Formation of sub-Hinze scale bubbles in turbulence and bubble dynamics under breaking waves

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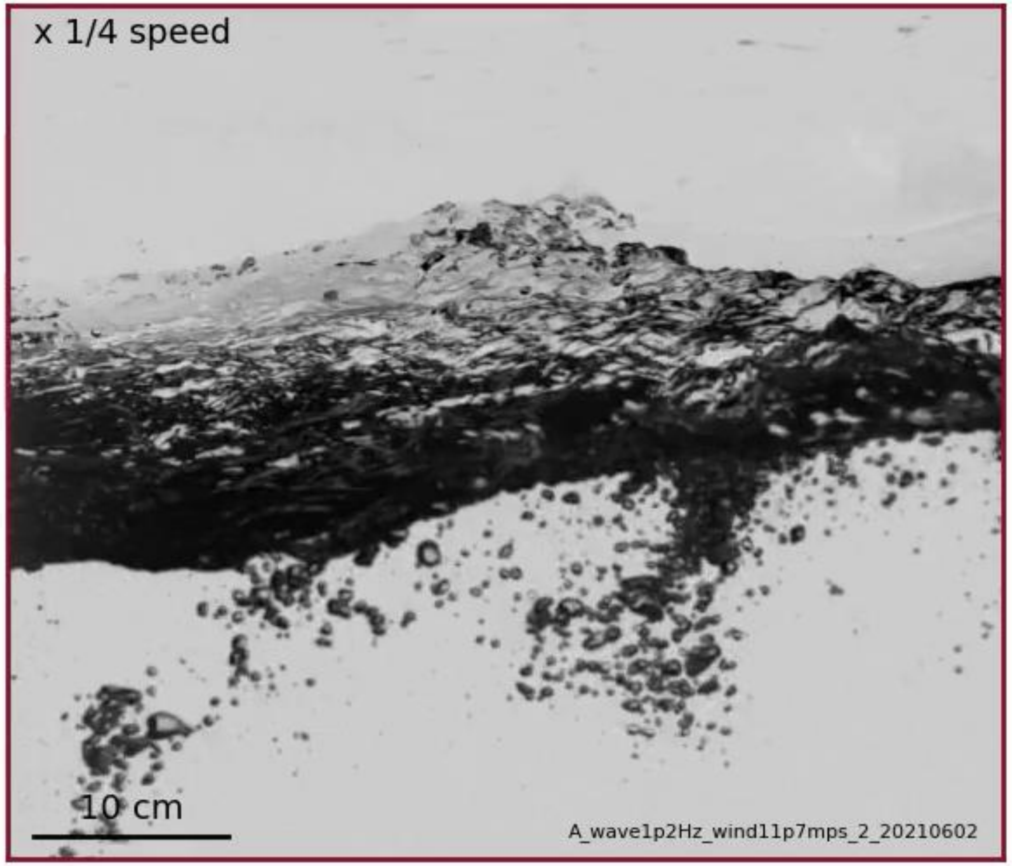
The 8th International Symposium on Gas Transfer at Water Surfaces

