Fragmentation of bubbles in turbulence by small eddies

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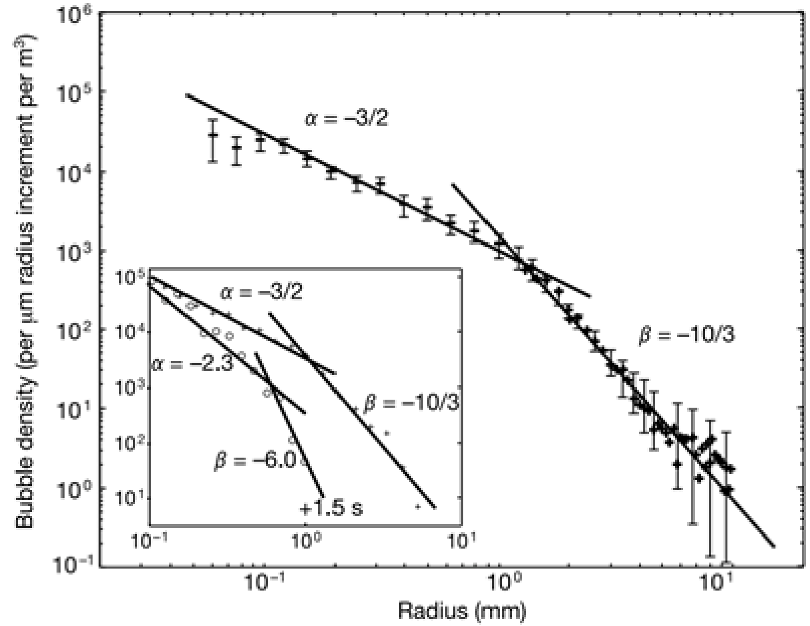
Fragmentation in turbulence

Breaking wave



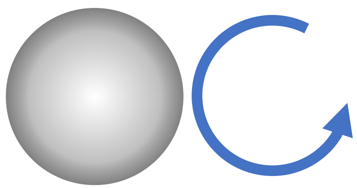
Fragmentation ⟶ Size spectrum ⟶ Interfacial area (mass transfer)
Rise velocity (lifetime)
Dispersion

Villermaux *Annu. Rev. Fluid Mech.* (2007)
Enders, et al. *Marine pollution bulletin* (2015)
Li, C., et al. J. Geophys. Res.: Oceans 122.10 (2017): 7938-7957.
Dean & Stokes. Nature. (2002)

Kolmogorov-Hinze (KH) framework

Kolmogorvo 1949;
Hinze 1955;

Basic assumption: bubble is broken by the eddy with similar size



KH theory --> bubble size is the only scale in the breakup problem

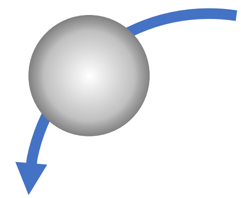
$$We = \frac{\rho u^2 D}{\sigma} \sim \frac{\rho (\epsilon D)^{2/3} D}{\sigma} = \frac{\rho \epsilon^{2/3} D^{5/3}}{\sigma}$$

$We > 1$, breakups happen.

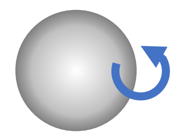
The critical Weber number We_{cr}

$$We_{cr} \sim [0.59, 7.8]$$

Large eddies only advect the bubble without deforming it



Small eddies effect can be filter by the bubble

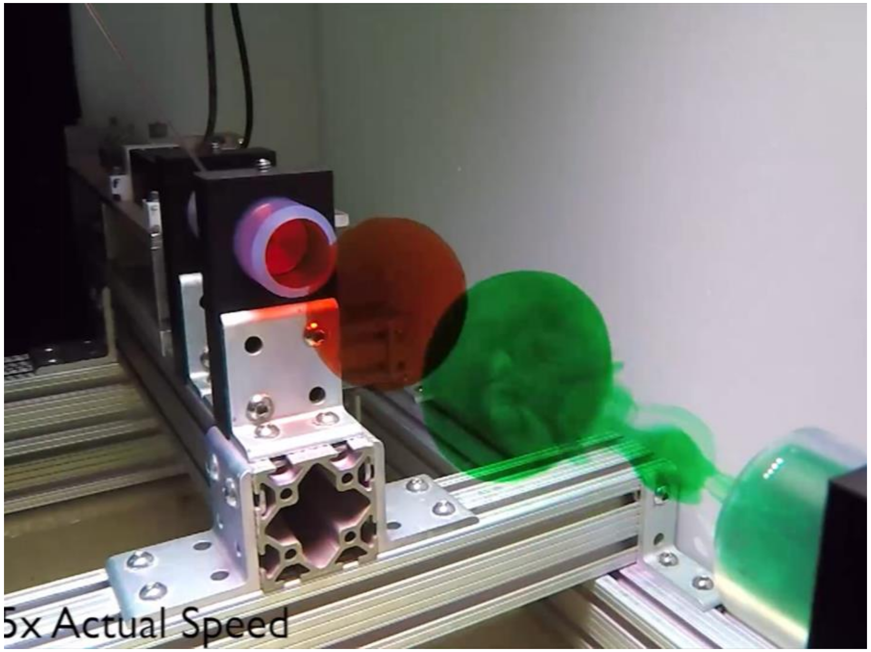


Is this right?

