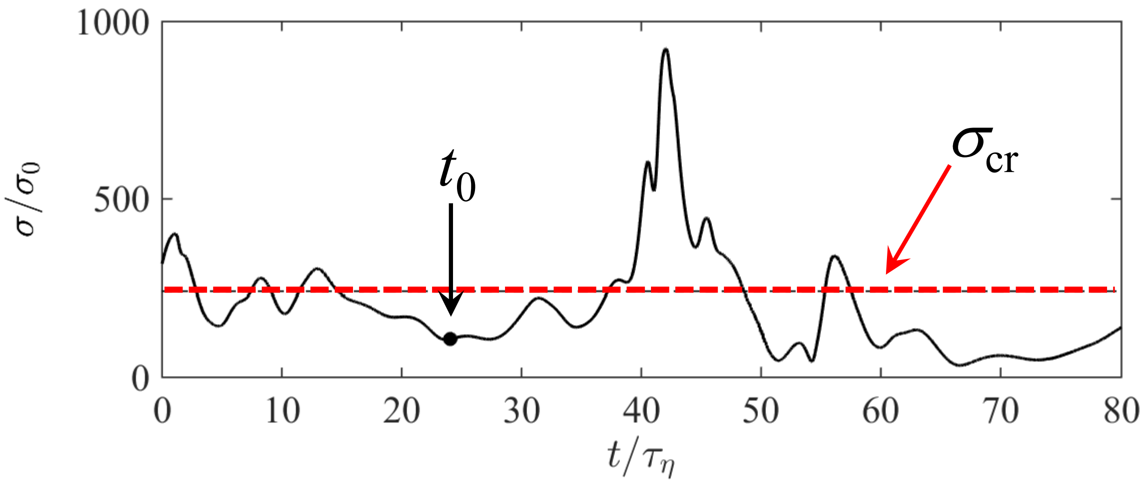
$$q \approx 0.35 - 0.55$$



Harshe, Lattuada, Soos, *Langmuir* (2011)

Numerical experiments

- Start with a stationary turbulent flow, consider aggregates of strength σ_{cr}
- At time t_0, release aggregate at random somewhere where $\sigma < \sigma_{cr}$
- Follow the aggregate until the first occurrence of $\sigma > \sigma_{cr}$
- The time from release until breakup defines the exit-time $\tau_{\sigma_{cr}}$



Babler, Biferale, Lanotte, *PRE* (2012)

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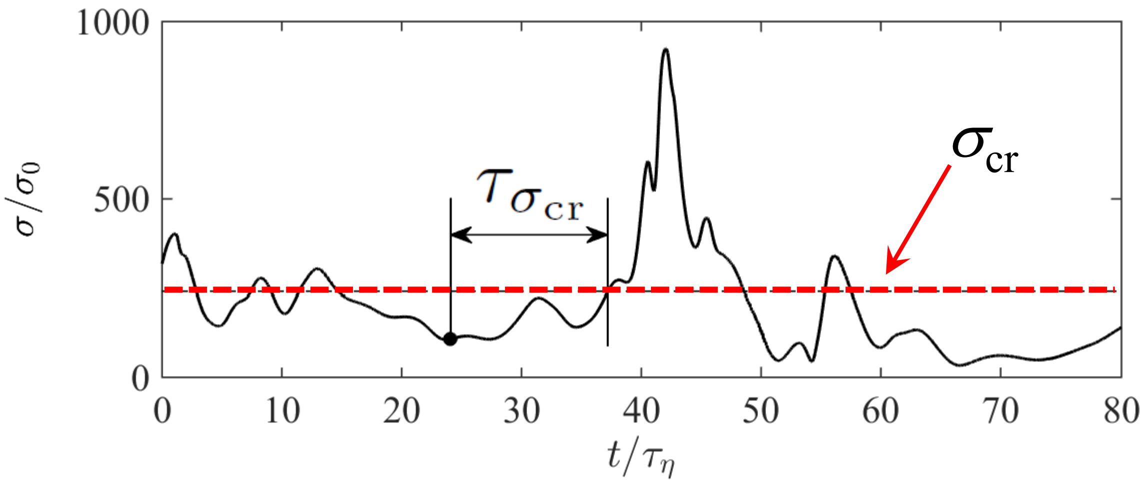

Breakup rate: $$f_{\sigma_{cr}} = \frac{1}{\langle \tau_{\sigma_{cr}} \rangle}$$

Babler, Biferale, Lanotte, *PRE* (2012)

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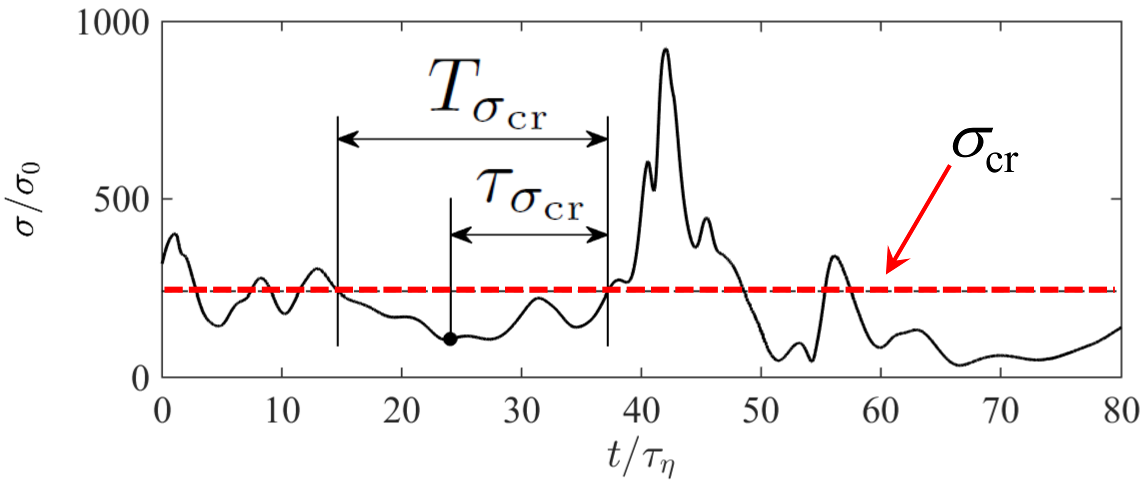


Breakup rate: $$f_{\sigma_{cr}} = \frac{1}{\langle \tau_{\sigma_{cr}} \rangle}$$

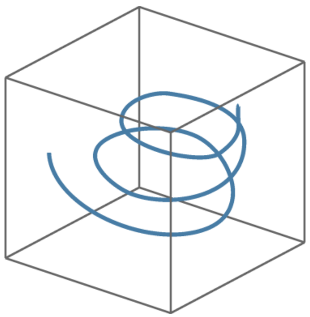
Quasi-Eulerian proxy:

$$f^{(E)}_{\sigma_{cr}} = \frac{1}{\langle T_{\sigma_{cr}} \rangle} = \frac{\int_0^\infty d\dot{\sigma}\, \dot{\sigma} p_2(\sigma_{cr}, \dot{\sigma})}{\int_0^{\sigma_{cr}} d\sigma\, p(\sigma)}$$

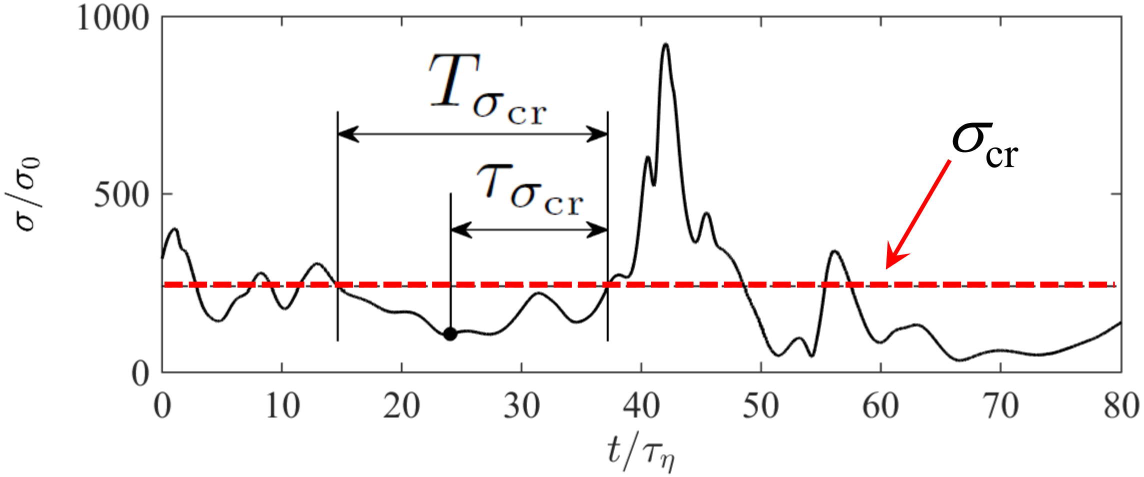
Babler, Biferale, Lanotte, *PRE* (2012)