May 2022

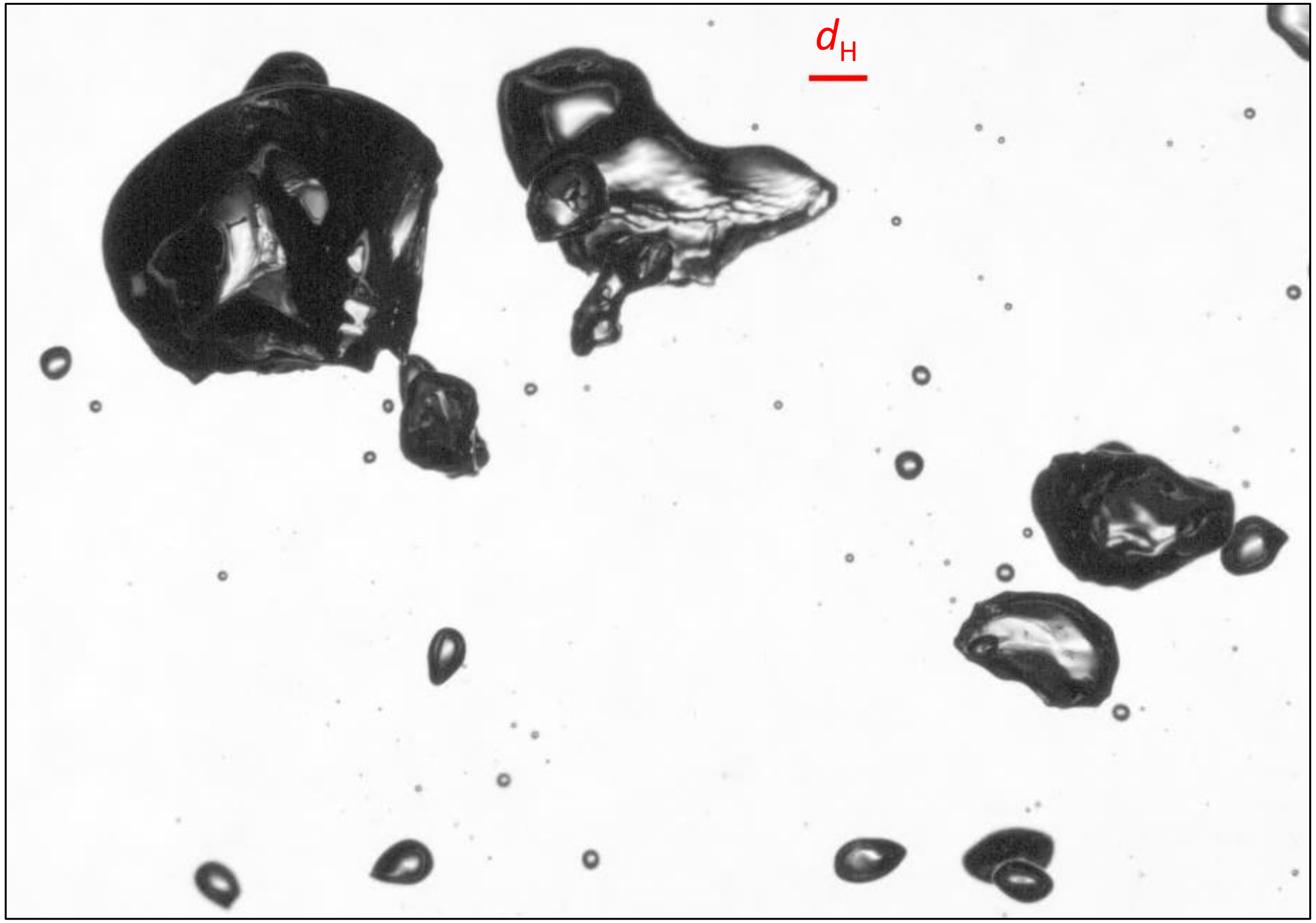
PRINCETON UNIVERSITY

Entrained bubbles experience a **turbulent flow** induced by the breaking wave



Mostert, W., Popinet, S., & Deike, L. (2022). **High-resolution direct simulation of deep water breaking waves: transition to turbulence, bubbles and droplets production.** (Manuscript in press at *Journal of Fluid Mechanics*.)

Bubbles formed by **wave breaking**



turbulence, surface tension effects are **balanced** at the **Hinze scale**[1],

$d_H \sim \varepsilon^{-2/5} (\sigma / \rho)^{3/5}$

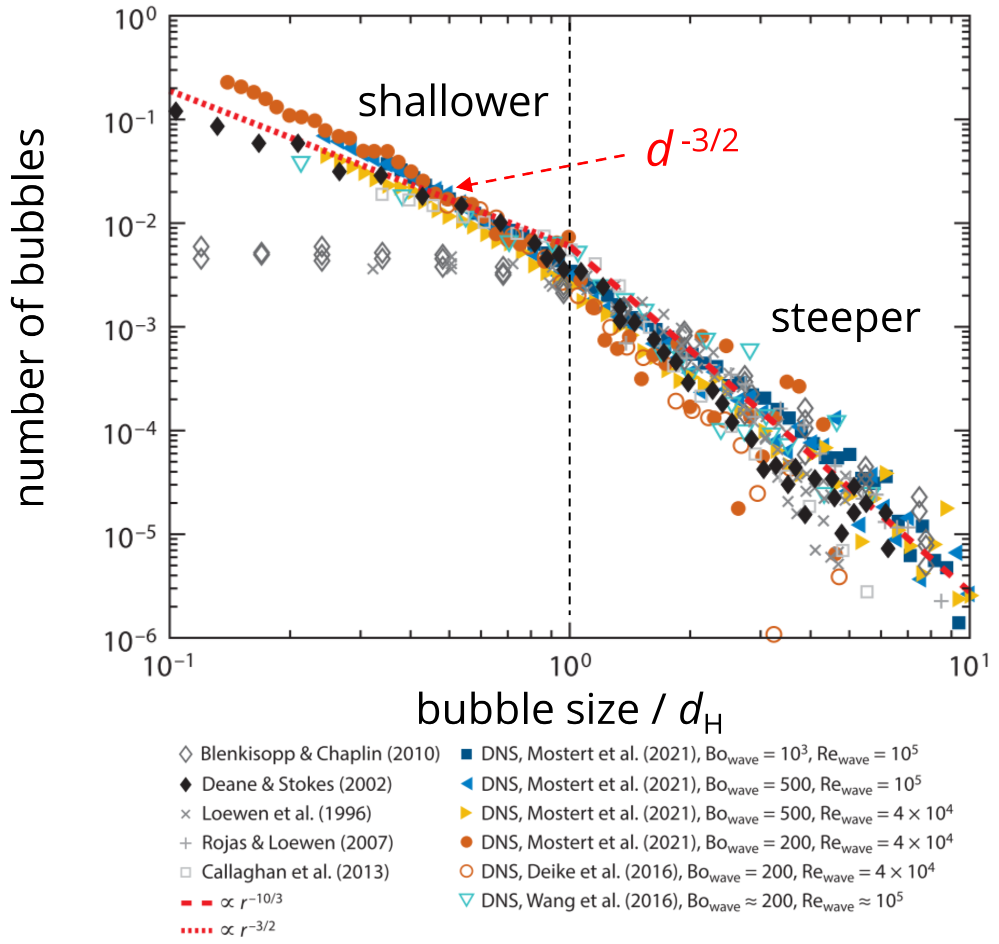
small bubbles: surface tension prevents break-up