Can we ignore small eddy contribution?

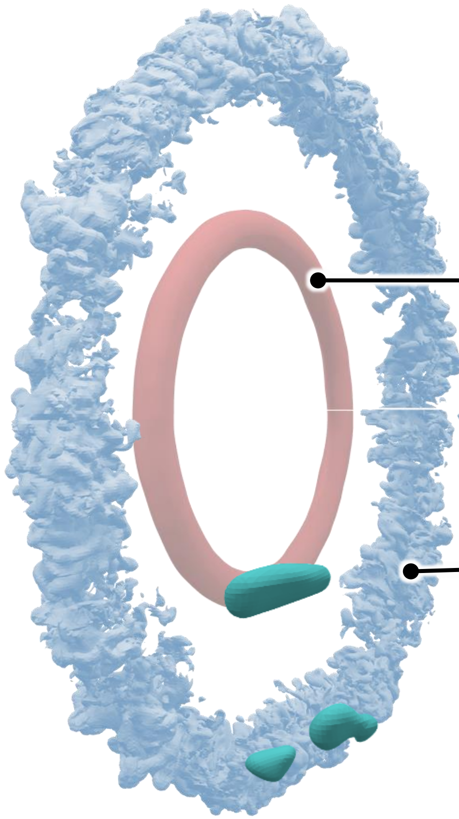
Sevik & Park 1973; Deane & Stokes 2002; Martinez-Bazan et al.1999; Risso & Fabre 1998

Introduction to the vortex ring collision



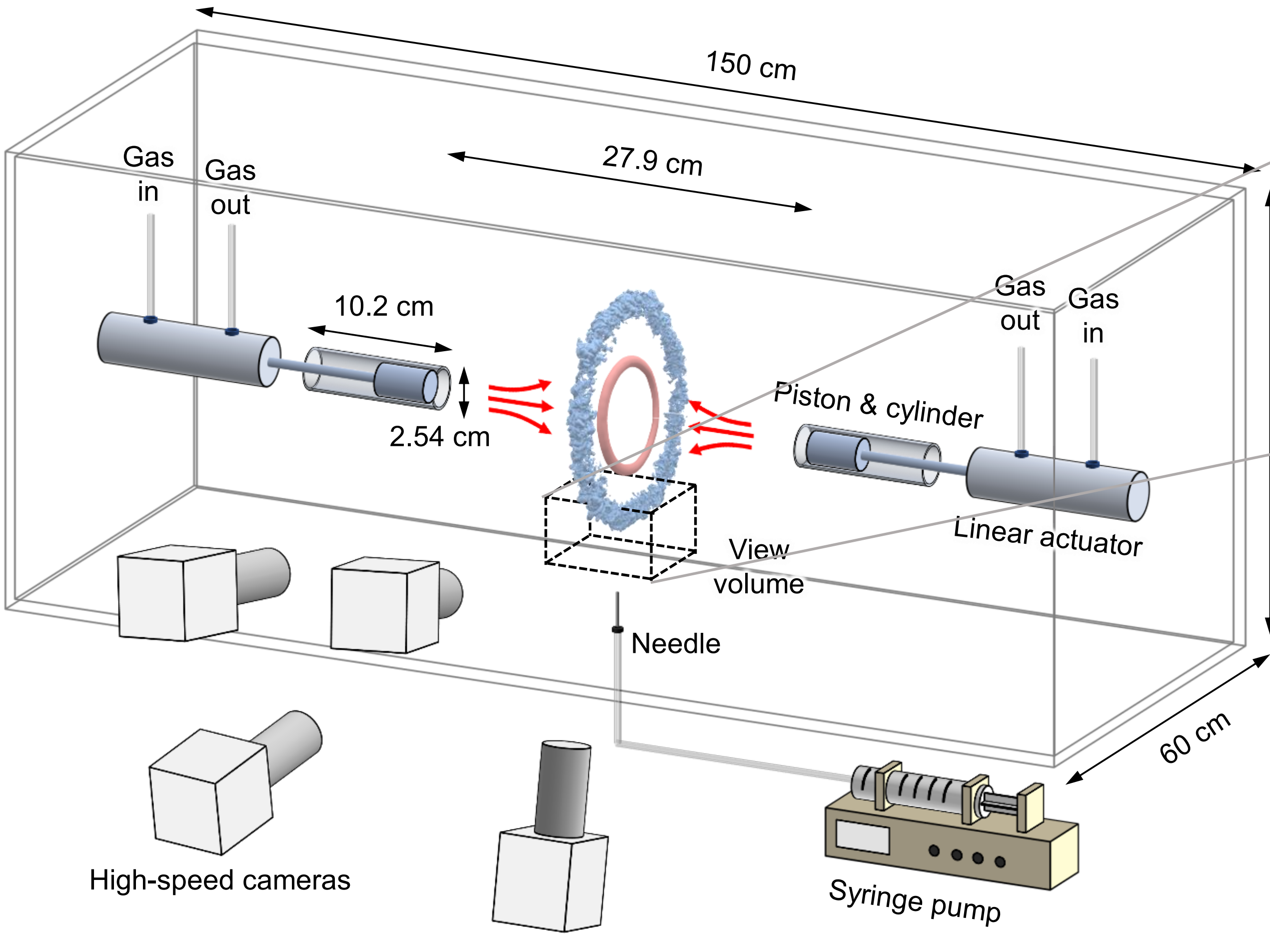
McKeown et al. 2018. PRF

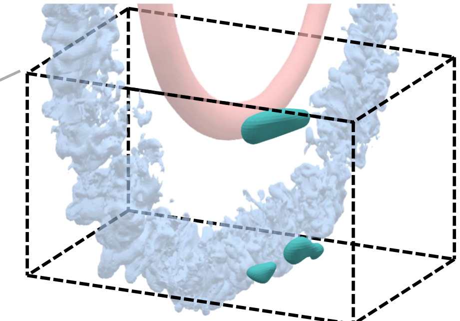
Instability leads to two stages
From large scale to small scale



credit: Rodolfo Ostilla Monico (University of Houston)

