14th Workshop on Two-Phase Flow Predictions

University of Halle-Wittenberg, Halle (Saale), September 7-10, 2015

Breakage of ductile aggregates in turbulent channel flow

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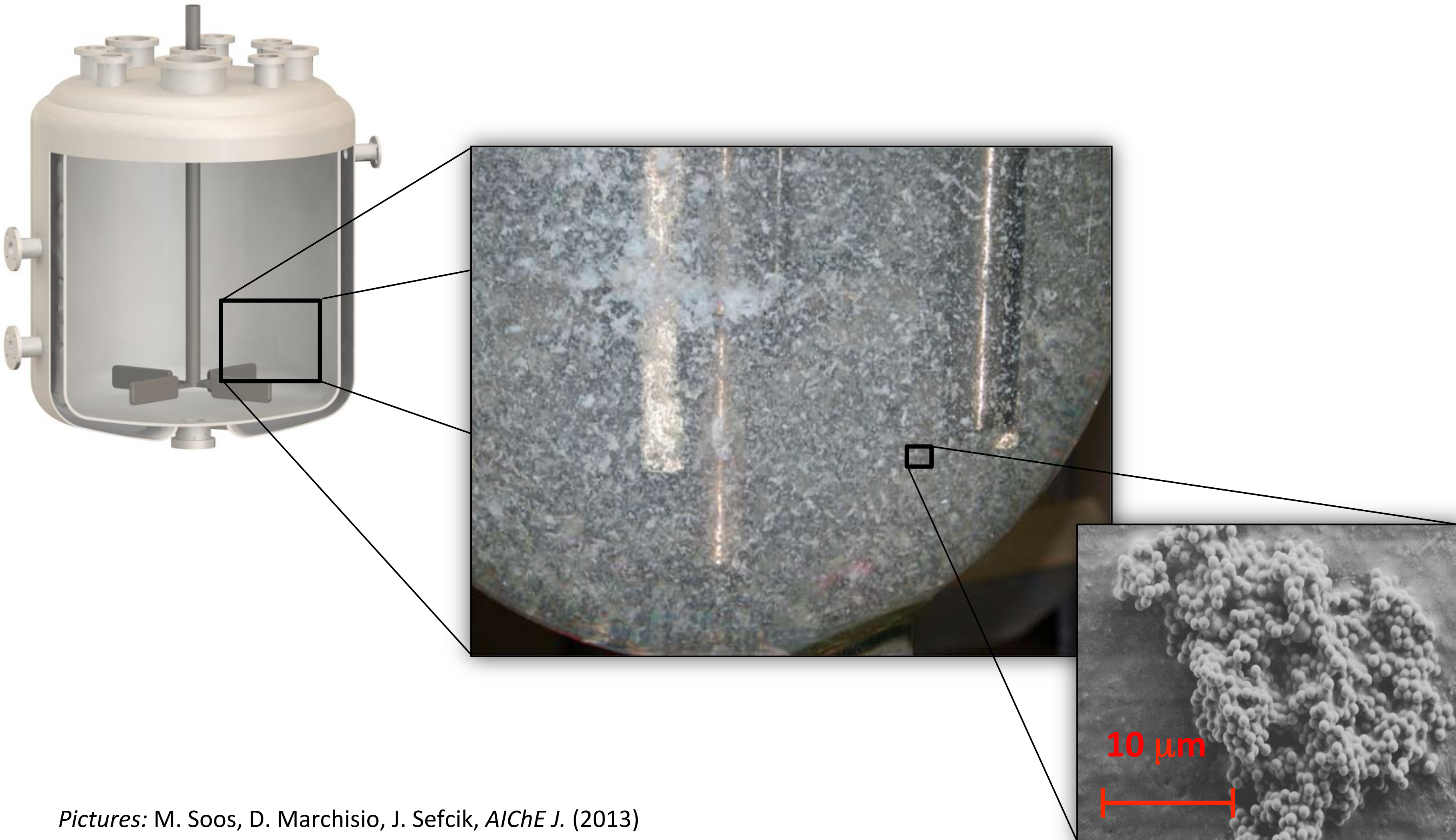
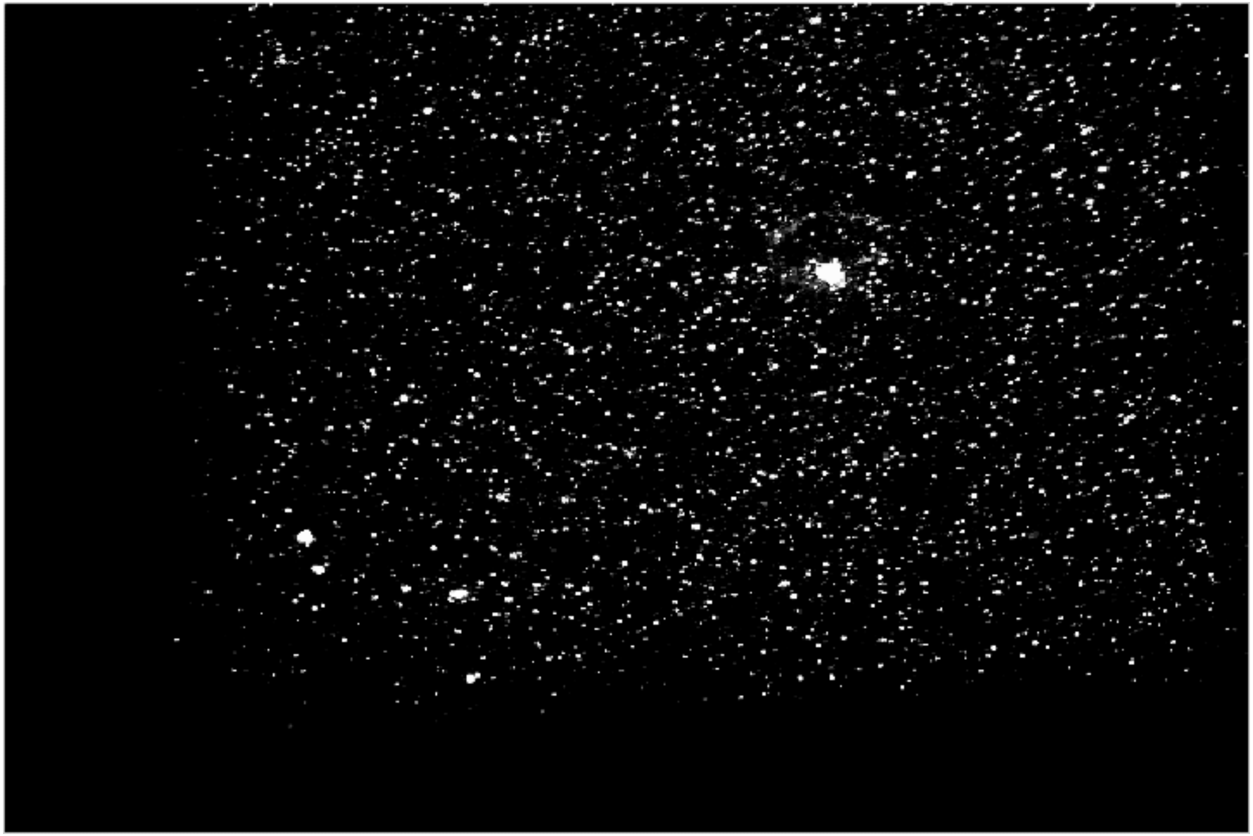
University of Udine

START FROM THE REAL DEVICE: COLLOIDAL AGGREGATES IN STR



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

BREAKAGE OF SMALL AGGREGATES IN TURBULENT FLOW



Polystyrene aggregate in a homogeneous and isotropic turbulent flow (resolved by PTV by B. Lüthi and co-workers, ETH Zurich, 2013).