large bubbles: broken apart by turbulence

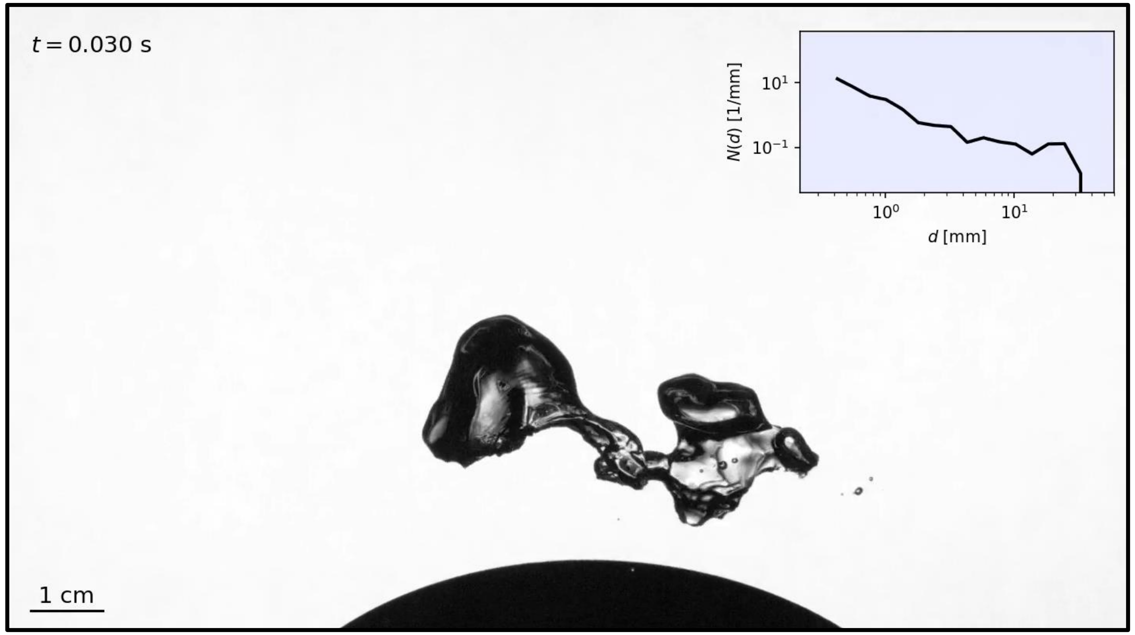
d_H

bubble size

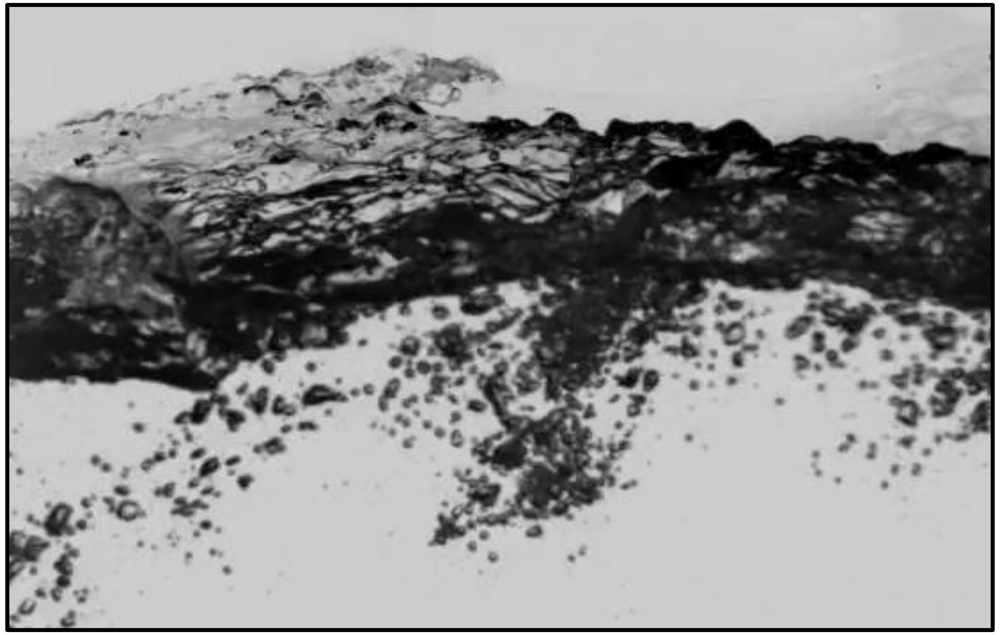
Bubbles formed by **wave breaking**



Deike, L. (2022). **Mass transfer at the ocean–atmosphere interface: The role of wave breaking, droplets, and bubbles.** *Annual Review of Fluid Mechanics*, *54*, 191-224.

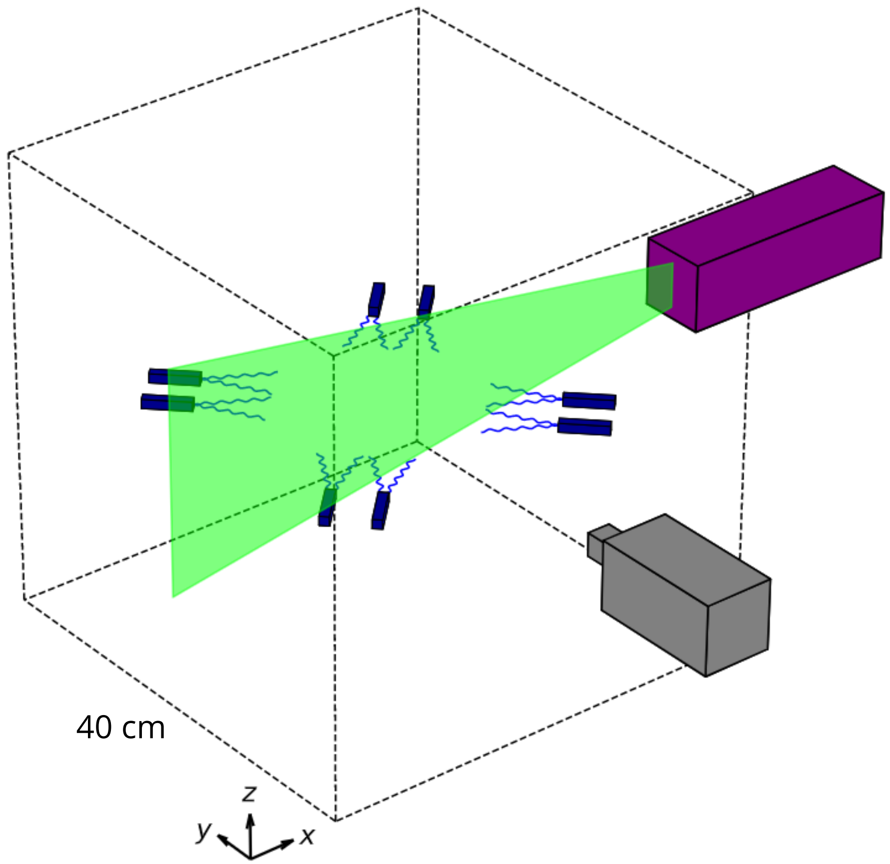


How do bubbles **break up** in turbulence?