Experimental setup





Shake the box

⬇

Particle trajectory

Visual hull method

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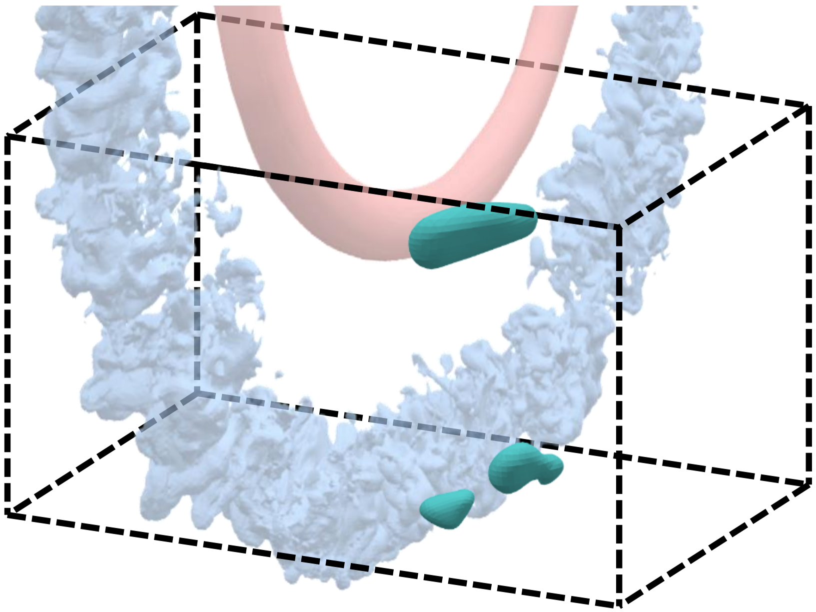
Bubble geometry and breakup

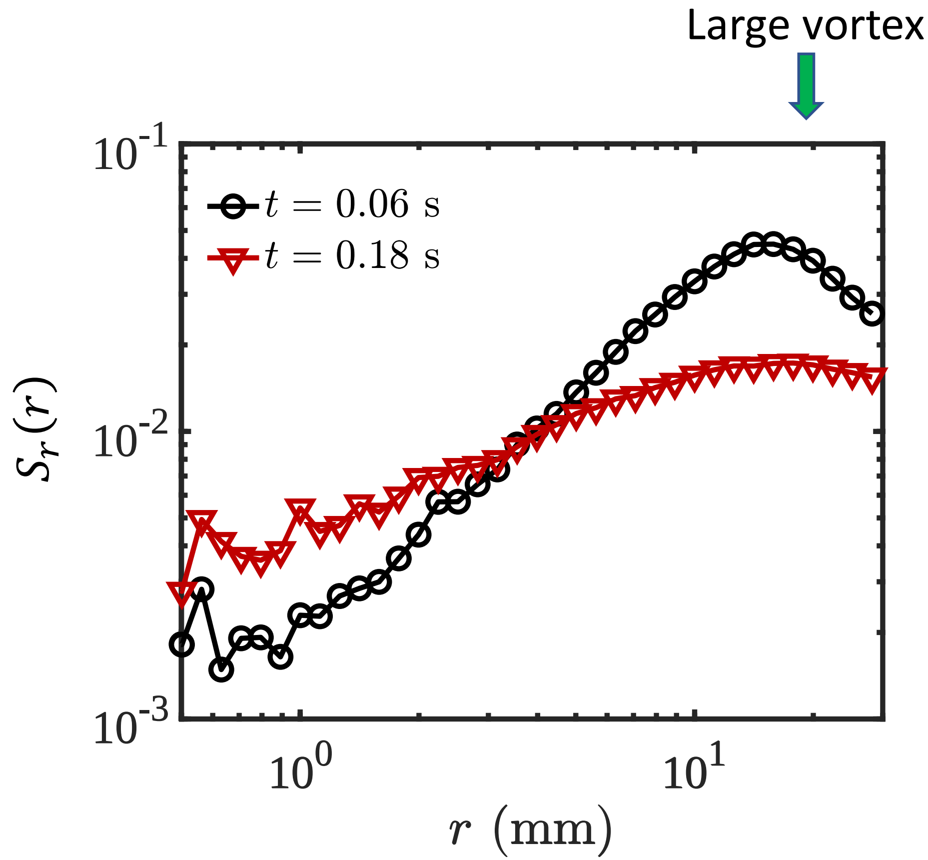
Linear actuator, syringe pump and cameras are all synchronized.

Tan et al. 2020., Mausk et al. 2019.