$Re_\lambda \approx 70$

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

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

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

$L/\eta = 120$

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

$$\varepsilon = \frac{1}{2}\nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)^2$$

MODELING BREAKUP RATE OF AGGREGATES IN TURBULENCE

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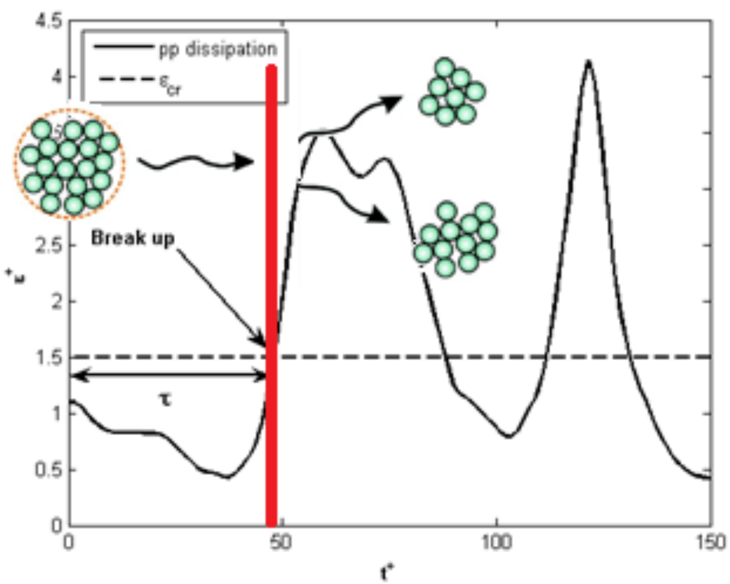
CURRENT ESTIMATES (DE BONA ET AL. 2013; BABLER ET AL. 2008) VALID FOR:

- HIT → $\sigma_{cr} \sim \mu(\varepsilon_{cr}/\nu)^{1/2}$
- TRACER AGGREGATES → $f \sim f(\varepsilon_{cr})$ BREAKUP RATE
- INSTANTANEOUS BREAKUP → $f(\varepsilon_{cr}) = \langle\tau(\varepsilon_{cr})\rangle^{-1}$ FOR $\varepsilon > \varepsilon_{cr}$

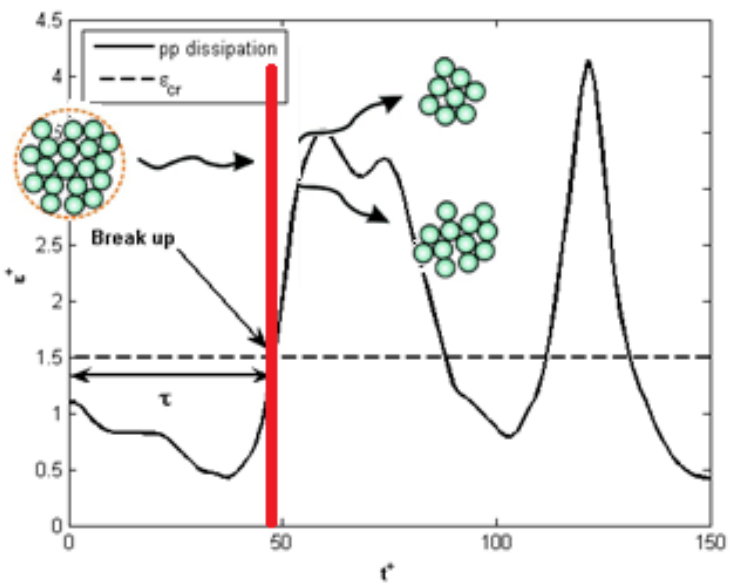


$$f(\varepsilon_{cr}) \propto \varepsilon_{cr}^{-\chi}, \ \chi > 0$$

Modeling breakup rate of aggregates in turbulence

Current estimates (de Bona et al. 2013; Babler et al. 2008) valid for:

- ~~HIT~~ → $\sigma_{cr} \sim \mu(\varepsilon_{cr}/\nu)^{1/2}$
- tracer aggregates → $f \sim f(\varepsilon_{cr})$ breakup rate
- ~~Instantaneous breakup~~ → $f(\varepsilon_{cr}) = <\tau(\varepsilon_{cr})>^{-1}$ for $\varepsilon > \varepsilon_{cr}$



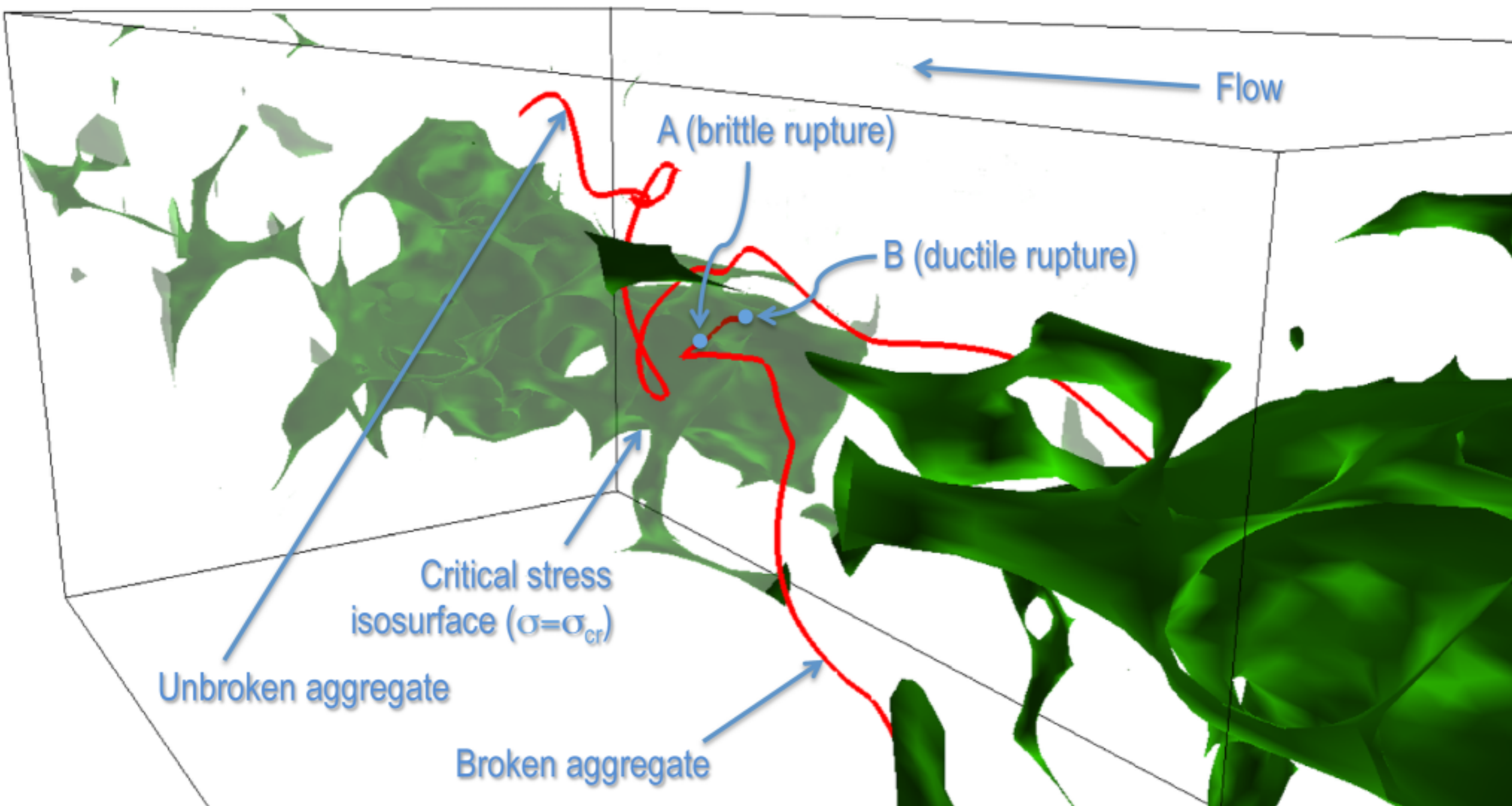
$$f(\varepsilon_{cr}) \propto \varepsilon_{cr}^{-\chi}, \ \chi > 0$$

Anisotropy ?

Ductility ?

MODELING BREAKUP RATE OF AGGREGATES IN TURBULENCE

Rendering of brittle and ductile rupture in turbulent flow



Problem: Dilute suspension in turbulent channel

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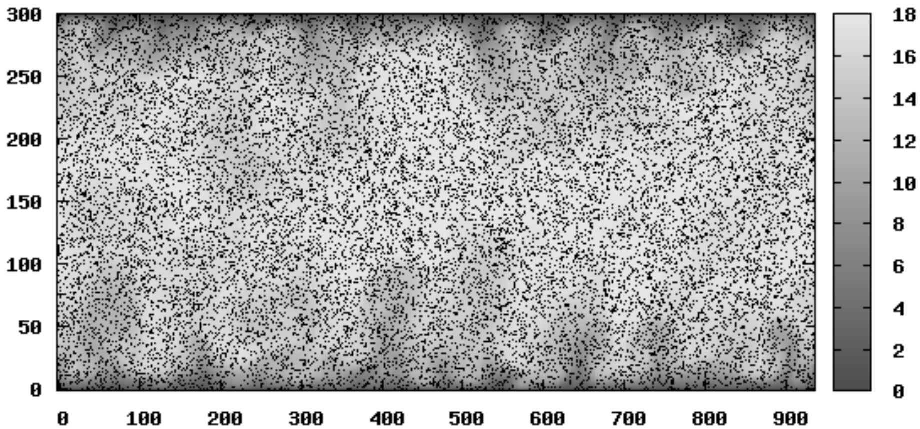
Tracers in turbulent channel flow (pseudo-spectral DNS @ $Re_\tau = 150$)