Numerical experiments

- *Task*: Measure σ along turbulent trajectories and detect crossings of σ_{cr}
- Turbulent trajectories for HIT are available:



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



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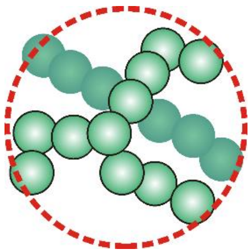
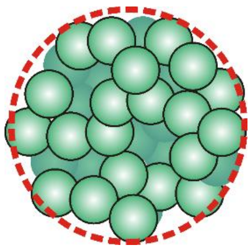
Bec, Biferale, Lanotte, Scagliarini, Toschi, *JFM* (2010)

Hydrodynamic stress

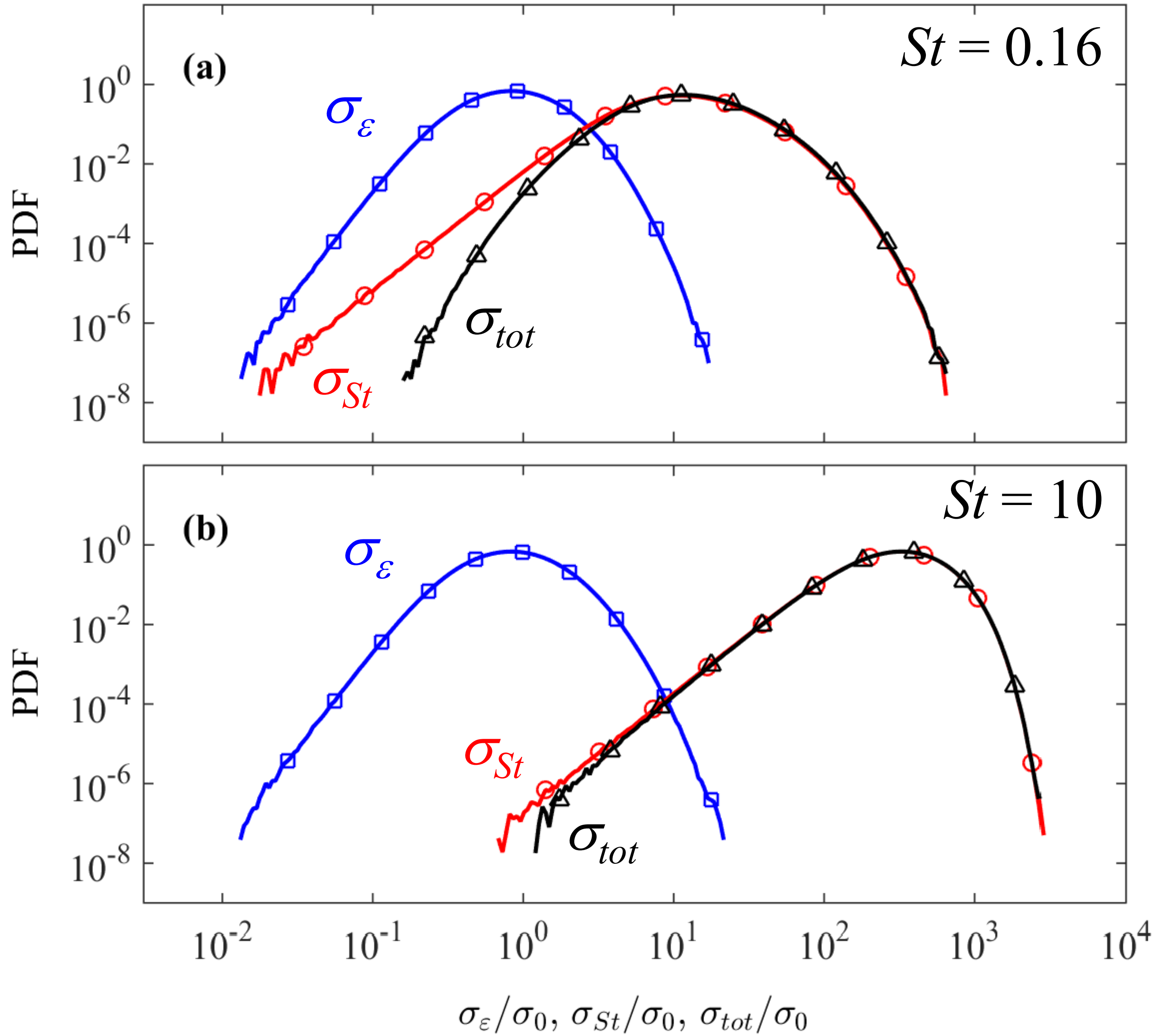
- Aggregates of size $R/\eta = 0.1$ and varying density



Open aggregate
Low density



Compact aggregate, high density



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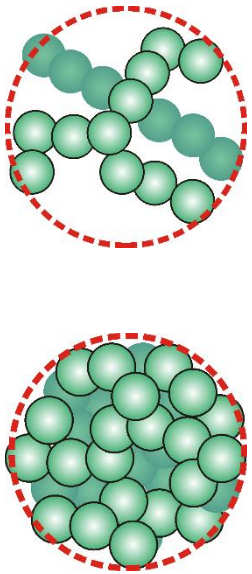
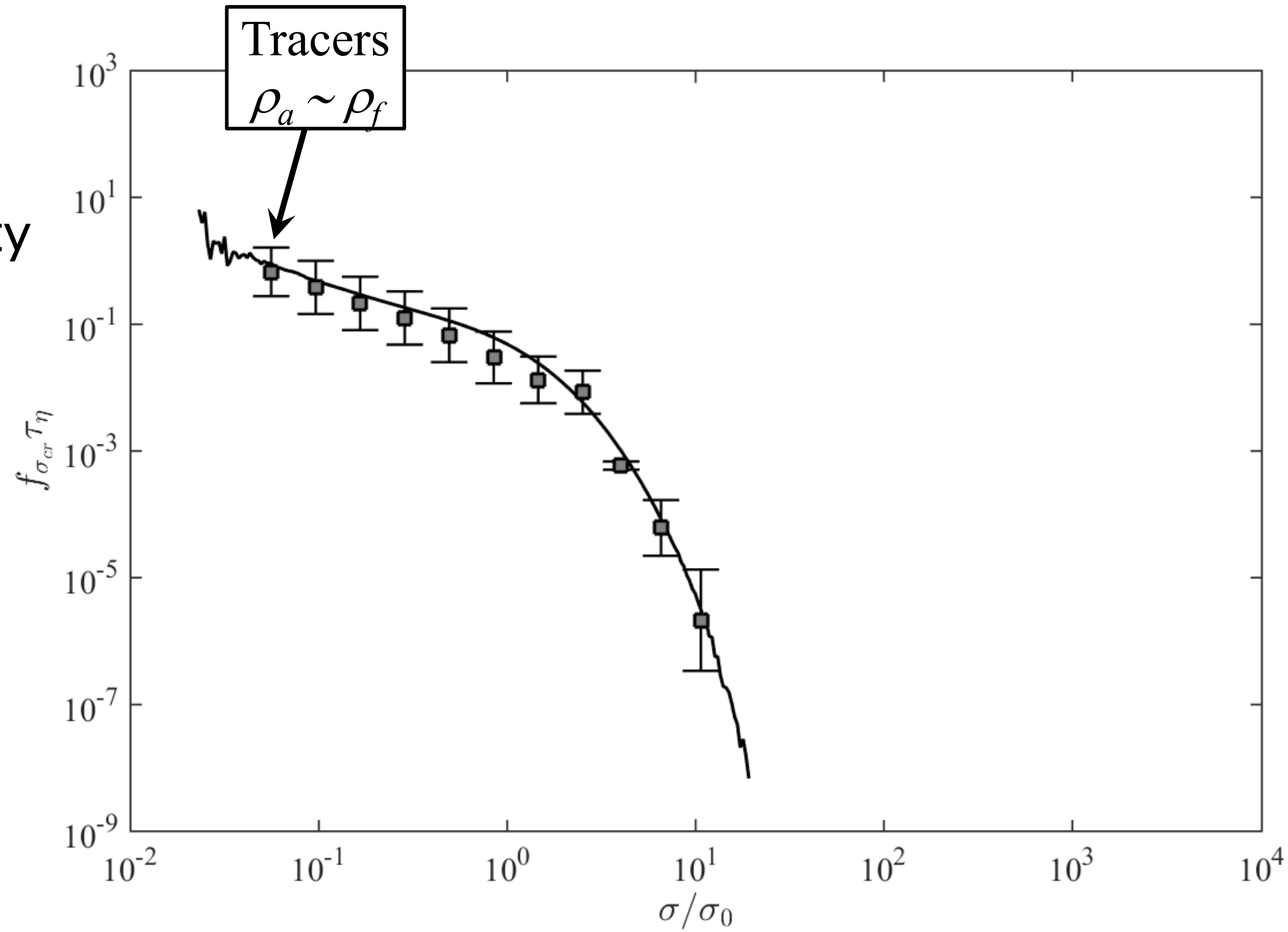