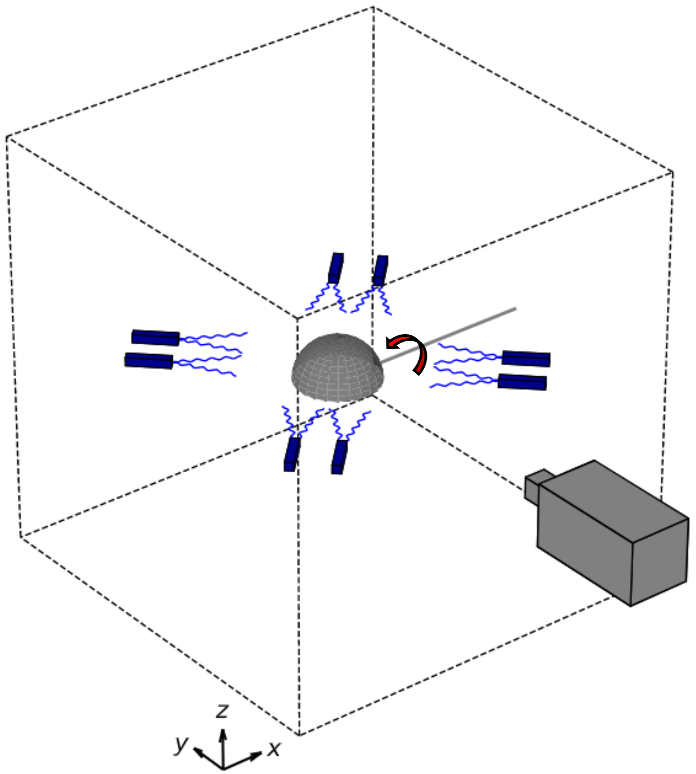


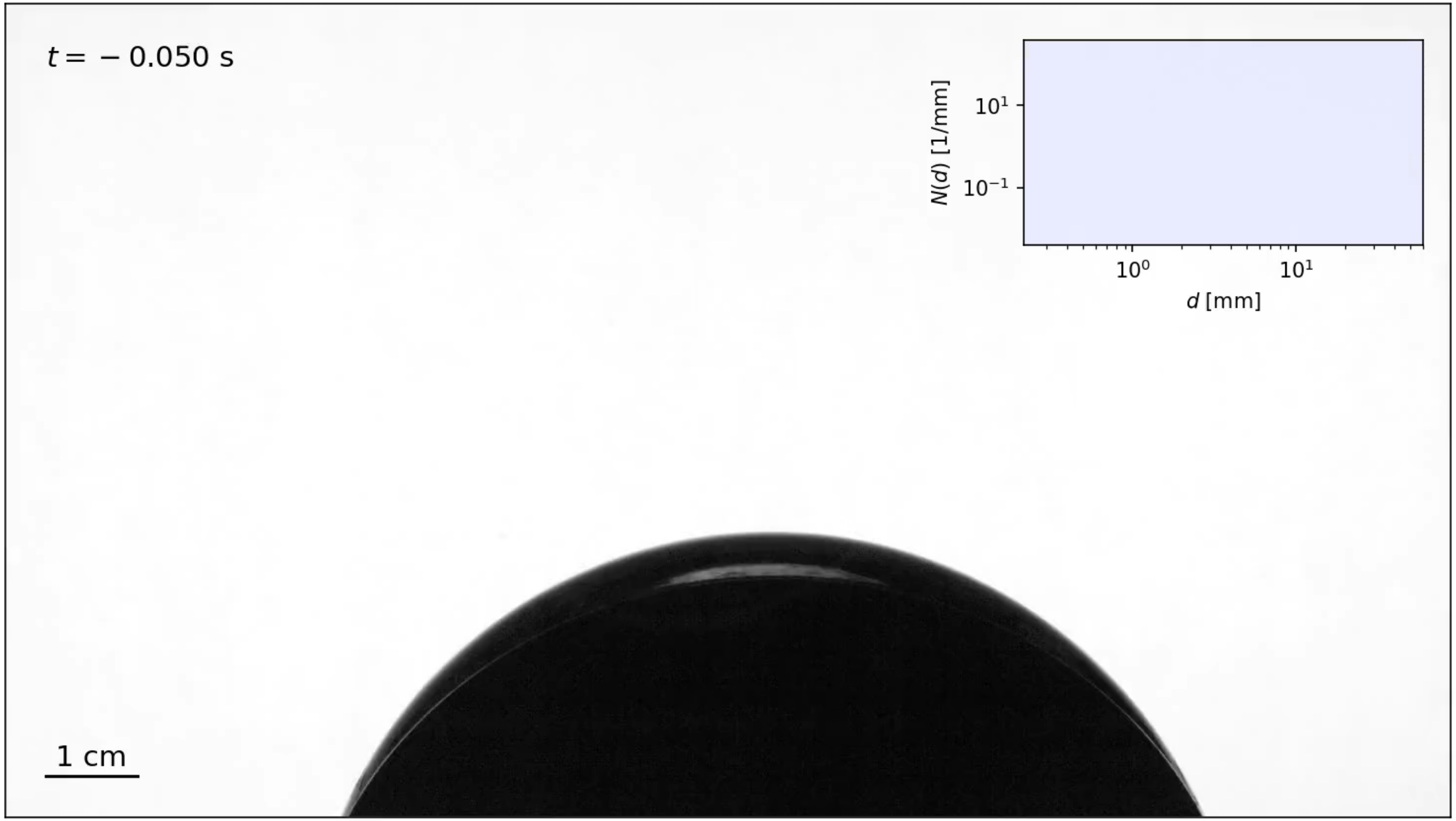
How are bubbles **entrained** and **transported** by **breaking waves**?