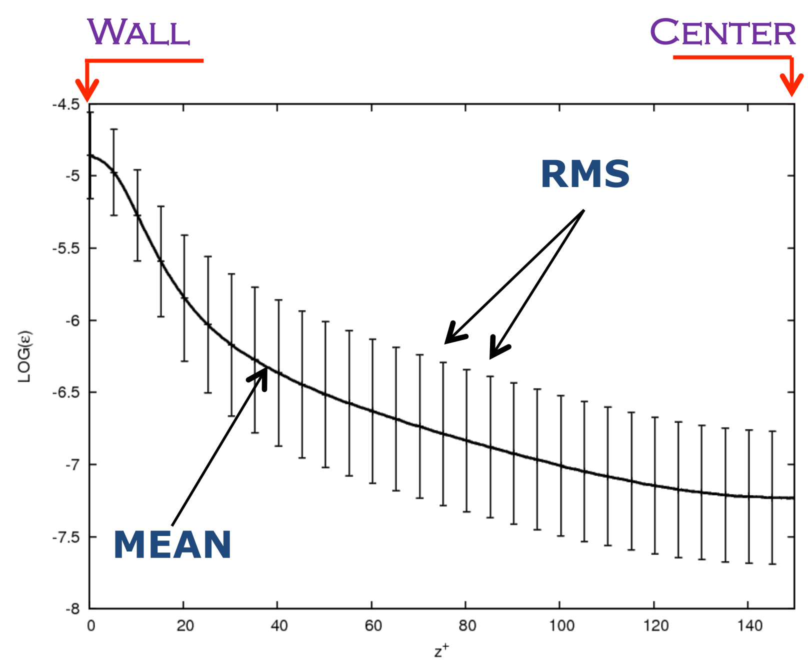
$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} = -u_j \frac{\partial u_i}{\partial x_j} + \frac{1}{Re_\tau} \frac{\partial^2 u_i}{\partial x_j^2} - \frac{\partial p}{\partial x_i} + \delta_{1,i}$$

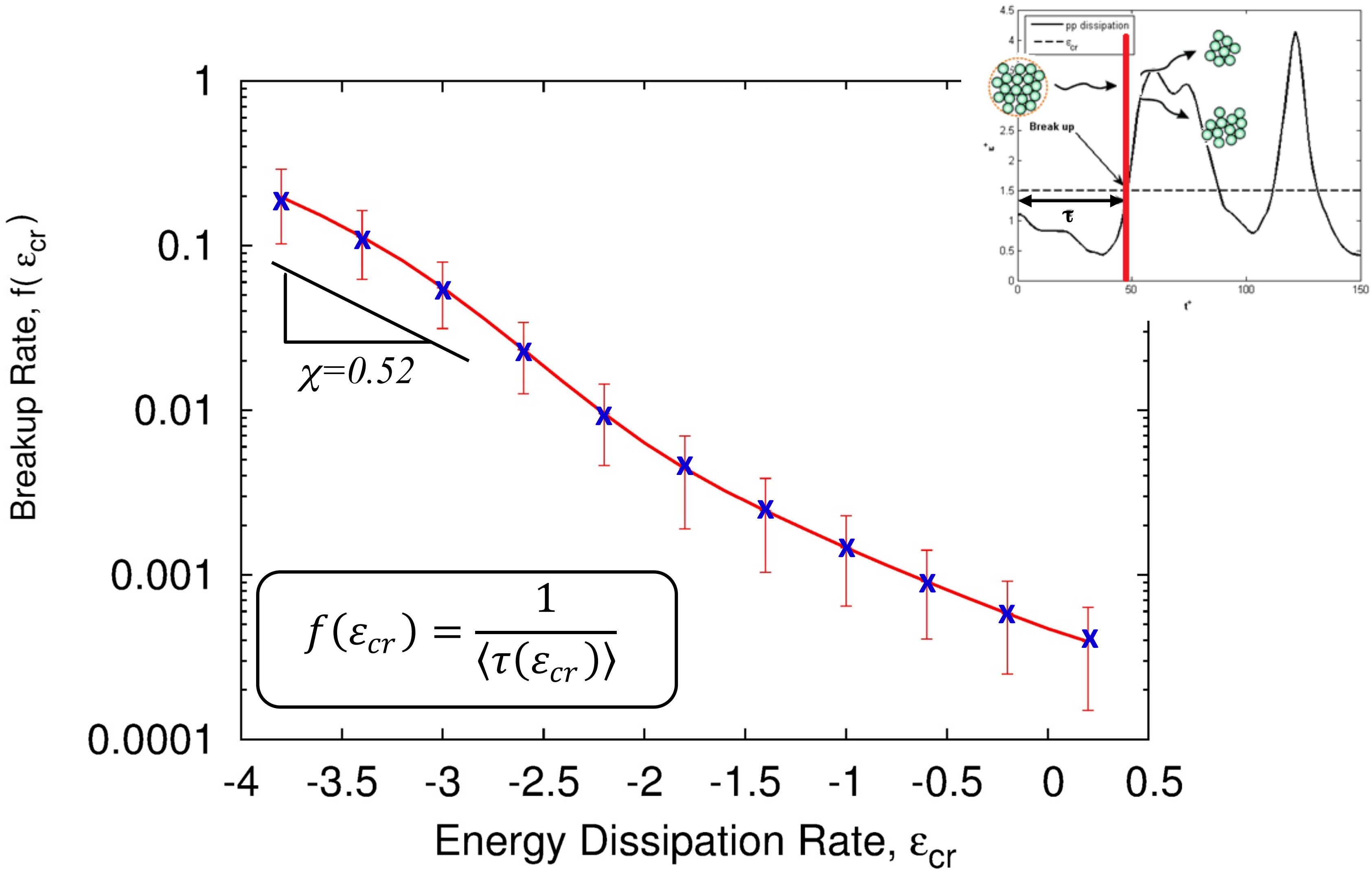
$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{u}(\boldsymbol{x}(t), t)$$

Wall-normal mean energy dissipation

$$\varepsilon = \frac{1}{2}\nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)^2$$



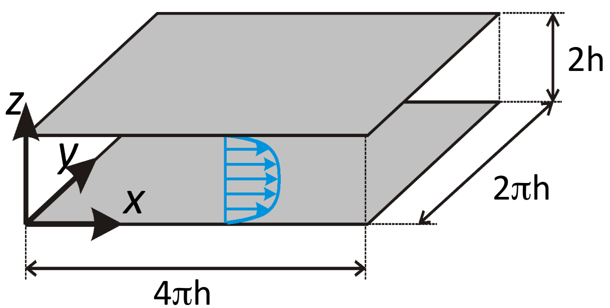
Breakage of brittle aggregates in TCF: deviations from power law



note: aggregates released In the channel centerplane

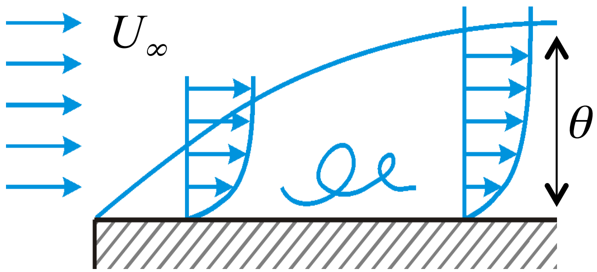
Breakage of brittle aggregates in TCF: comparison with TBL/HIT

Channel flow



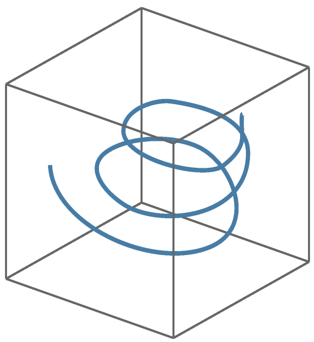
- Resolution 128×128×129
- $R_\tau = u_\tau h/\nu = 150$ (u_τ = shear velocity)

Developing boundary layer flow



- Resolution 4096×301×384
- $R_\theta = U_\infty \theta/\nu = 2500$ (θ=momentum-loss thickn.)

H.I.T.

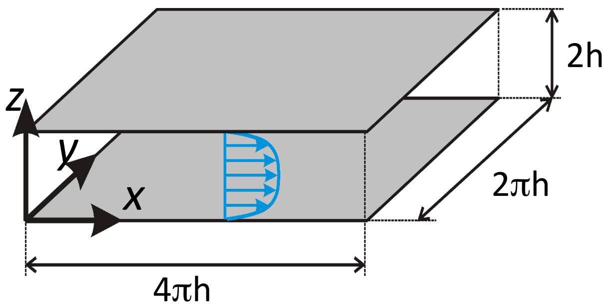


- Resolution 2048^3
- $Re_\lambda = 400$

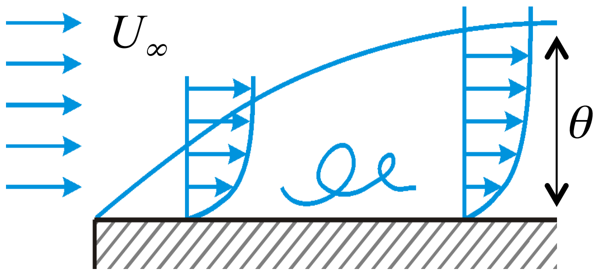
Results from: Babler *et al.*, *J. Fluid Mech.* **766**, 104-128 (2015)

Breakage of brittle aggregates in TCF: comparison with TBL/HIT

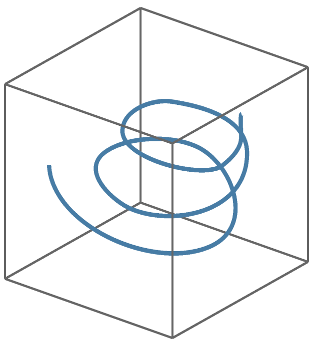
Channel flow



Developing boundary layer flow



H.I.T.