Open aggregate Low density

Compact aggregate, high density



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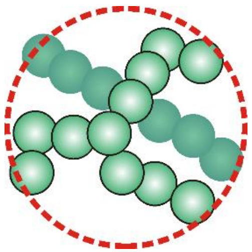

Open aggregate
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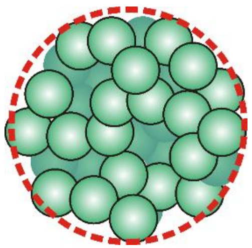
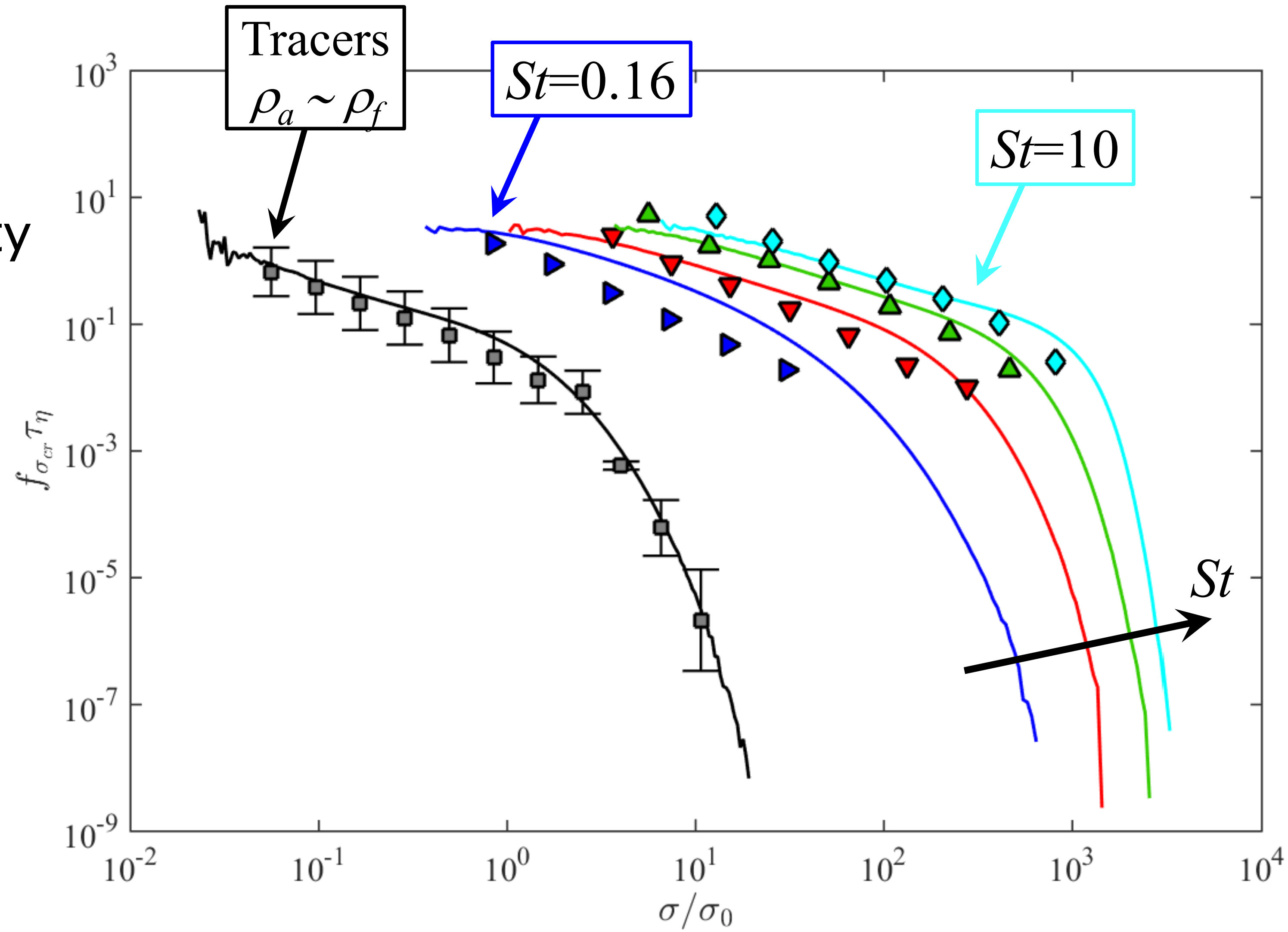


Compact aggregate, high density



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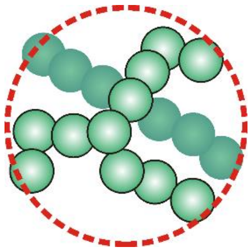

Open aggregate
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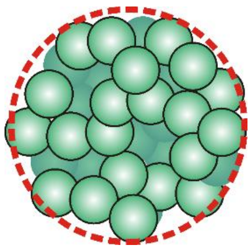

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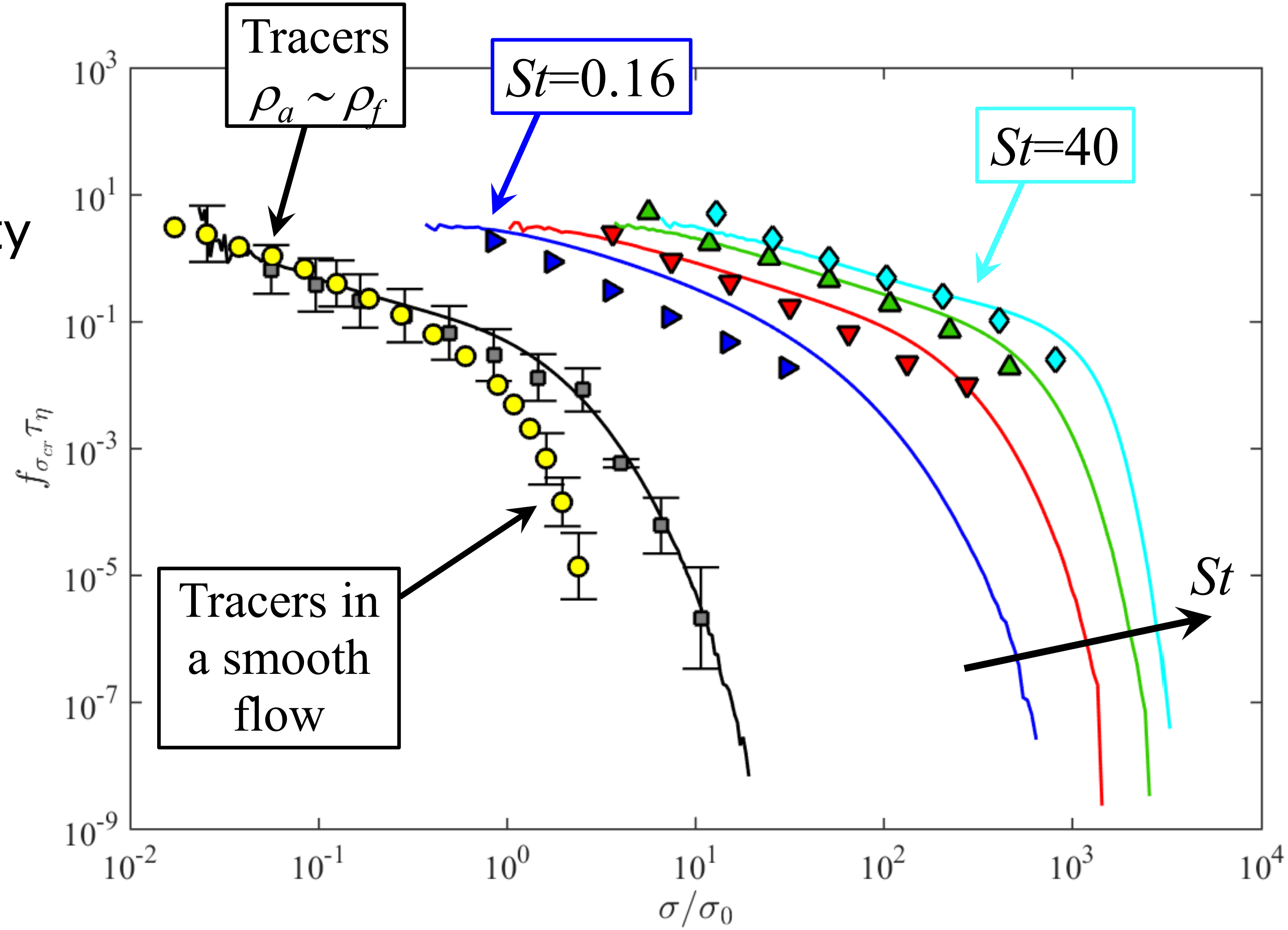

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Conclusions

- We considered the breakup of inertial aggregates due to hydrodynamic stress in homogeneous and isotropic turbulence.