Turbulence generation



A population of **child bubbles** is created when a large **parent bubble** is exposed to **turbulence**

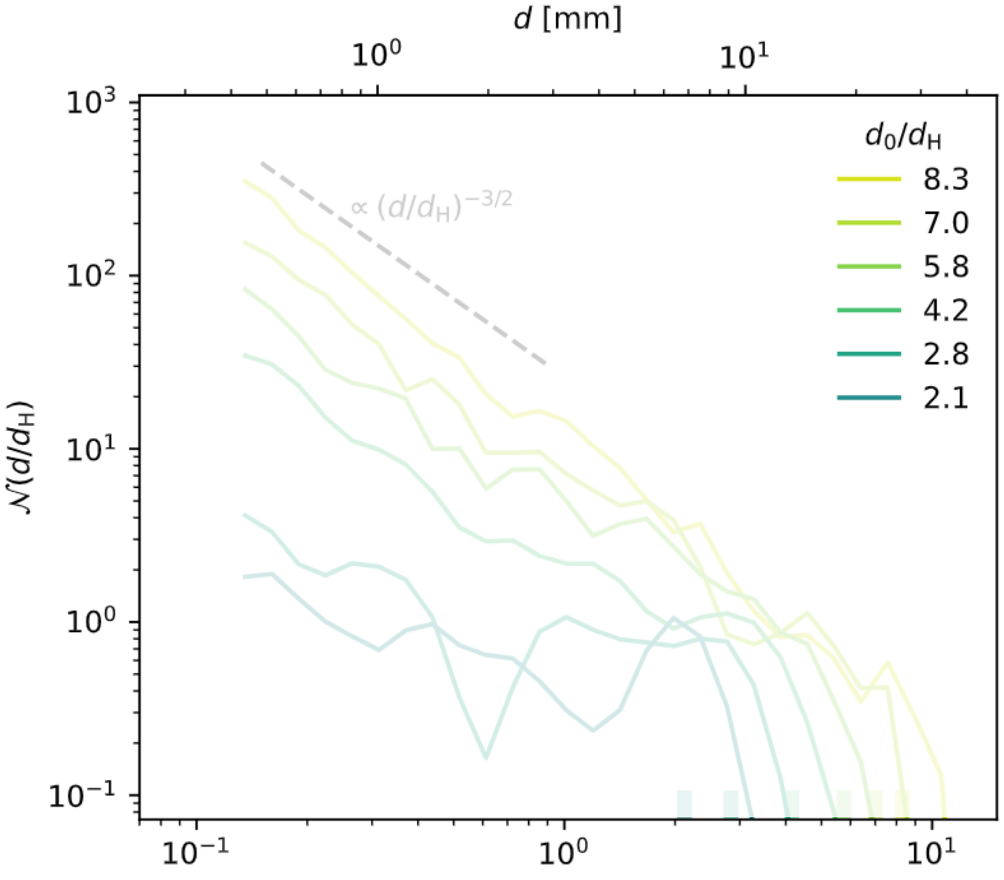




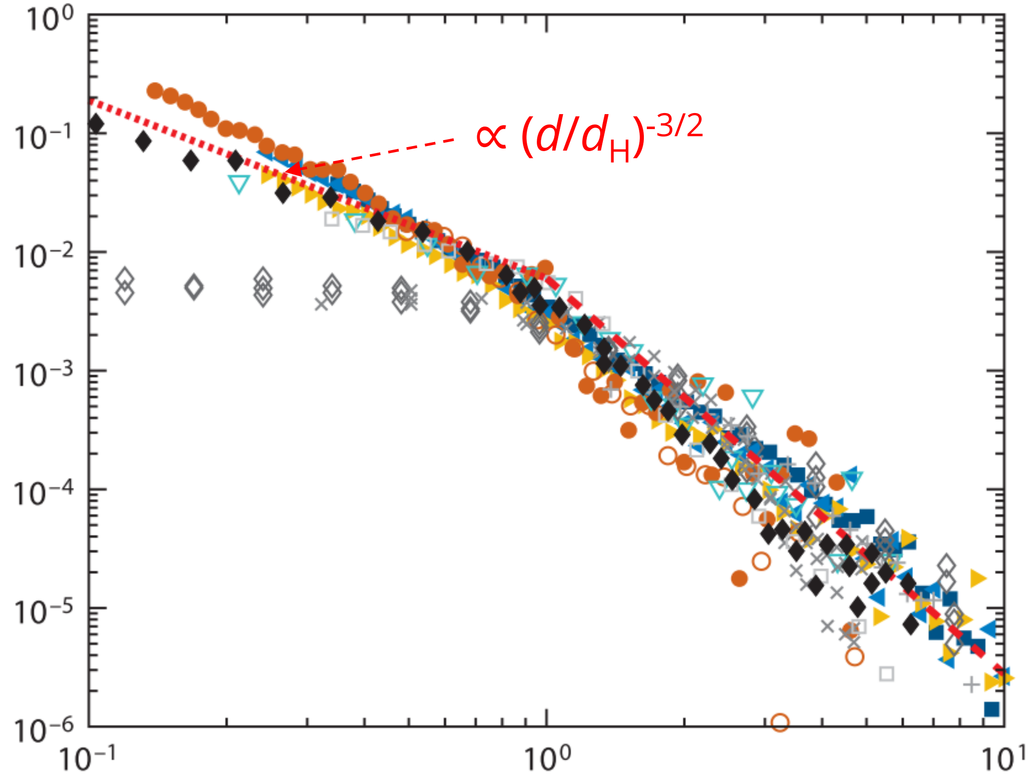
A population of **child bubbles** is created when a large **parent bubble** is exposed to **turbulence**