Seeding regions:

- Center-plane
- Near-wall region

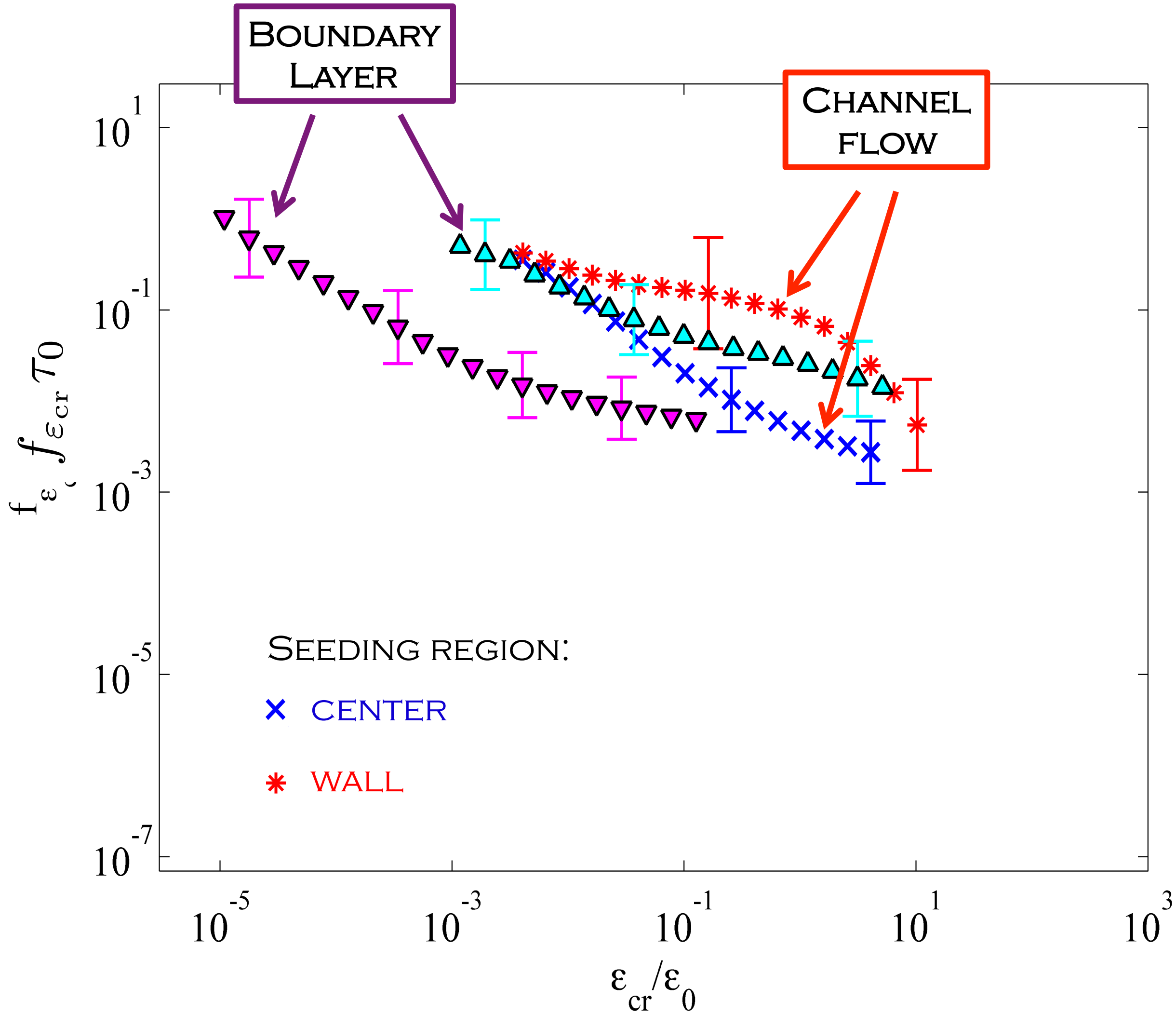
- Outside the BL
- Inside the BL

- homogeneous release

Results from: Babler *et al.*, *J. Fluid Mech.* **766**, 104-128 (2015)

Breakage of brittle aggregates in TCF: comparison with TBL/HIT

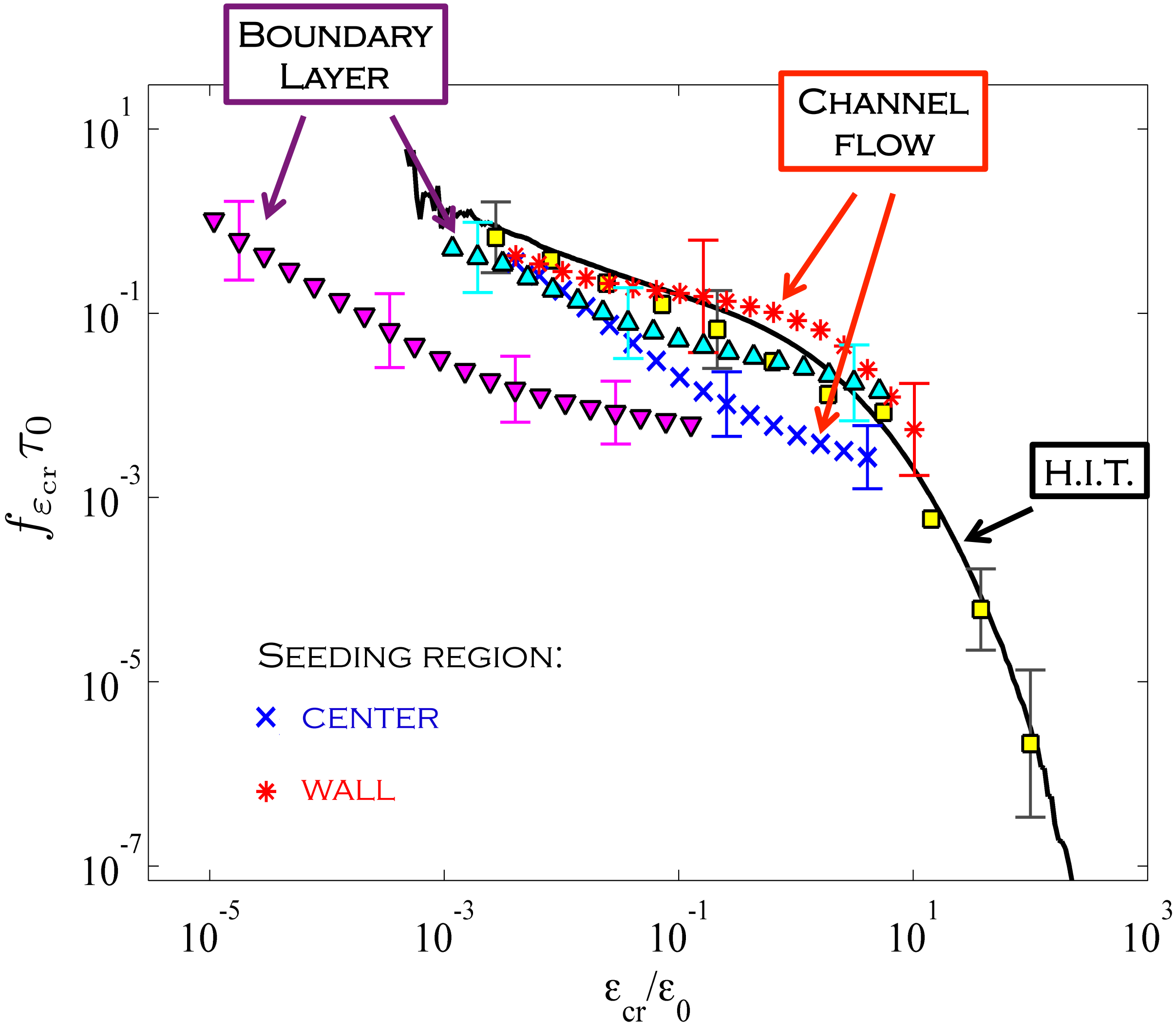
- **Channel flow**
  ε_0=volume average
  $\tau_0=(\nu/\varepsilon_0)^{1/2}$
- **Boundary layer**
  ε_0=volume average of inner seeding region
  $\tau_0=(\nu/\varepsilon_0)^{1/2}$



Results from: Babler *et al.*, *J. Fluid Mech.* **766**, 104-128 (2015)