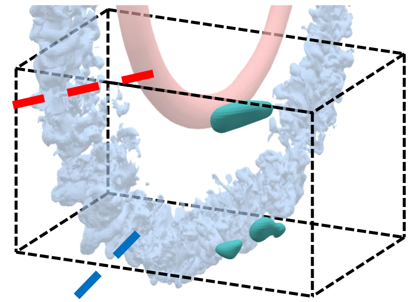
From large to small scale

$$S_r(r) = \langle [u(x+r) - u(x)]^2 \rangle$$

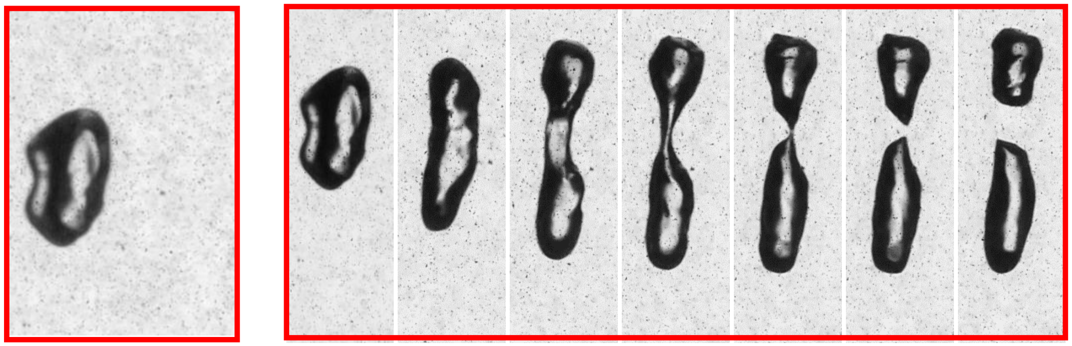




Bubble breakup modes

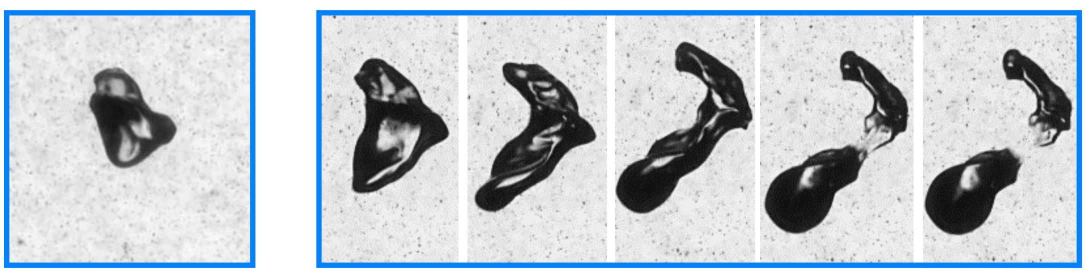


Primary breakup (slow and moderate)

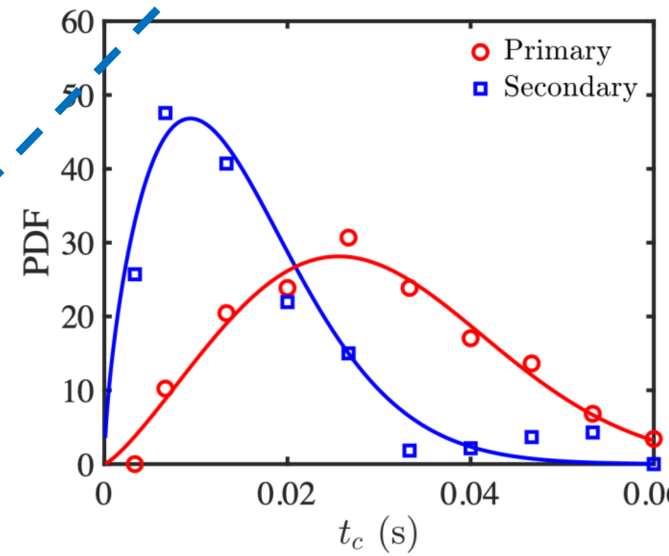


$t_c = 34$ ms

Secondary breakup (rapid and violent)