bubble size distribution

bubbles in laboratory-forced turbulence



bubbles under breaking waves



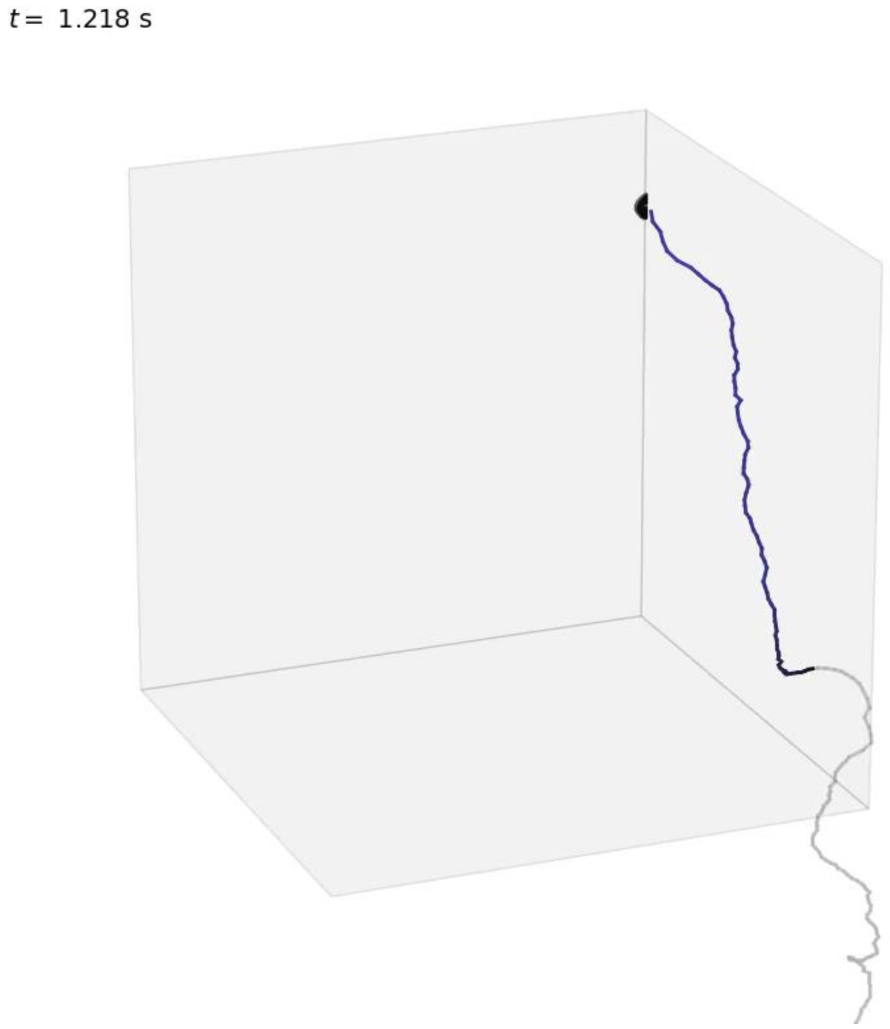
d/d_H, bubble size relative to Hinze scale

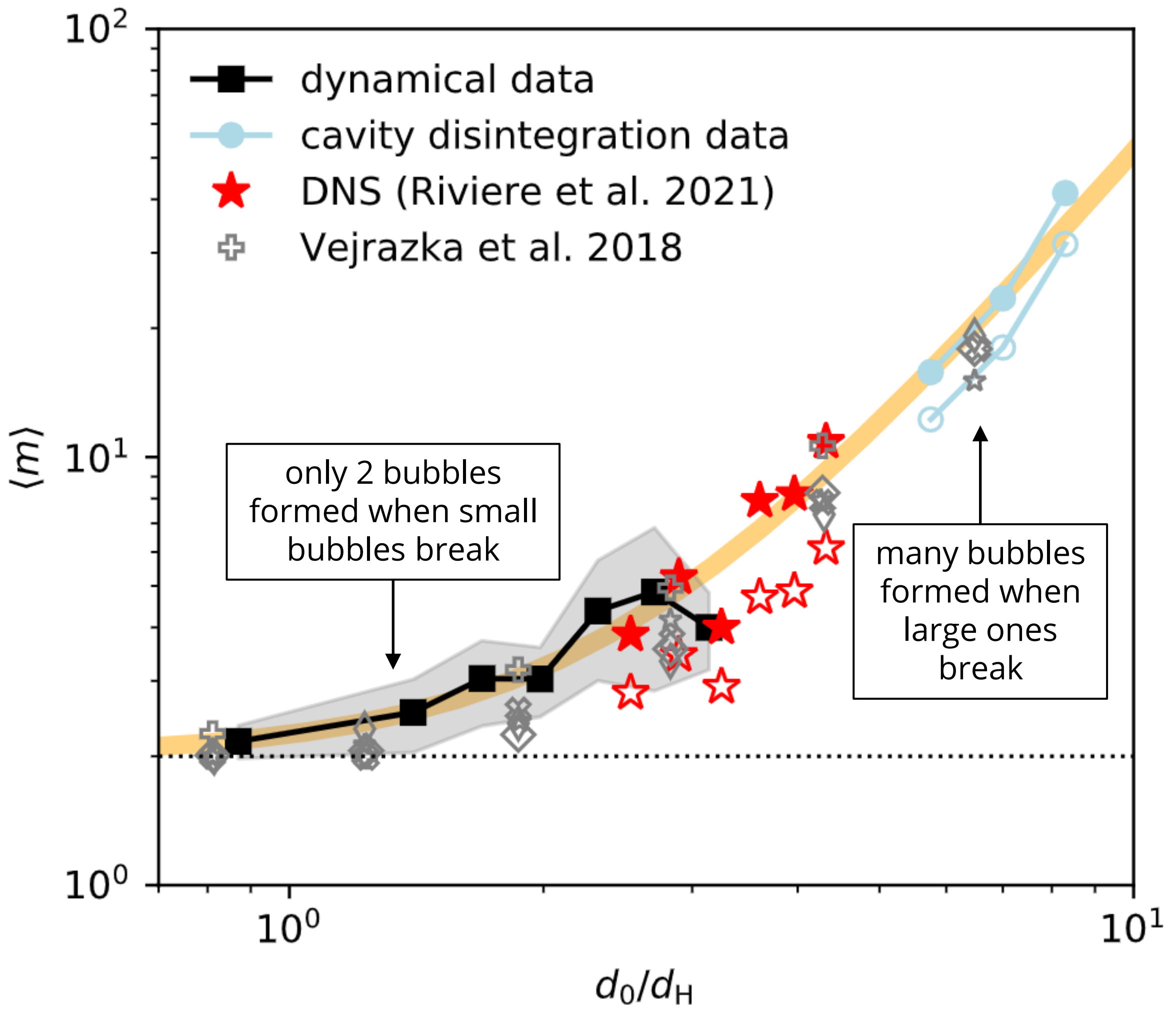
Smallest bubbles originate in **capillary instabilities**