Breakage of brittle aggregates in TCF: comparison with TBL/HIT

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



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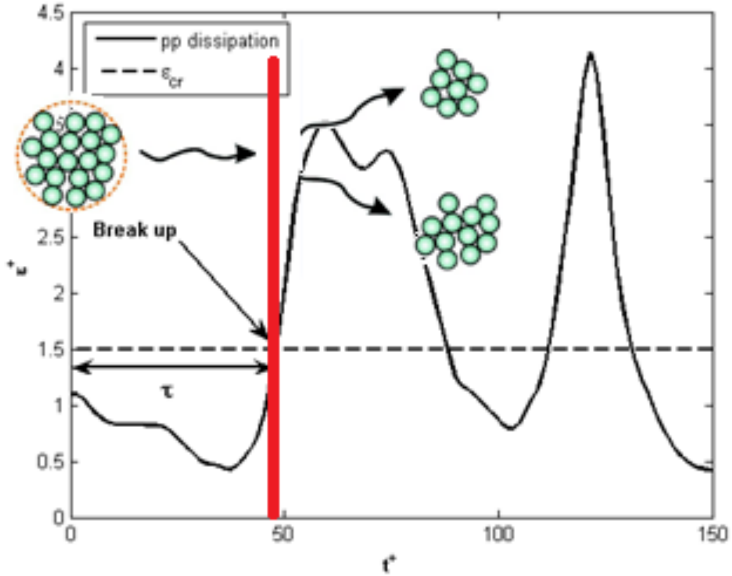
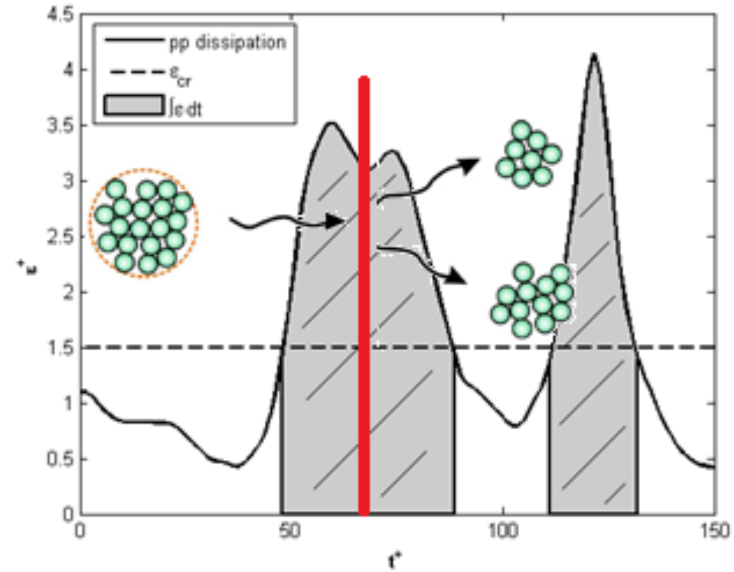
Open Question: "Ductility" effects on breakage rate?

Brittle vs Ductile aggregates





Brittle aggregates break immediately if:

$\varepsilon > \varepsilon_{cr}$ (power per unit mass)

Ductile aggregates break if:

- They start to deform: $\varepsilon > \varepsilon_{cr}$
- Deformation exceeds critical value:

$$E = \int_{\varepsilon > \varepsilon_{cr}} \varepsilon(t)dt > E_{cr}$$

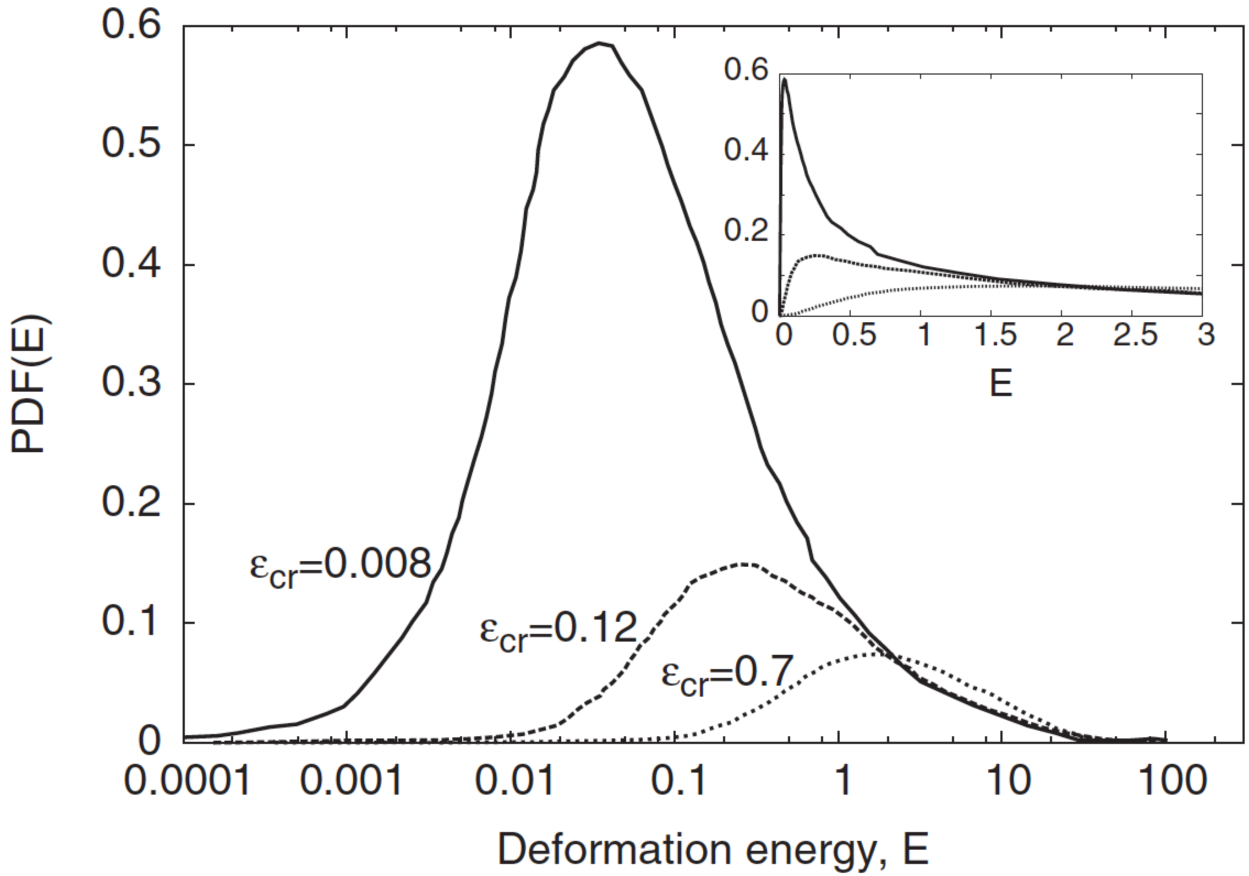
$$f(\varepsilon_{cr}) = \frac{1}{\langle \tau(\varepsilon_{cr}) \rangle}$$

Break-up rate

$$f(\varepsilon_{cr}, E_{cr}) = \frac{1}{\langle \tau(\varepsilon_{cr}, E_{cr}) \rangle}$$

Open Question: "Ductility" effects on breakage rate?

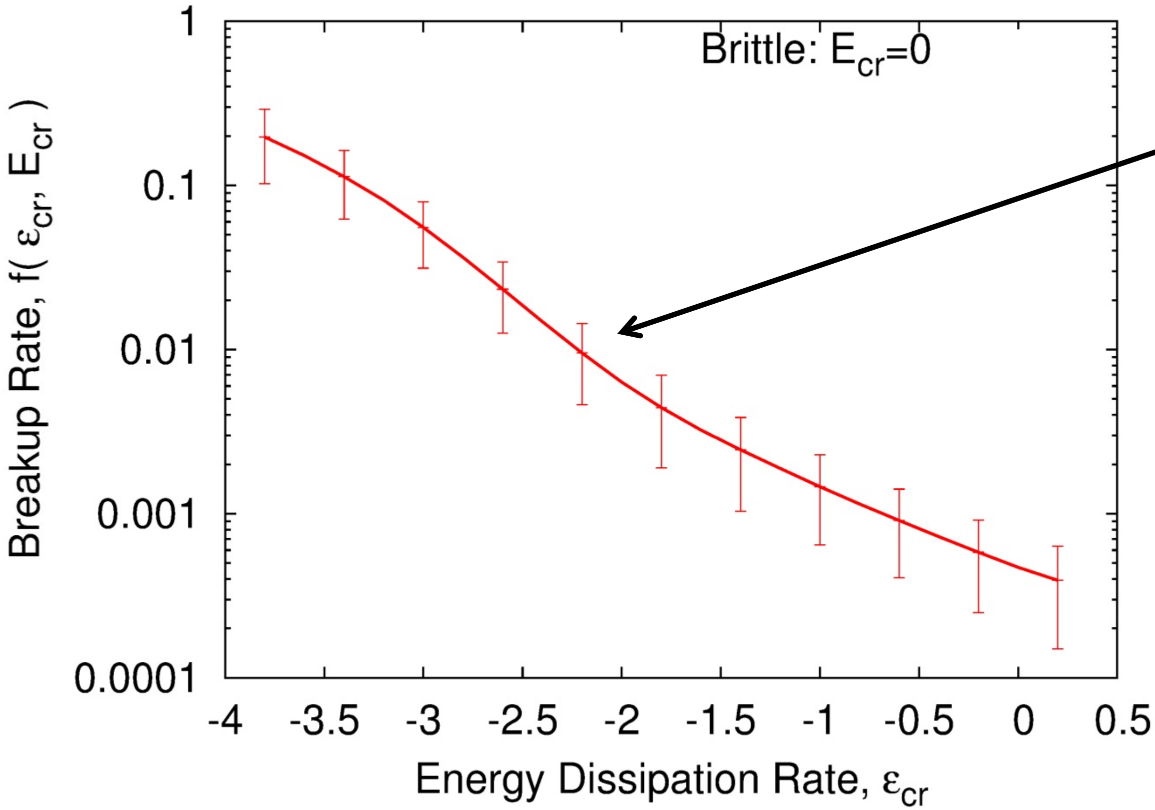
PDF of deformation energy in the channel