  The most simple criterion for breakup is adopted where breakup occurs when the stress exceeds a critical threshold σ_{cr}, characteristic for a given aggregate.

- For an aggregate with a given Stokes, the breakup rate as a function of σ_{cr} shows power-law behavior for small σ_{cr}, followed by a sharp cut-off as σ_{cr} increases.

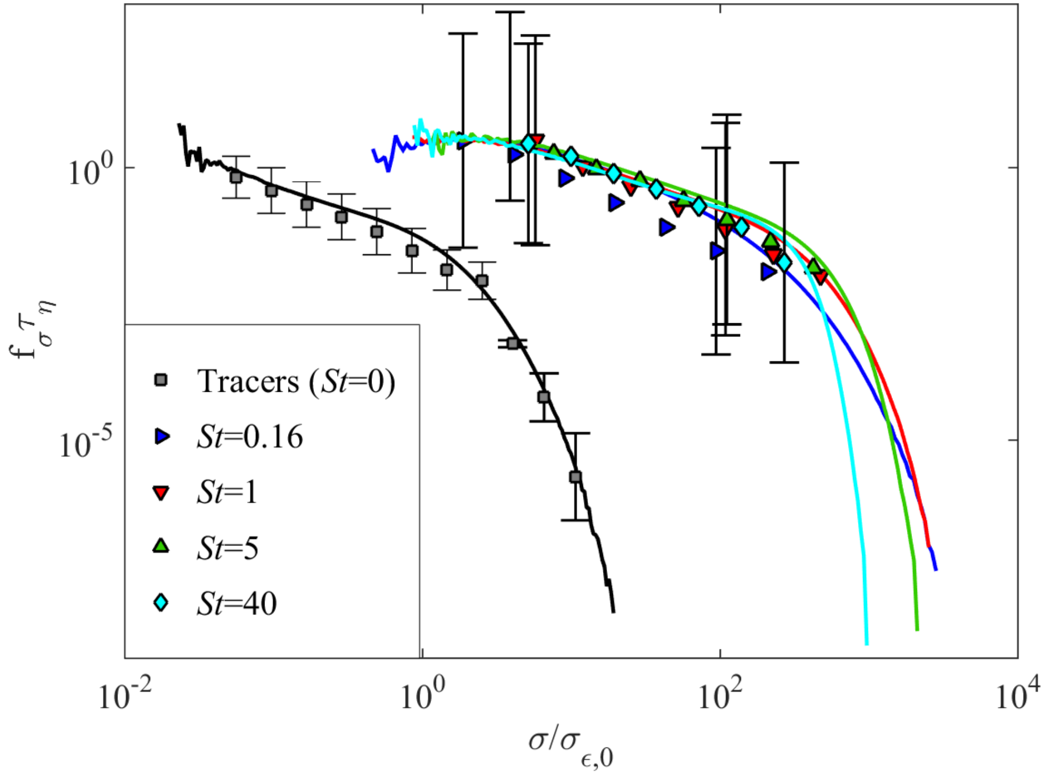
- The power-law behavior is controlled by Gaussian fluctuations, as confirmed by measuring the breakup rate in a synthetic turbulent flow with Gaussian statistics

- The power-law behavior is well established for small and large Stokes, while some distortion is seen for intermediate Stokes. This might be due to the preferential sampling of the flow field of particles with St $\approx$ 1.