large-scale
deformation by
turbulent eddies of the
bubble’s size

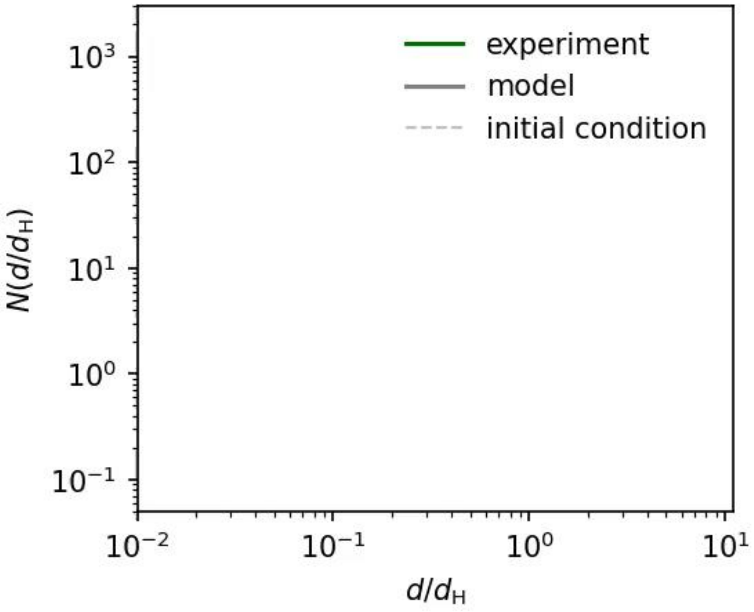
Smallest bubbles originate in **capillary instabilities**