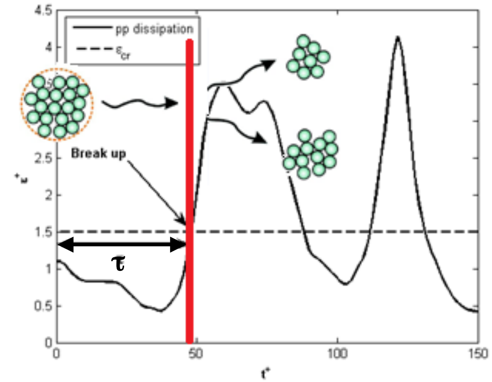


Results from: Marchioli & Soldati., *Phys. Rev. E* **91**, 053003 (2015)

Breakage of ductile aggregates
effect of "ductility"

note: aggregates released In the centerplane!





$$f(\varepsilon_{cr}, E_{cr}) = \frac{1}{\langle \tau(\varepsilon_{cr}, E_{cr}) \rangle}$$

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Breakage of ductile aggregates

effect of "ductility"

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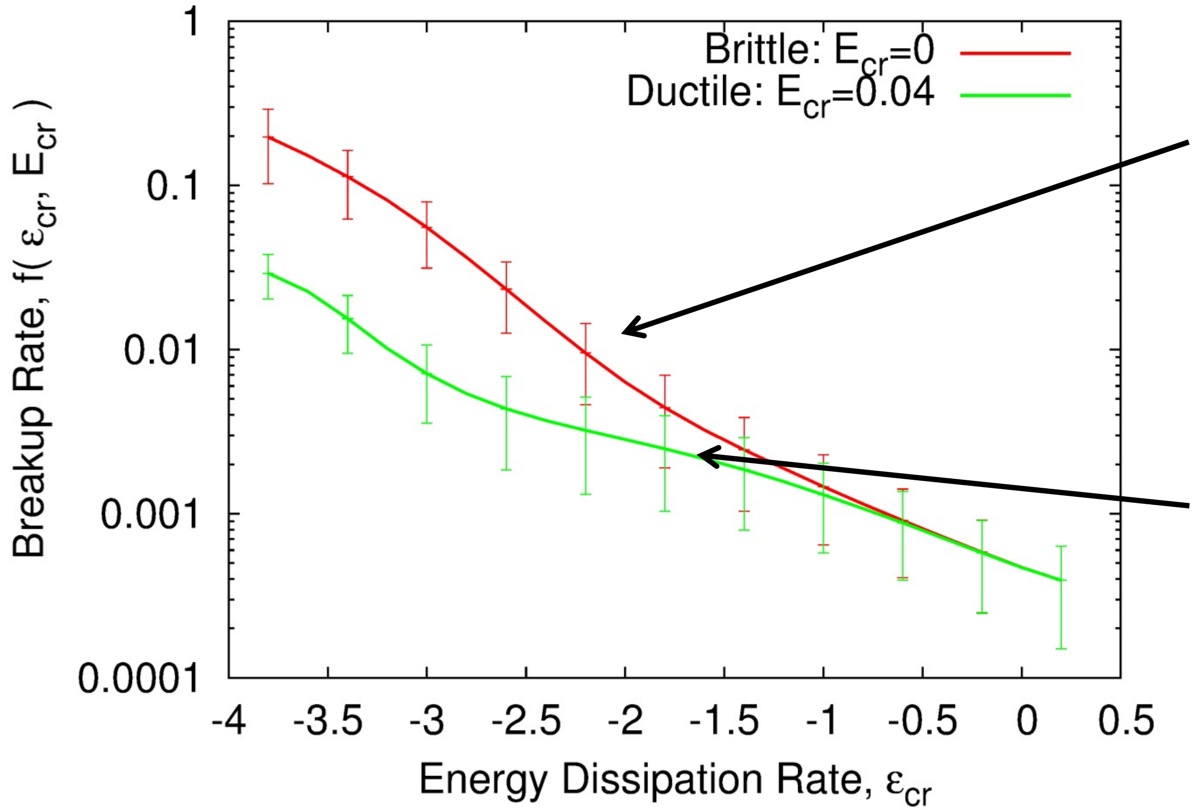