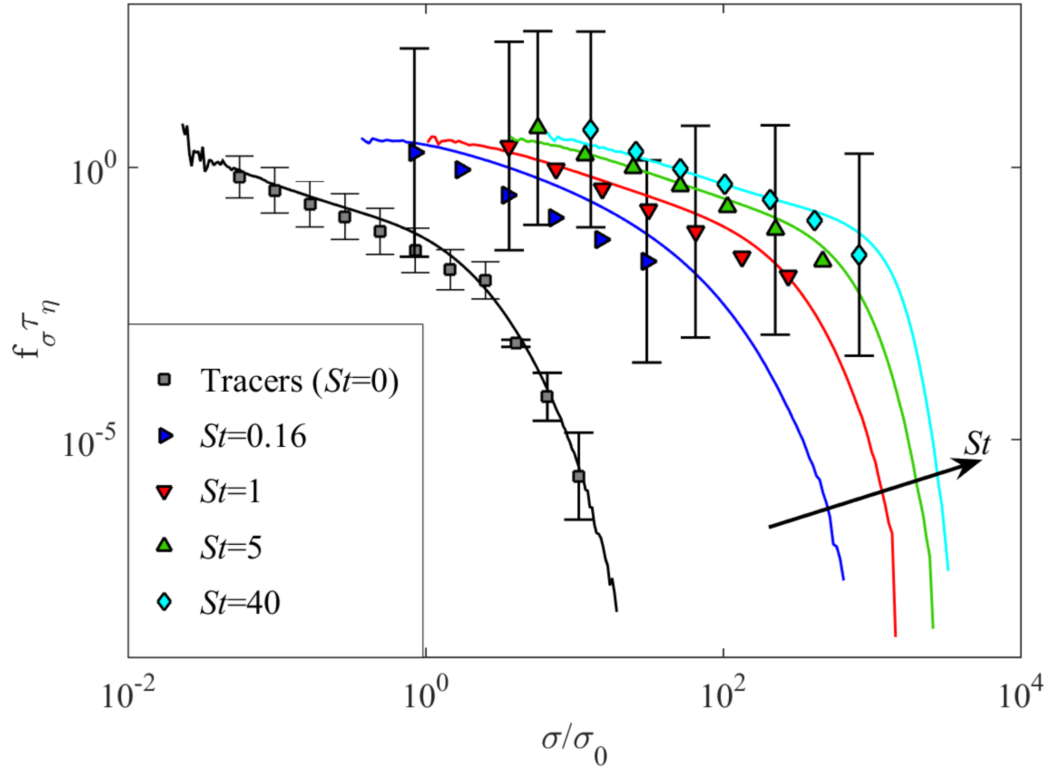
Backup Slide

Breakup rate, case A and B

Constant density, $\beta = 10^{-3}$
varying size

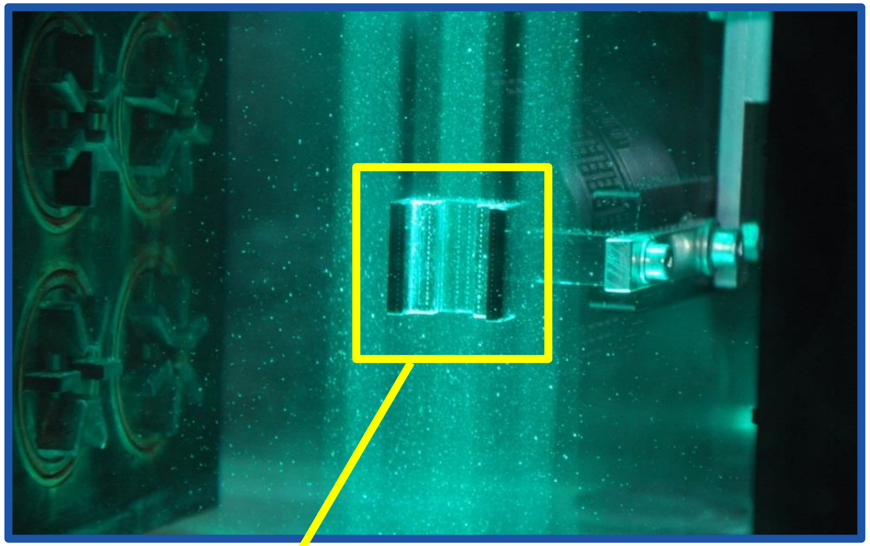


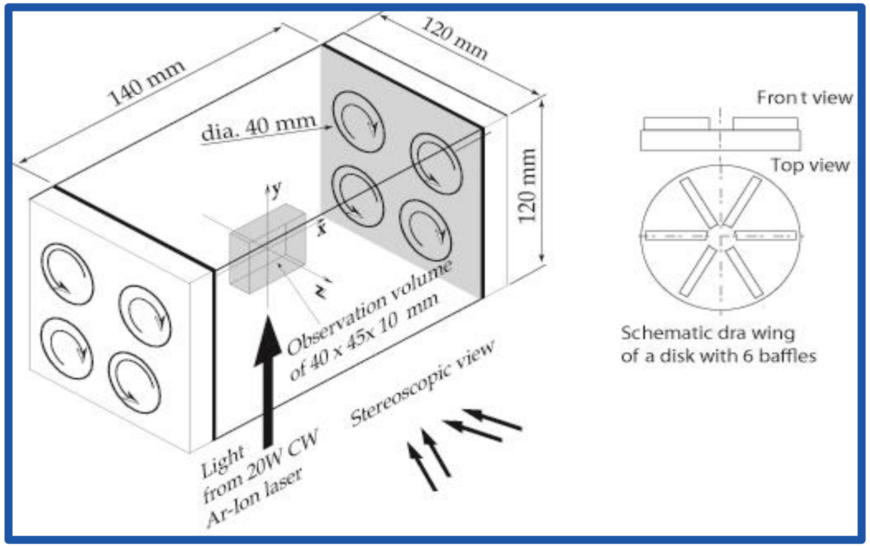
Constant size $R/\eta = 0.1$
varying density



Backup Slide

Breakup experiments by PTV





Observation domain,
40mm × 30mm × 20 mm

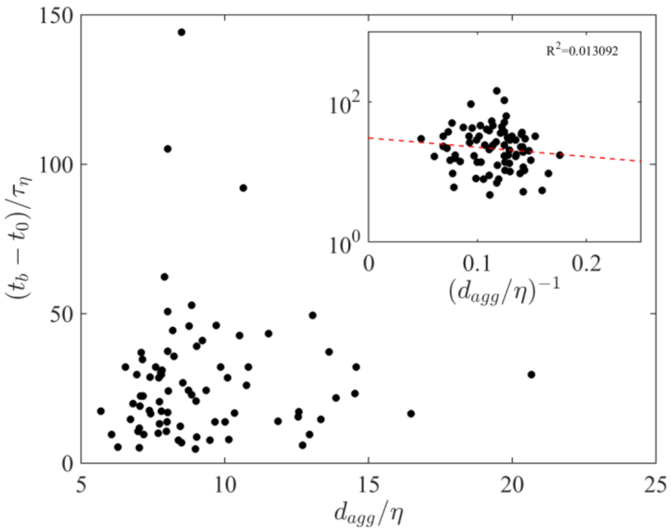
Flow forcing: eight counter rotationg disks (diameter 40mm) Operating at 100 rpm

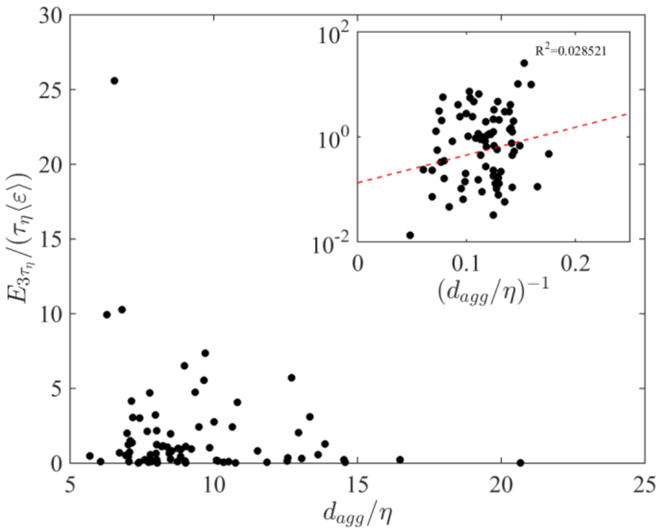
U_{rms}	L	ε	Re_λ	η	τ_η	G	Δ/η
0.03 ms^{-1}	40 mm	9×10^{-5} m^2s^{-3}	70	0.33 mm	0.1 s	10 s^{-1}	12

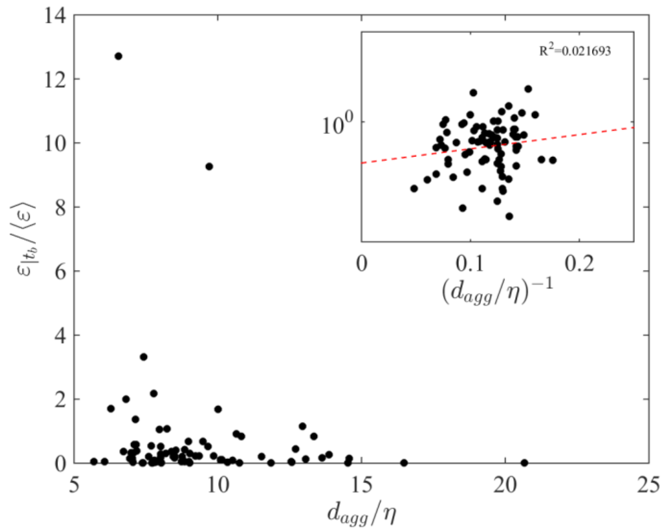
D. Saha, *Experimental analysis of aggregate breakup in flows observed by three dimensional particle tracking velocimetry.* Diss. ETH (2013)

Breakup criteria

- Monitoring breakup events by PTV
- Aggreagte strength decreases with increasing aggregate size







Criteria 1: "Slow breakup" Duration over which stress is applied controls breakup, turbulent fluctuations do not influence breakup

Criteria 2: "Intermediate breakup:" Breakup requires accumulation of stress.

$$E_\Delta = \int_{t_b-\Delta t_b}^{t_b} \varepsilon(t)\,dt$$

Criteria 3: "Fast breakup" Local stress (local in time and space) controls breakup. Breakup upon crossing a critical threshold

Flow configurations

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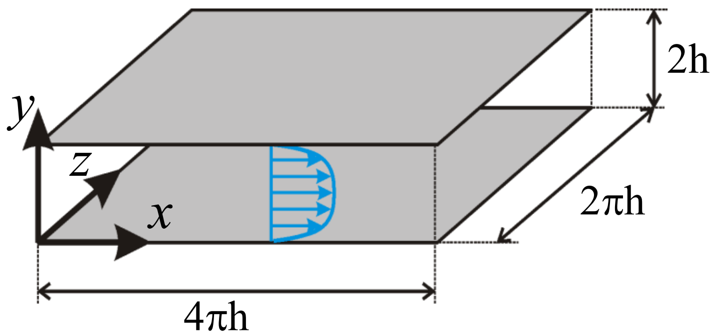
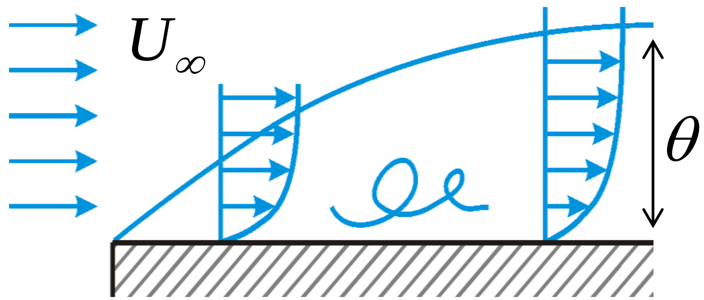
Channel flow



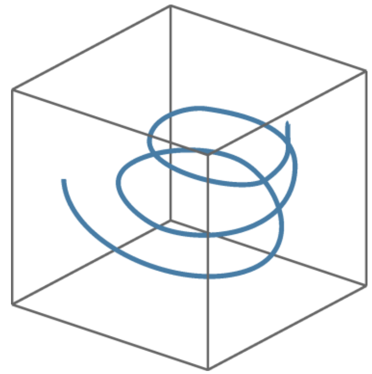
- Periodic in x and z, Resolution 128×128×129
- $R_\tau = u_\tau h / \nu = 150$ (u_τ = shear velocity)

Developing boundary layer flow



- Resolution 4096×301×384
- $R_\theta = U_\infty \theta / \nu = 200\text{-}2500$ (θ=momentum-loss thickness)

H.I.T.