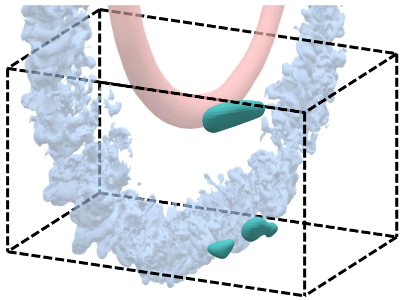
$t_c = 5$ ms



Breakup time PDF

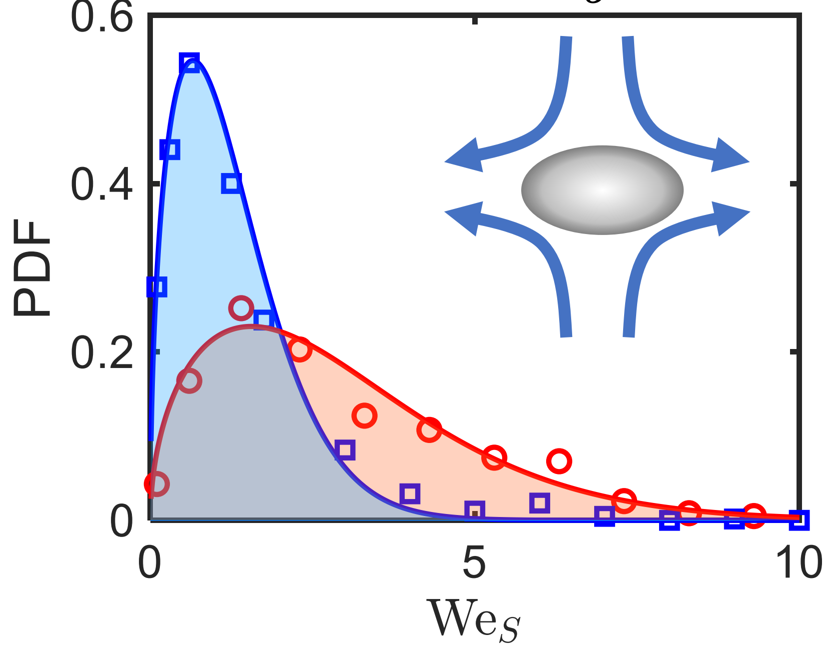
Can KH theory explain this?

Weber number (Kolmogorov-Hinze)

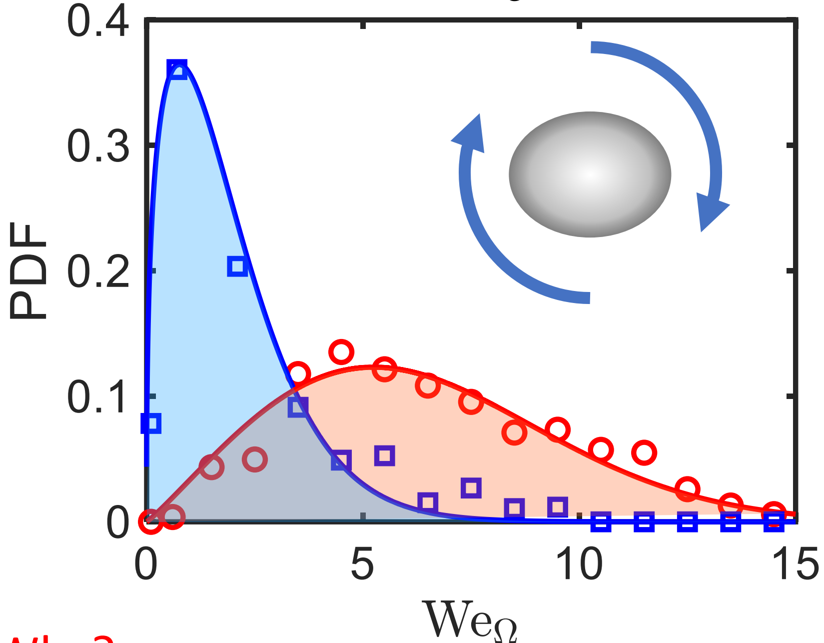


Weber number around the bubble

$$We_S = \frac{\rho(\lambda_3 D)^2 D}{\sigma}$$



$$We_\Omega = \frac{\rho(\omega D)^2 D}{\sigma}$$



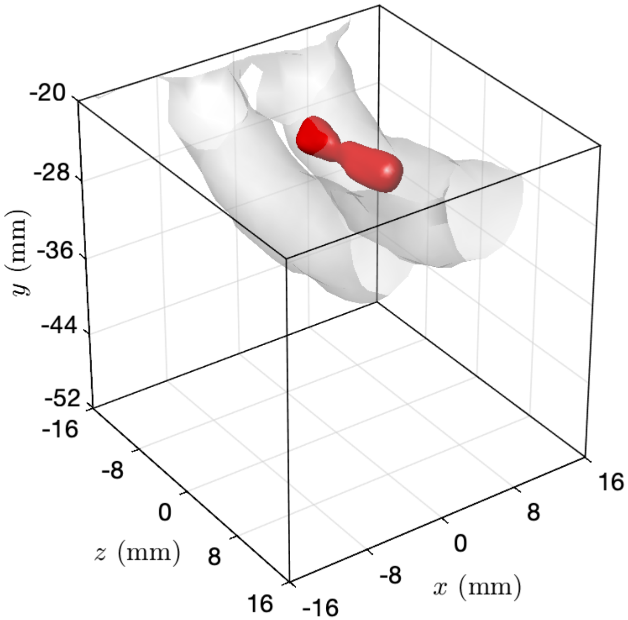
Secondary breakups generally have smaller weber number

Why?

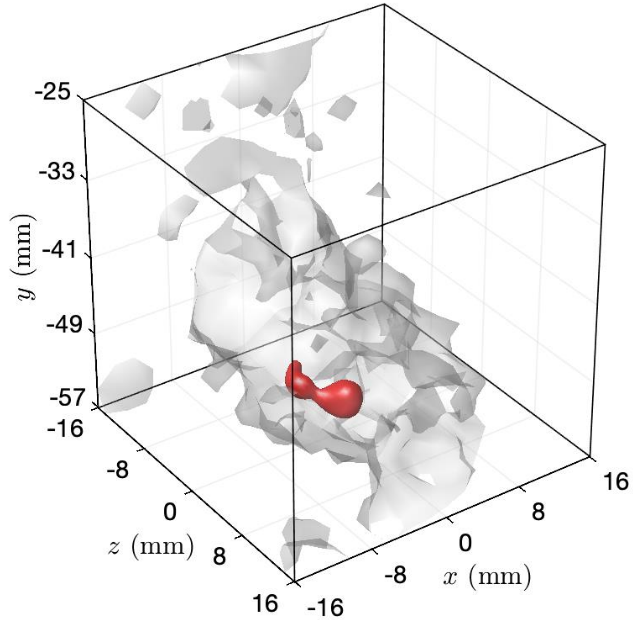
Secondary breakups are more violent. Expect larger Weber number