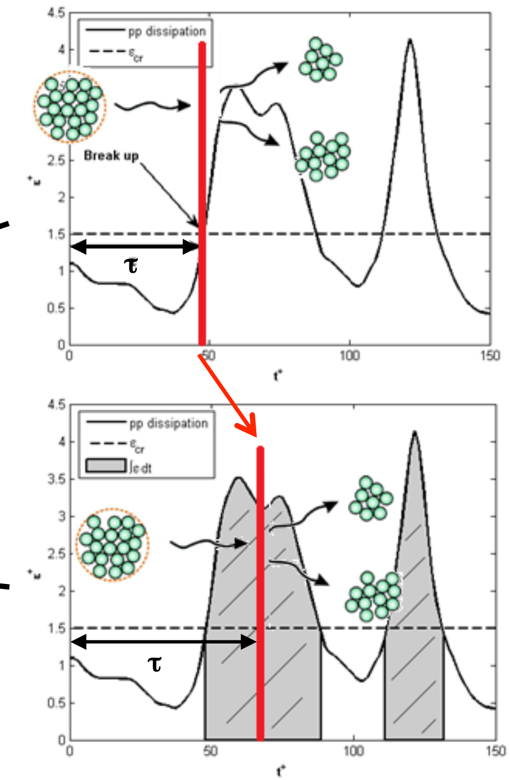

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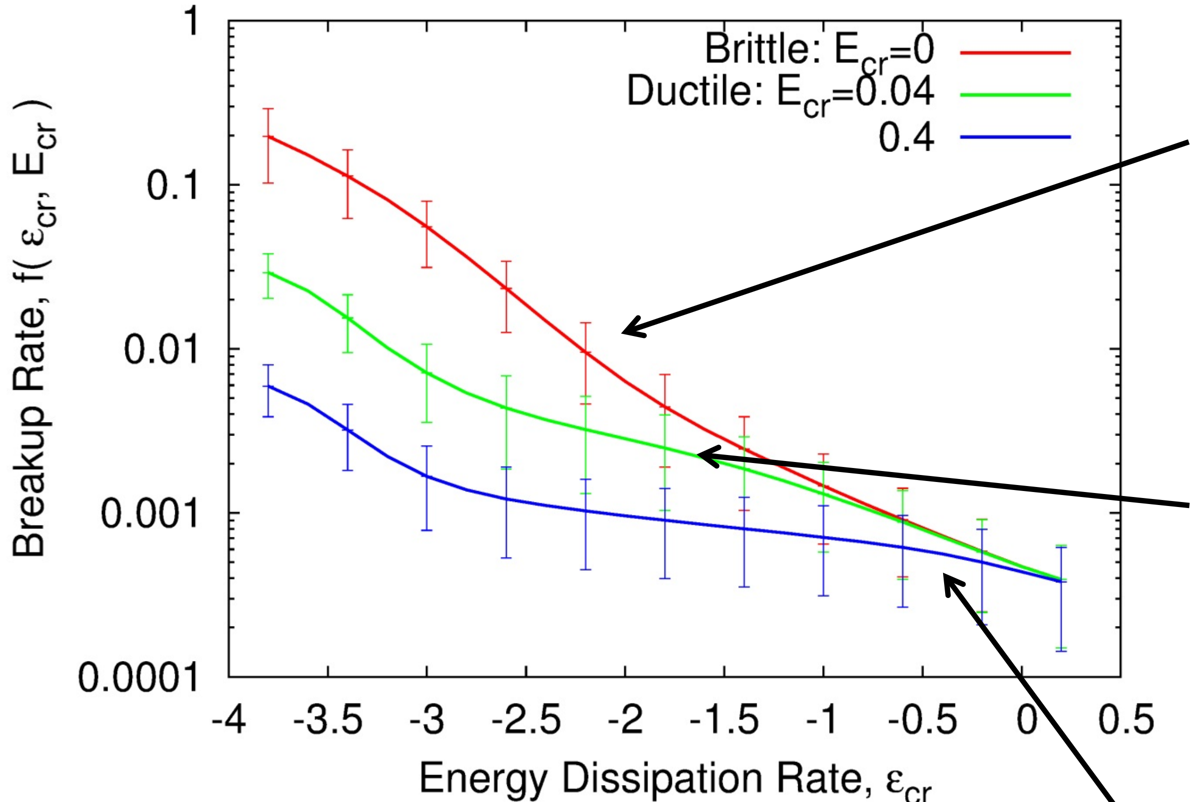
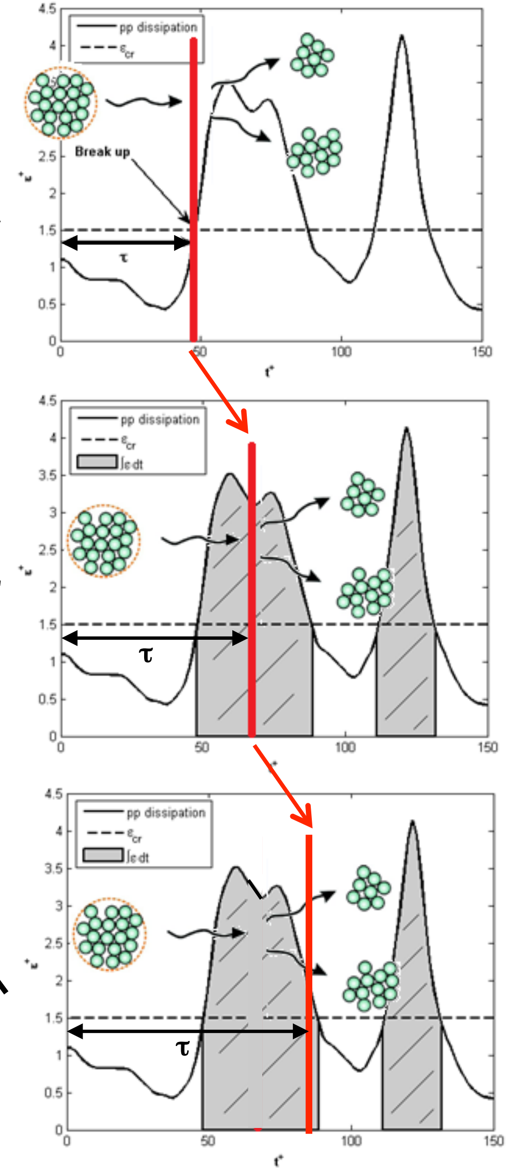
Breakage of ductile aggregates

effect of "ductility"

NOTE: AGGREGATES RELEASED IN THE CENTERPLANE!





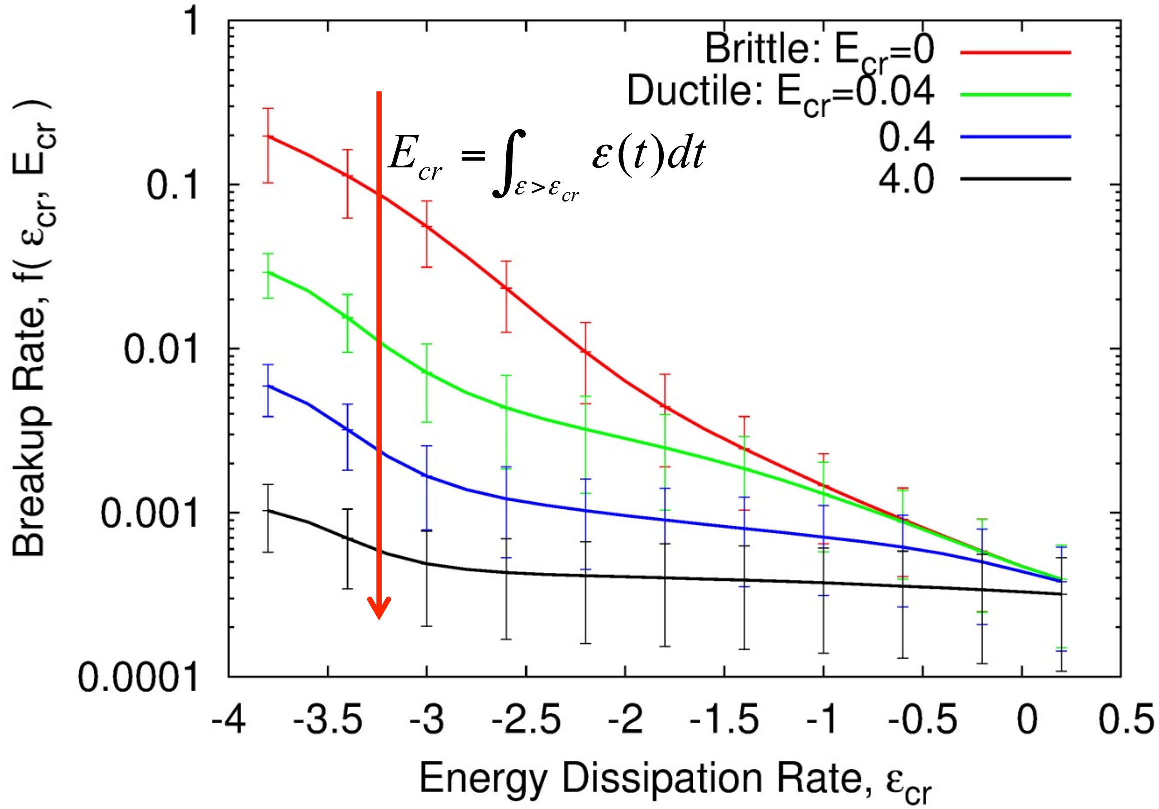
$$f(\varepsilon_{cr}, E_{cr}) = \frac{1}{\langle \tau(\varepsilon_{cr}, E_{cr}) \rangle}$$

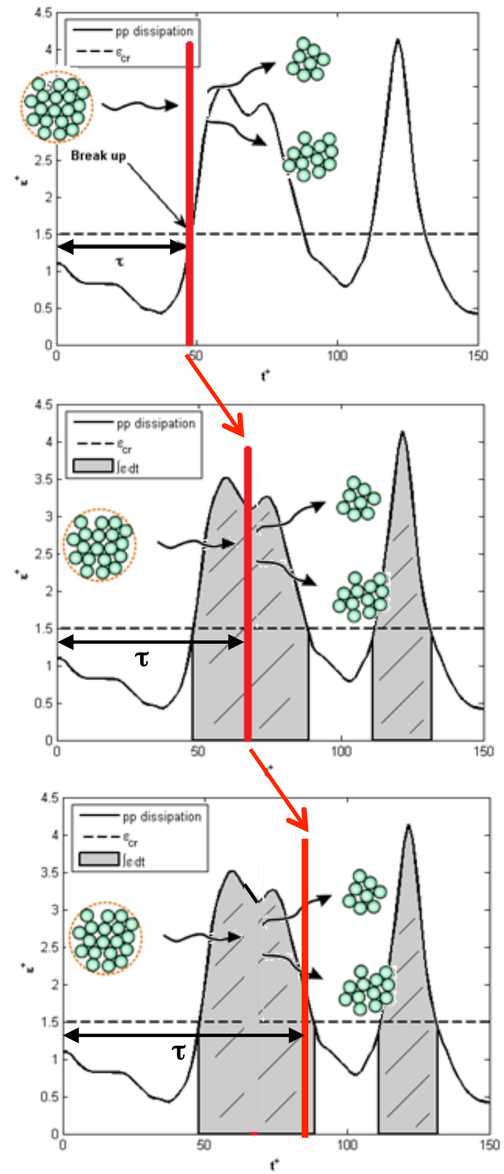
RESULTS FROM: MARCHIOLI & SOLDATI., *PHYS. REV. E* **91**, 053003 (2015)

Breakage of ductile aggregates

effect of "ductility"

note: aggregates released In the centerplane!