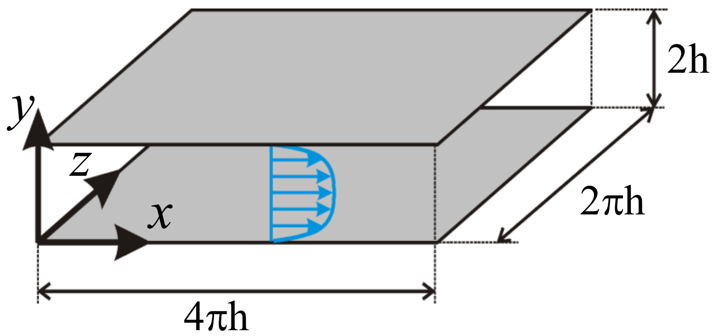


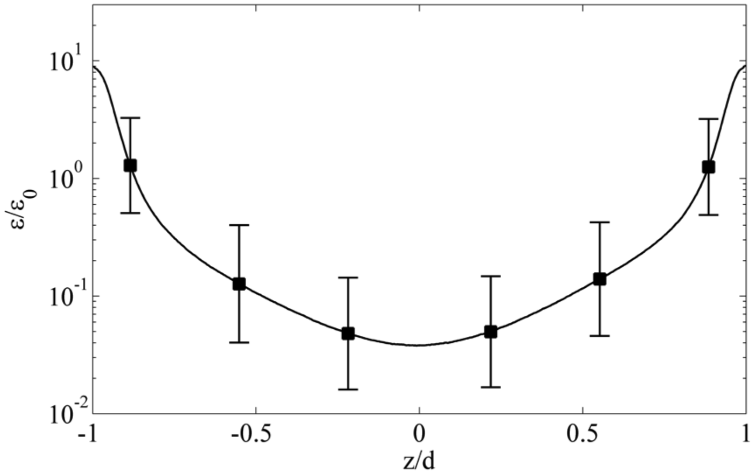
- Resolution 2048^3
- $Re_\lambda = 400$

E. Pitton, C. Marchioli, V. Lavezzo, A. Soldati, F. Toschi, *Phys. Fluids* **24** (2012) 073305
G. Sardina, P. Schlatter, F. Picano, C.M. Casciola, L. Brandt, D.S. Henningson, *J. Fluid Mech.* **706** (2012) 584
J. Bec, L. Biferale, A.S. Lanotte, A. Scagliarini, F. Toschi, *J. Fluid Mech.* **645** (2010) 497

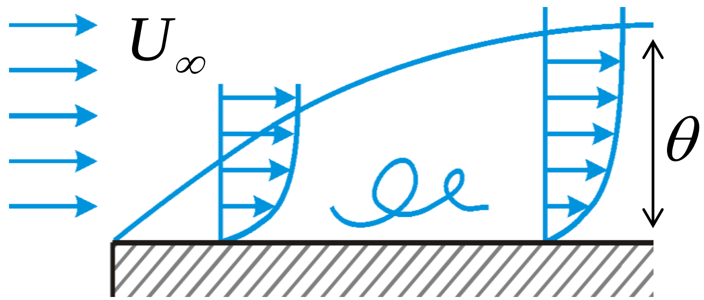
Flow configurations

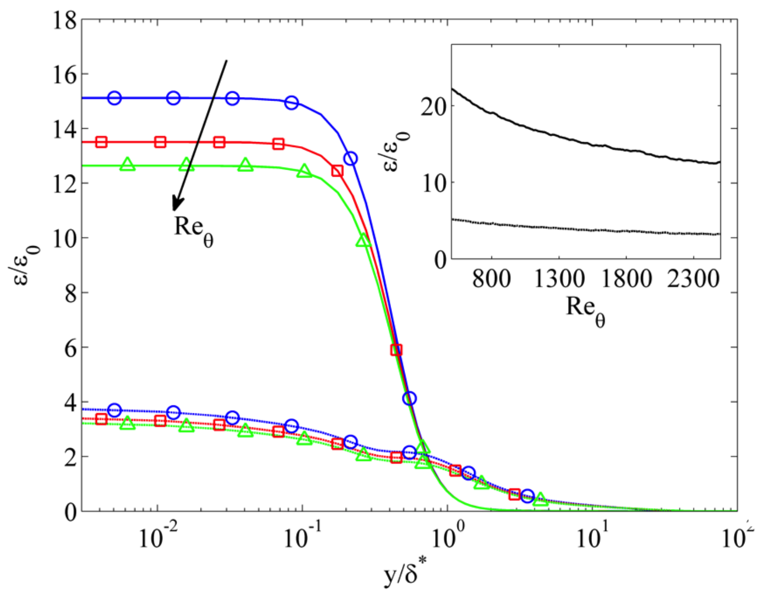
Channel flow





Developing boundary layer flow





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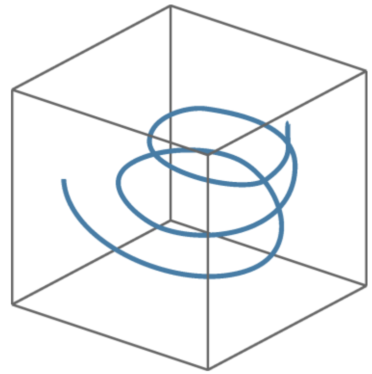
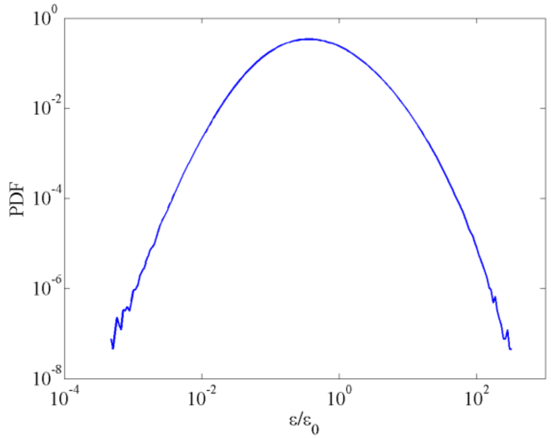
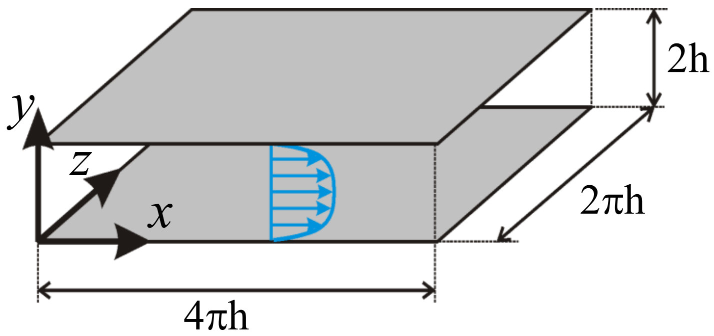




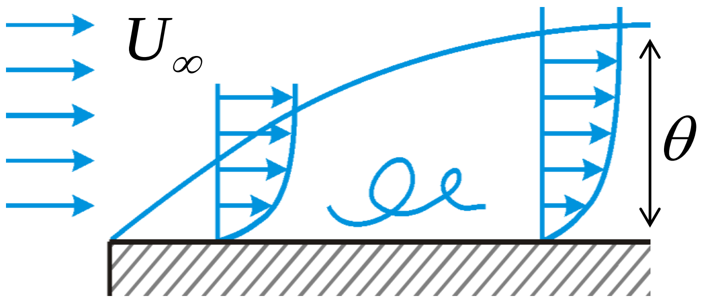
Seeding regions

Channel flow



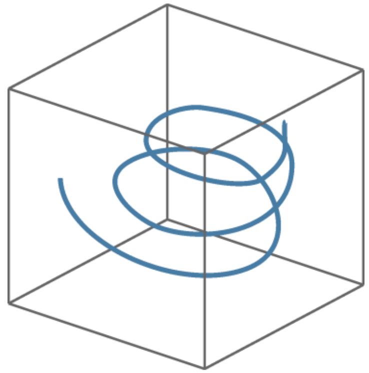
- Center-plane
- Near-wall region

Developing boundary layer flow



- Inside the BL
- Outside the BL

H.I.T.