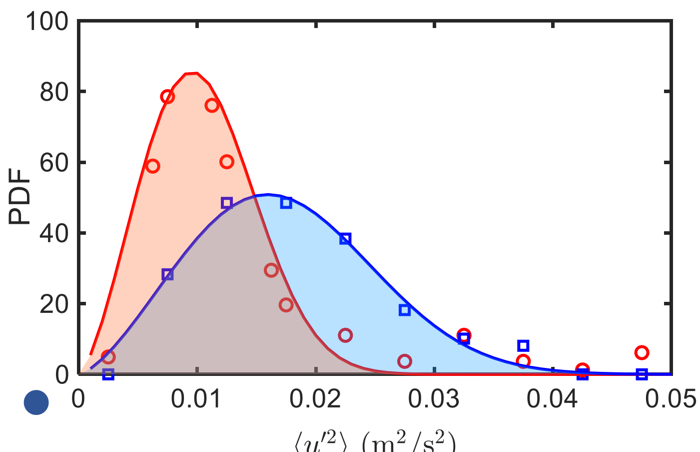
Flow around the bubble

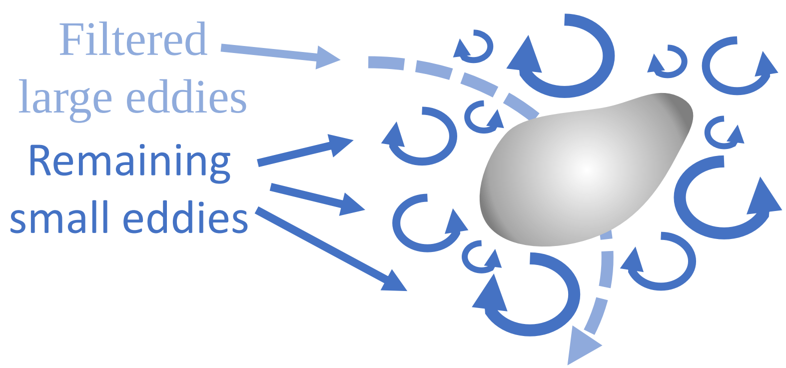
Primary breakup



Secondary breakup







How to improve KH framework

A new breakup model

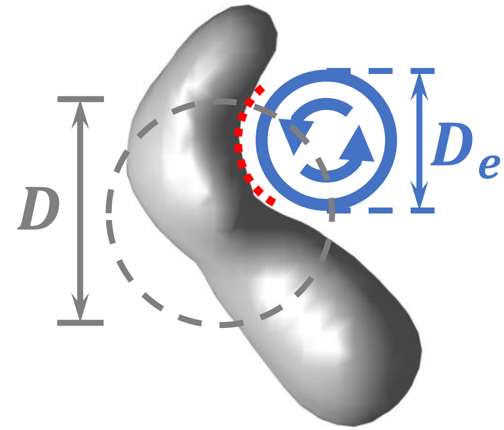
Stress criterion:

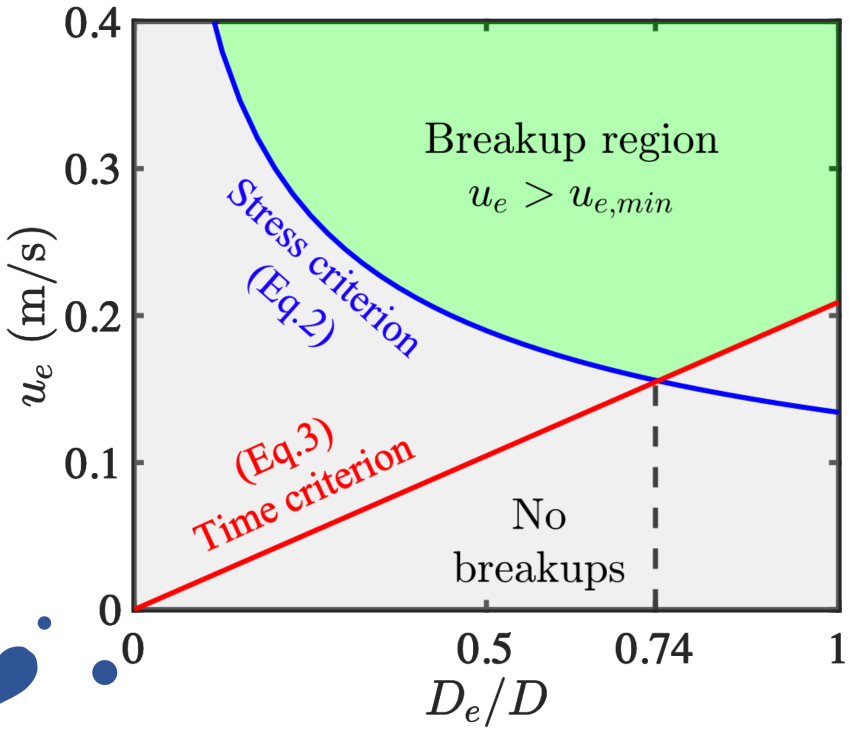
$\rho u_e^2 > \sigma / D_e$

Time criterion:

$D_e / u_e < 2\pi\sqrt{\rho D^3 / 96\sigma}$

$$\begin{cases} \dfrac{\rho u_e^2 D_e}{\sigma} > 1 \\[2ex] \dfrac{\rho u_e^2 D^3 / D_e^2}{\sigma} > \dfrac{96}{4\pi^2} \end{cases}$$





Minimum eddy velocity required to break a bubble

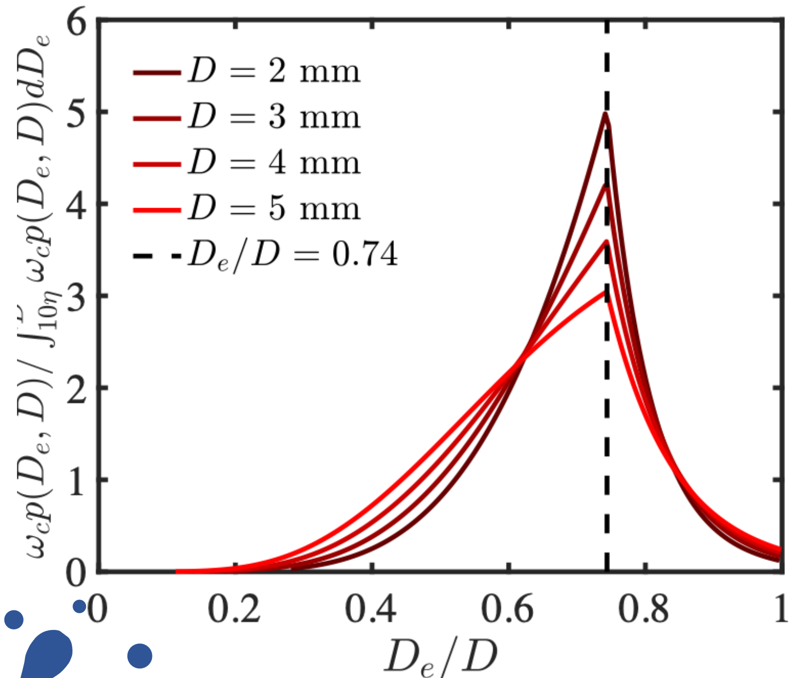
$$u_{e,min}(D_e, D) = \max\left(\sqrt{\frac{\sigma}{\rho D_e}}, \sqrt{\frac{96}{4\pi}\frac{\sigma}{\rho D^3/D_e^2}}\right)$$

Eddy contribution

Distribution of dissipation rate $$P(\epsilon_e) = \frac{1}{\epsilon_e}\frac{1}{\sqrt{2\pi\sigma^2_{\ln\epsilon}}}\exp\left[-\frac{\left(\ln\left(\epsilon_e/\langle\epsilon\rangle\right)+\sigma^2_{\ln\epsilon}/2\right)^2}{2\sigma^2_{\ln\epsilon}}\right]$$

Distribution of eddy velocity $$P(u_e|D_e) = \frac{3\sqrt{2}}{2}\epsilon_e^{2/3}D_e^{-1/3}P(\epsilon_e)$$