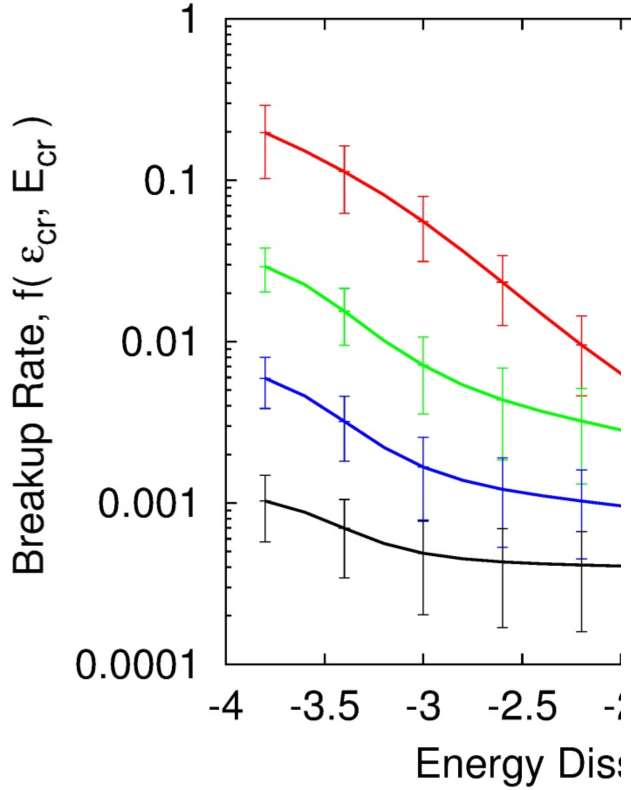




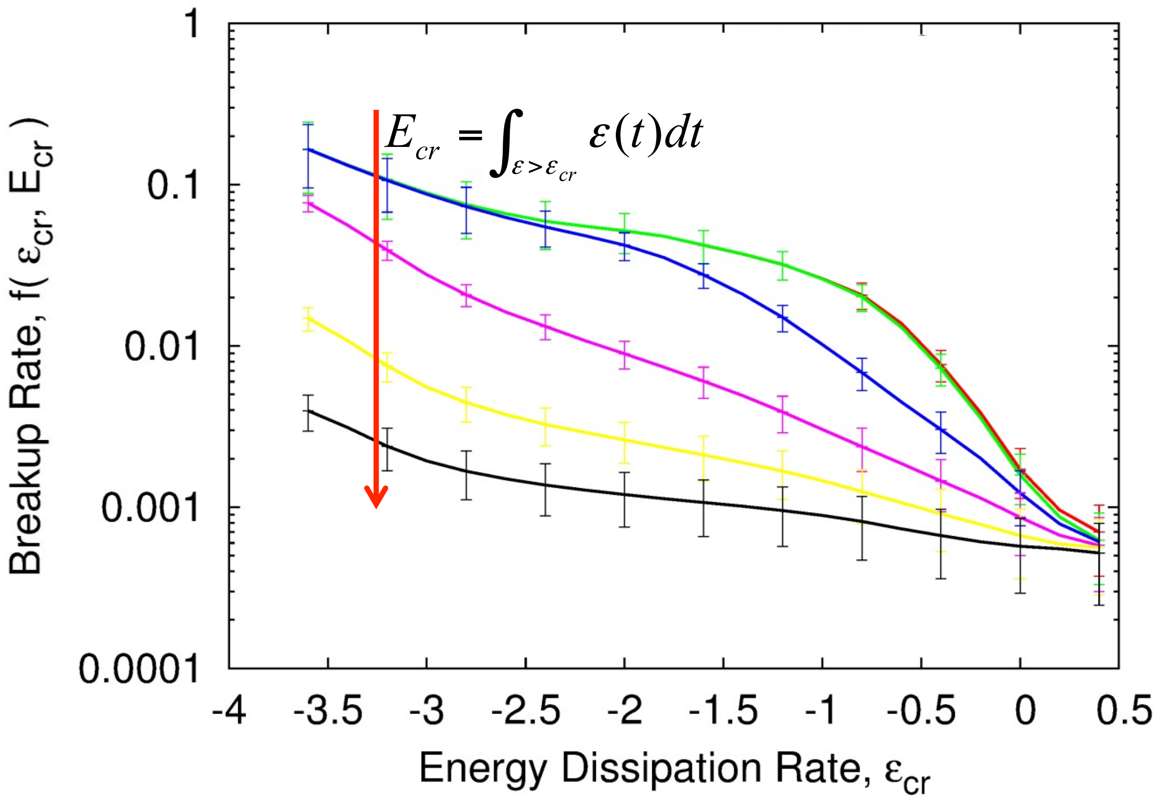
$$f(\varepsilon_{cr}, E_{cr}) = \frac{1}{\langle \tau(\varepsilon_{cr}, E_{cr}) \rangle}$$

Results from: Marchioli & Soldati., *Phys. Rev. E* **91**, 053003 (2015)

Breakage of ductile aggregates effect or seeding region



Breakage rate for aggregates released In the near-wall region



Results from: Marchioli & Soldati., *Phys. Rev. E* 91, 053003 (2015)

Concluding remarks

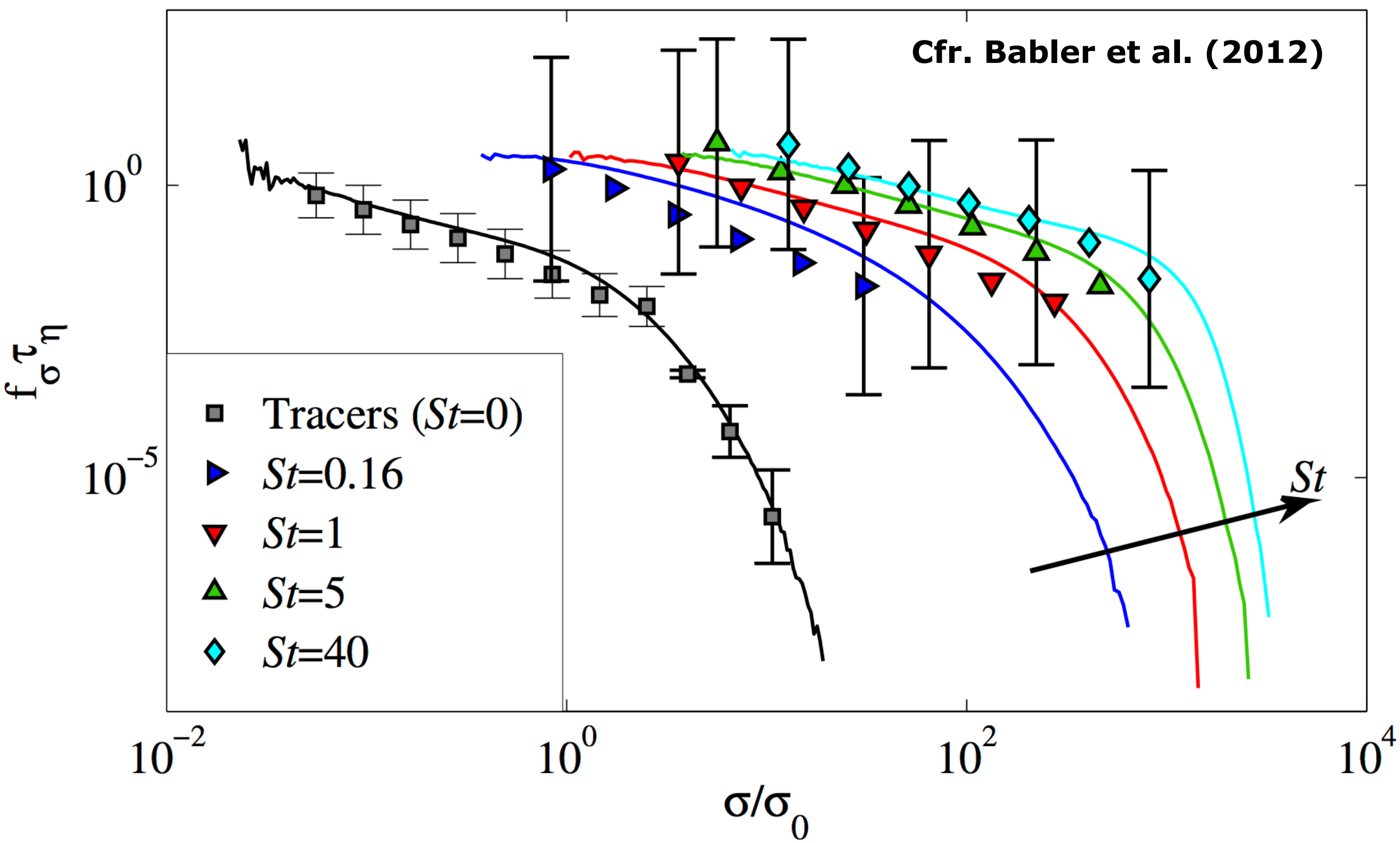
- A simple method for measuring breakage of small (tracer-like) aggregates driven by local hydrodynamic stress has been applied to non-homogeneous anisotropic dilute turbulent flow.
- The breakage rate of small brittle aggregates shows power law behavior for small stress (small energy dissipation events).
- The breakage rate of small ductile aggregates is lower and levels off when strong deformation is required to break the aggregate.
- Flow anisotropy has a strong effect on breakage rate via its effect on energy dissipation rate and deformation events to which the aggregates are exposed.
- Future development: Extension to heavy (inertial) aggregates

$$\sigma = \sqrt{\frac{2}{15}\varepsilon} + \frac{3}{2}\frac{|\mathbf{v}_{rel}|}{d_p} \longrightarrow \sigma = \frac{\partial u_i'}{\partial x_j} + \frac{3}{2}\frac{|\mathbf{v}_{rel}|}{d_p}$$

Another Open Question: inertial effects on break-up rate

Tracer-like vs Inertial aggregates

$$\sigma \sim \mu(\varepsilon/\nu)^{1/2} + \mu|v_{rel}|/d_p$$



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