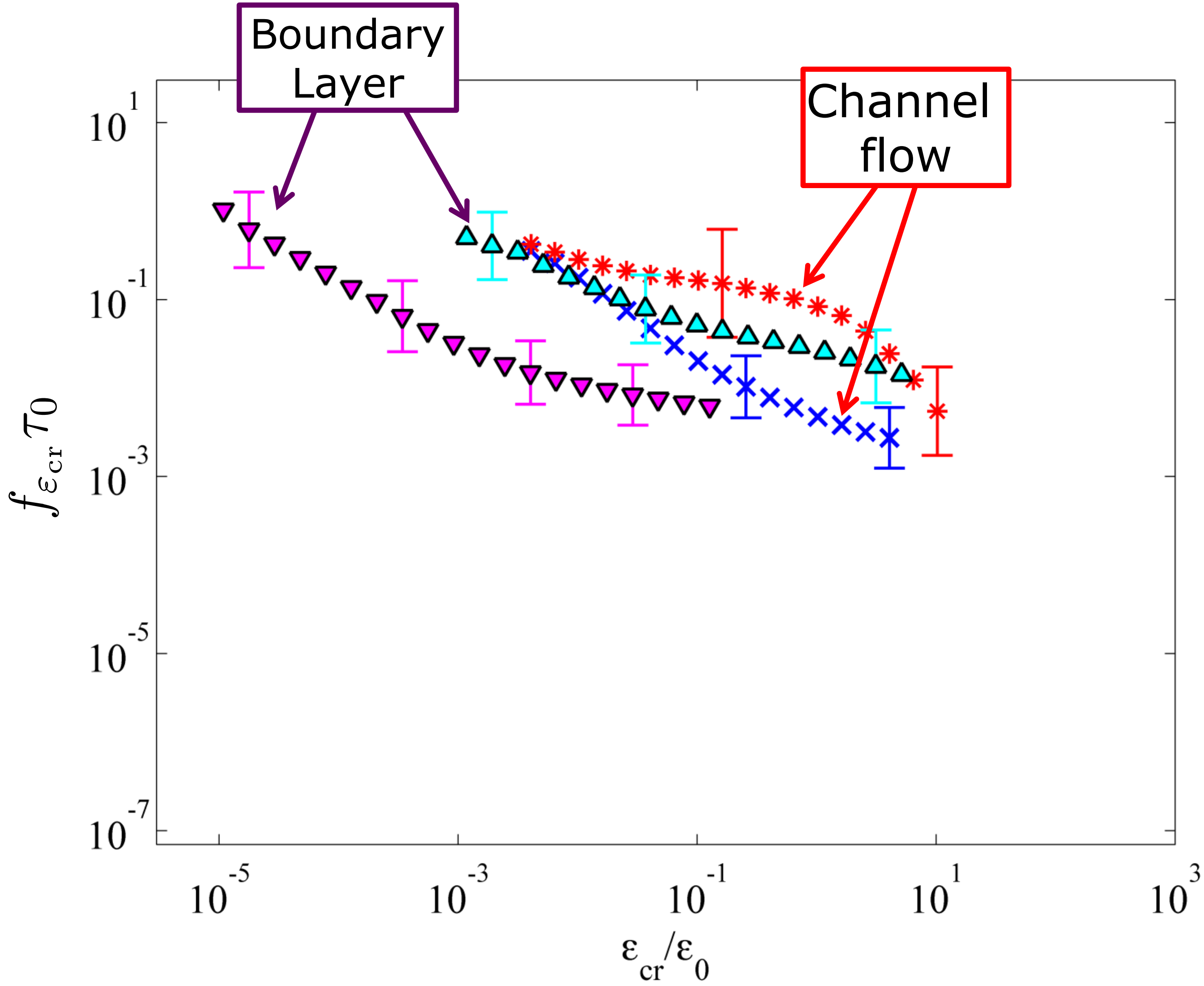


Aggregates are released homogenously

Results

- **Channel flow**
  ε_0=volume average
  $\tau_0=(\nu/\varepsilon_0)^{1/2}$

- **Boundary layer**
  ε_0=volume average
  inner seeding region
  $\tau_0=(\nu/\varepsilon_0)^{1/2}$



Babler *et al.*, *J. Fluid Mech. Submitted* (2014)

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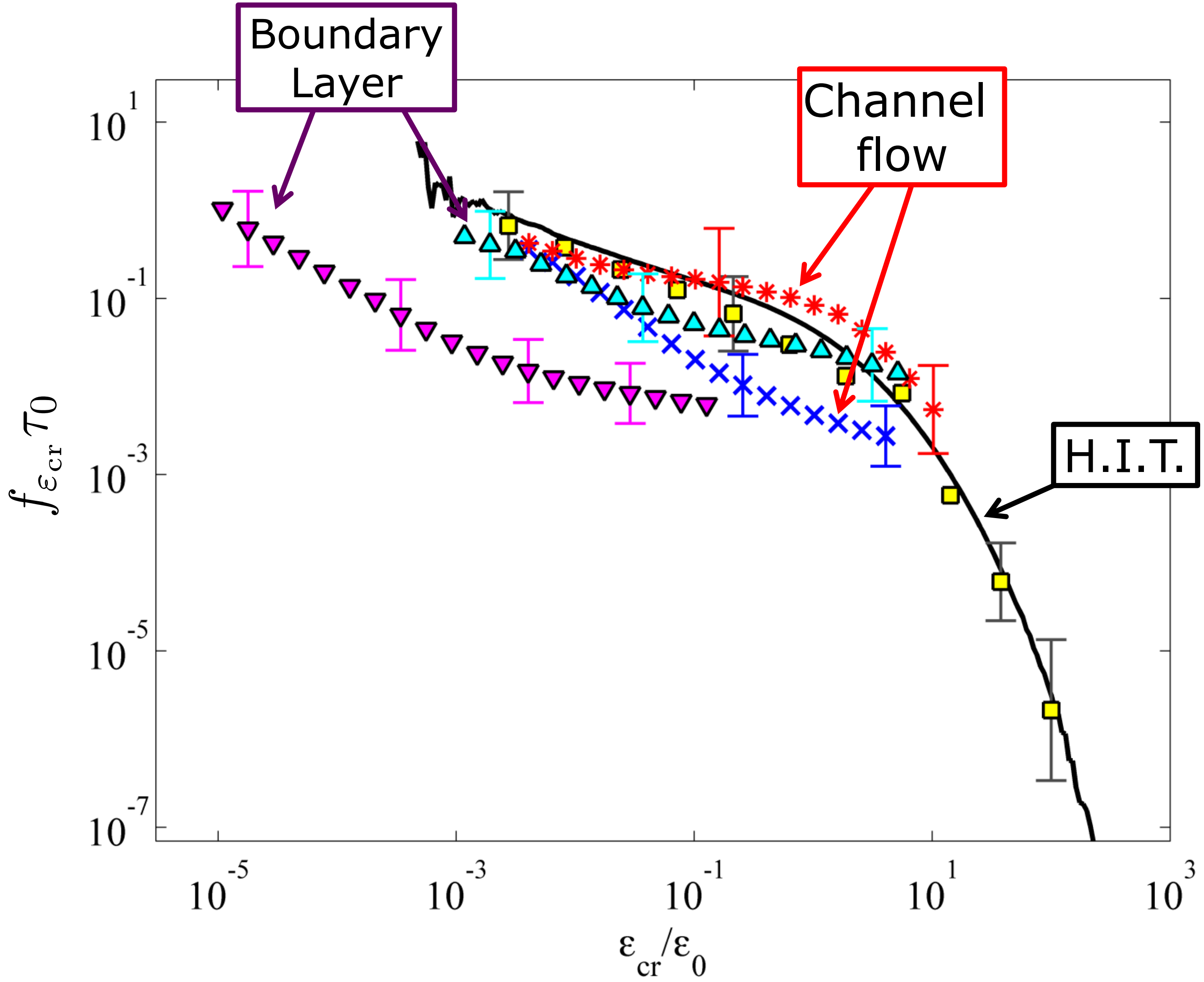
  ε_0=volume average
  $\tau_0=(\nu/\varepsilon_0)^{1/2}$
- **Boundary layer**
  ε_0=volume average
  inner seeding region
  $\tau_0=(\nu/\varepsilon_0)^{1/2}$
- **H.I.T.**
  ε_0=mean dissipation
  $\tau_0=(\nu/\varepsilon_0)^{1/2}$



Babler *et al.*, *J. Fluid Mech. Submitted* (2014)