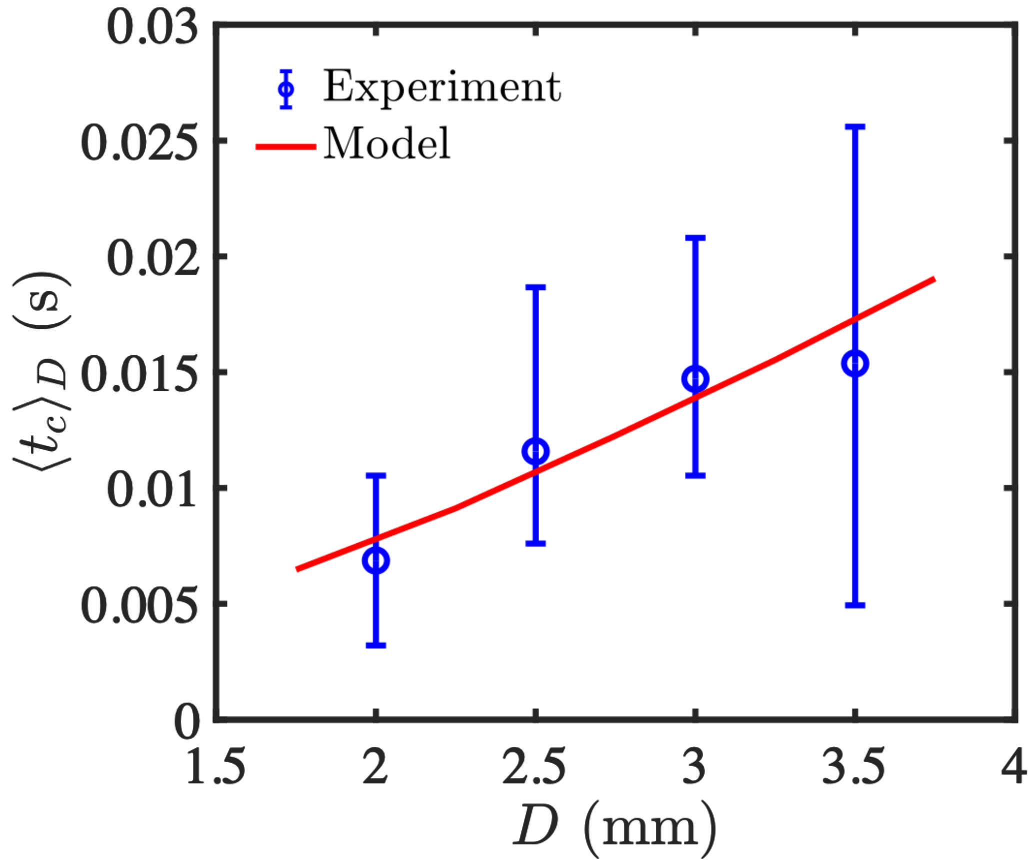
Considering collision frequency



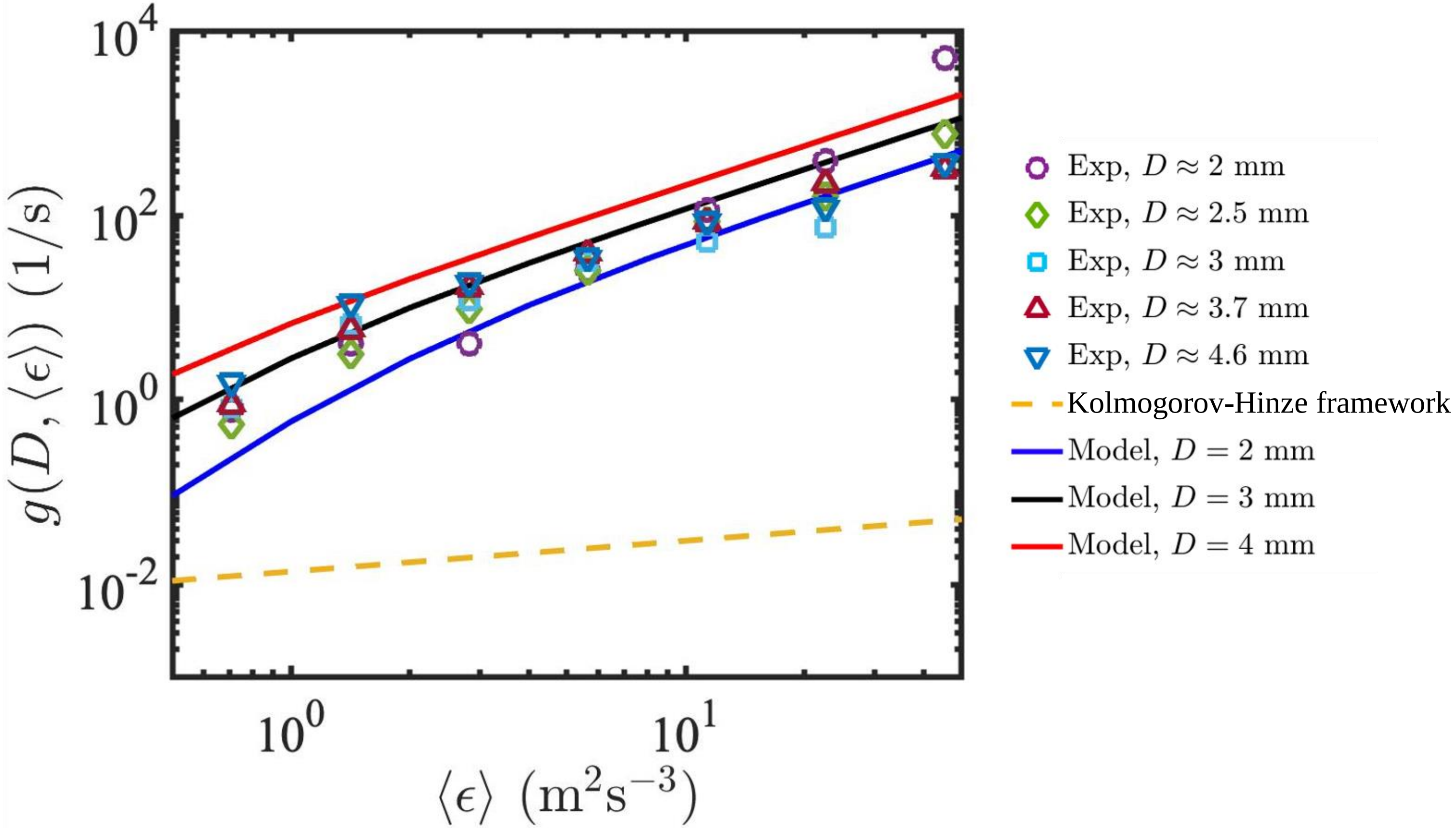
Sub-bubble-scale eddies are more important for bubble fragmentation.

Meneveau & Sreenivasan 1991
Kolmogorov 1962

Our experiment (vortex ring collision)



Fully-developed turbulence



Vejrazka et al. 2018

Summary

- Vortex ring collision provides a magic knife to separate different eddy scale
- Secondary breakups with smaller Weber number exhibit violent breakup mode
- Sub-bubble scale eddies play an important role in breakups
- A new bubble breakup model is proposed considering the eddy scale