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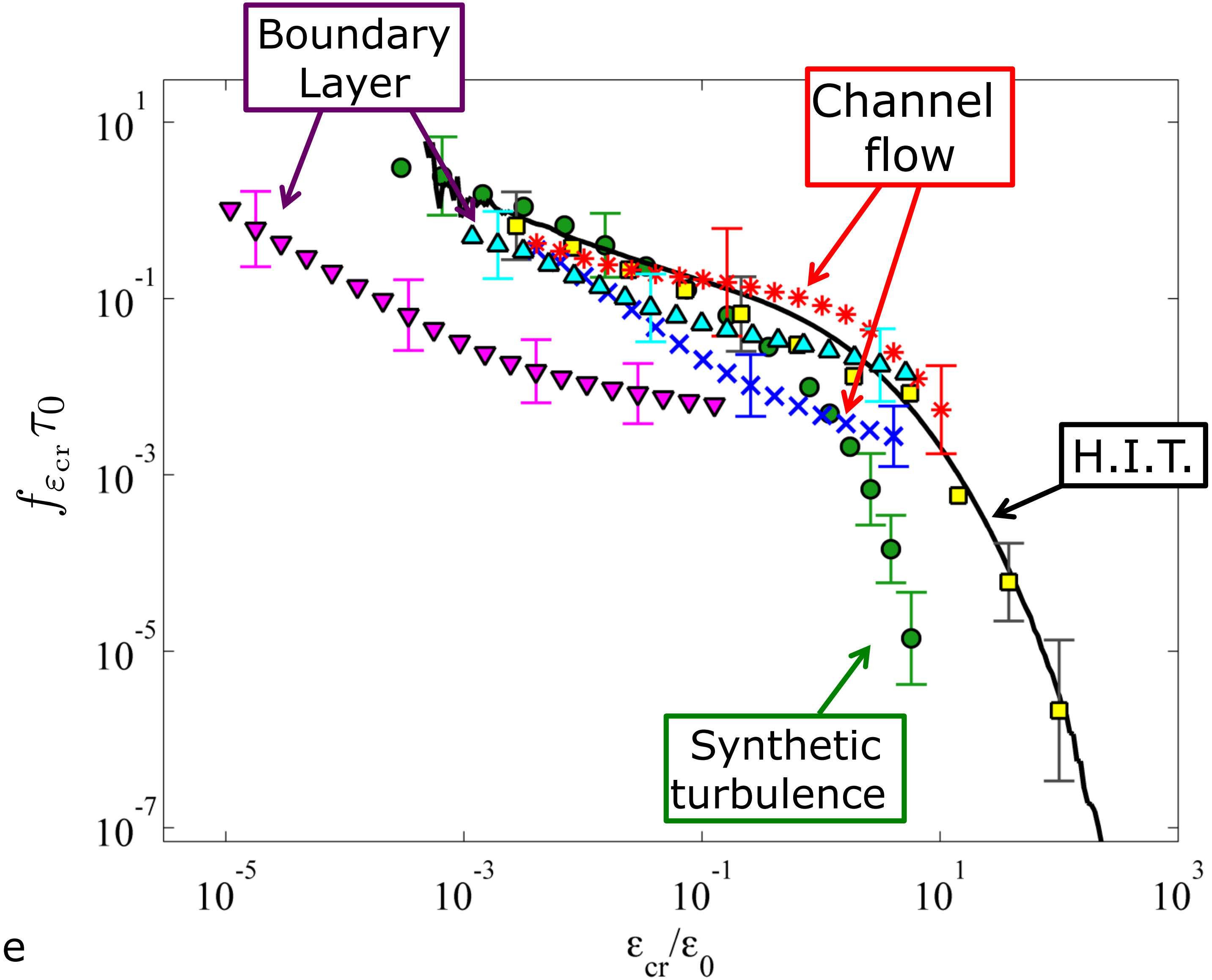
- **Channel flow**
  ε_0=volume average
  $\tau_0=(\nu/\varepsilon_0)^{1/2}$
- **Boundary layer**
  ε_0=volume average
  inner seeding region
  $\tau_0=(\nu/\varepsilon_0)^{1/2}$
- **H.I.T.**
  ε_0=mean dissipation
  $\tau_0=(\nu/\varepsilon_0)^{1/2}$
- **Synthetic turbulence**
  ε_0=mean dissipation
  τ_0=acceleration timescale

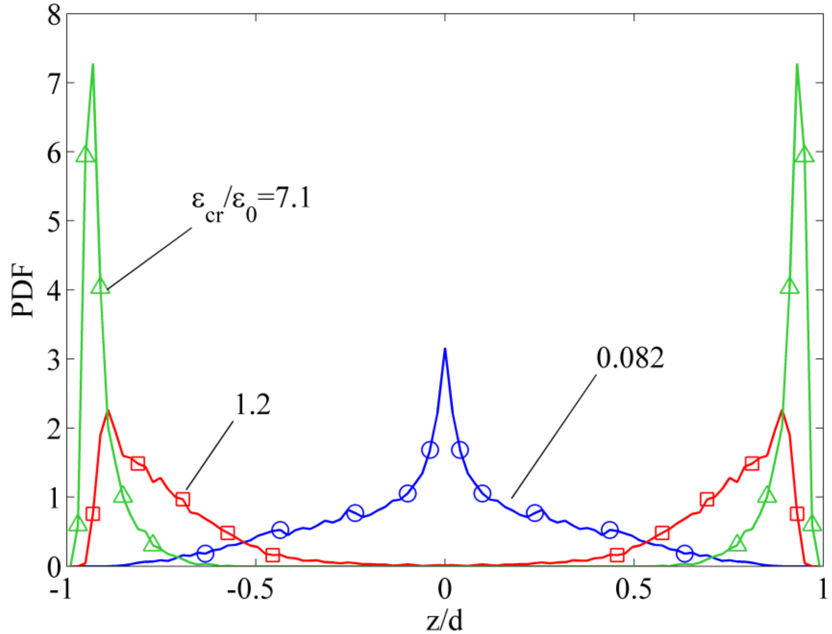


Babler *et al.*, *J. Fluid Mech. Submitted* (2014)

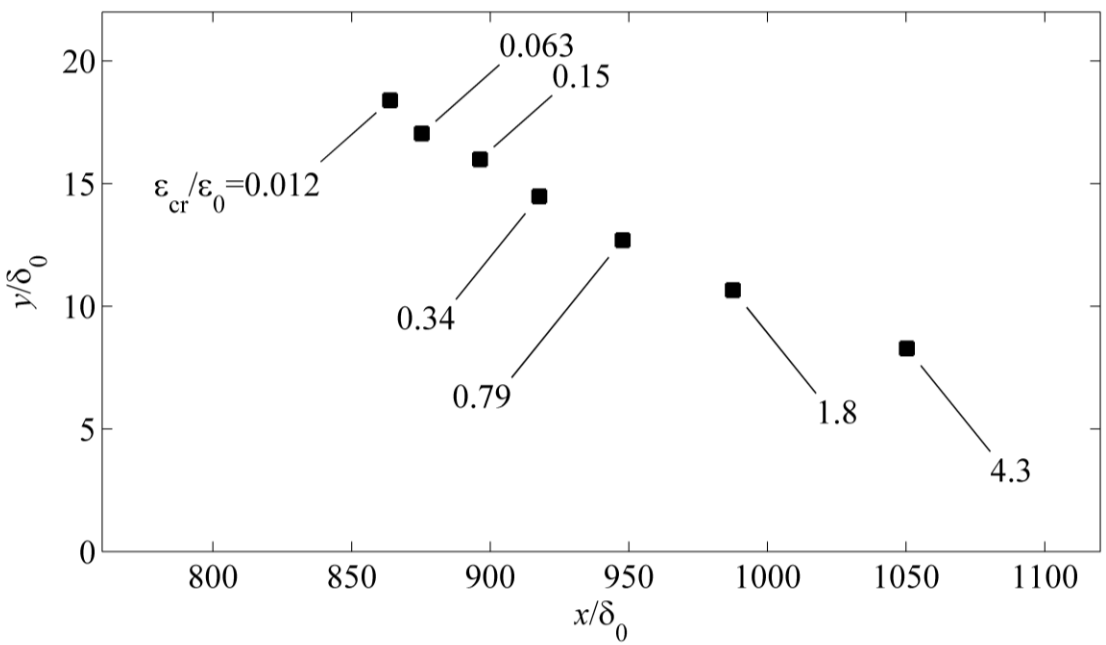
Conclusions

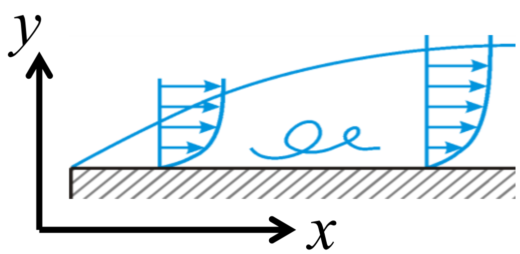
- Numerical experiments were performed to systematically study aggregate breakup in different flow configurations.
- Breakup in bounded flows is the result of two competing effects: the systematic influence of the mean flow profile and the intermittent burst caused by turbulent fluctuations.
- Breakup of weak aggregates exhibits a qualitatively similar power law behavior among the different flows. Inspection shows that weak aggregates break up in the close vicinity of the point of release. Fluctuations causing breakup are independent of the flow configuration.
- Breakup of strong aggregates is influenced by the mean flow profile and depends on the flow configuration.

Breakup location



Breakup location in the channel flow.





Breakup location in the boundary layer flow