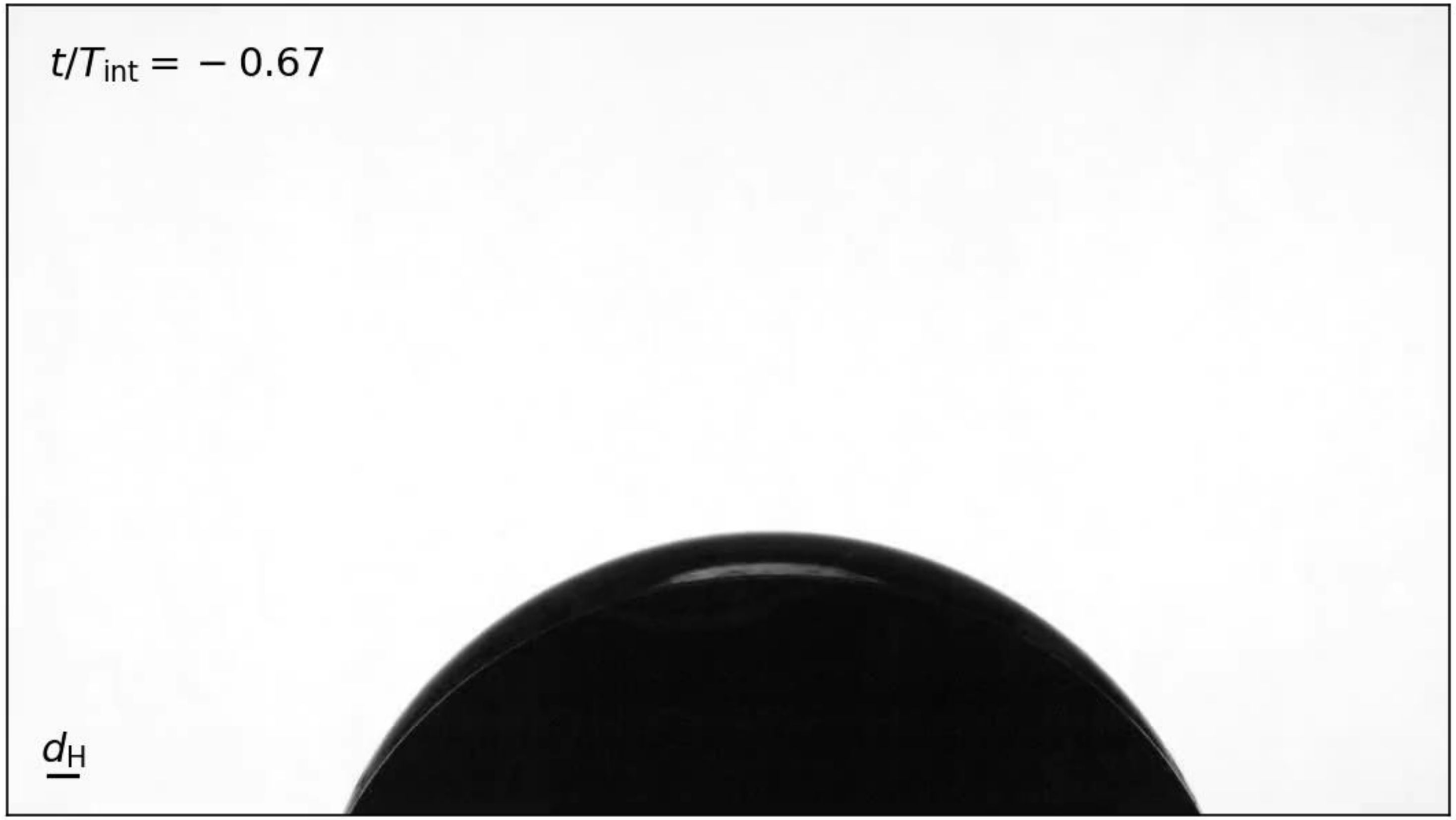
3-D tracking of individual break-ups

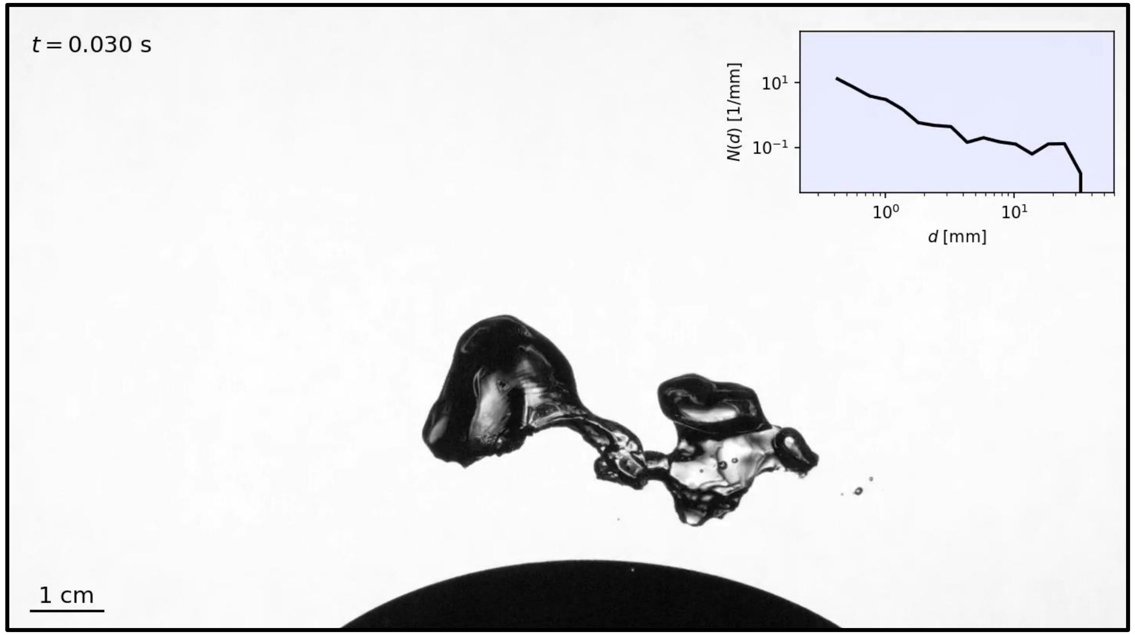




A model for bubble break-up

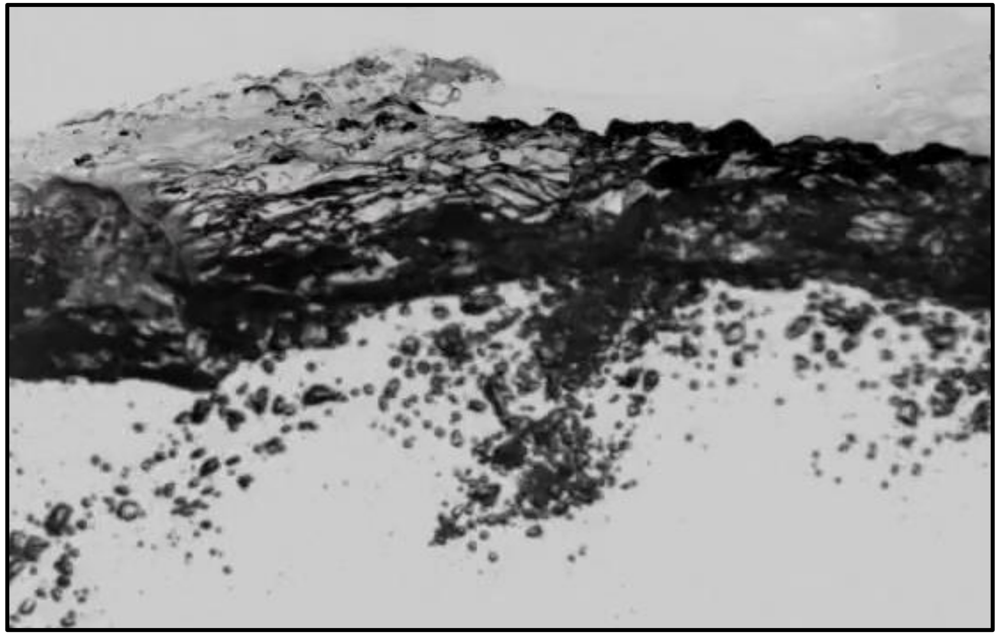




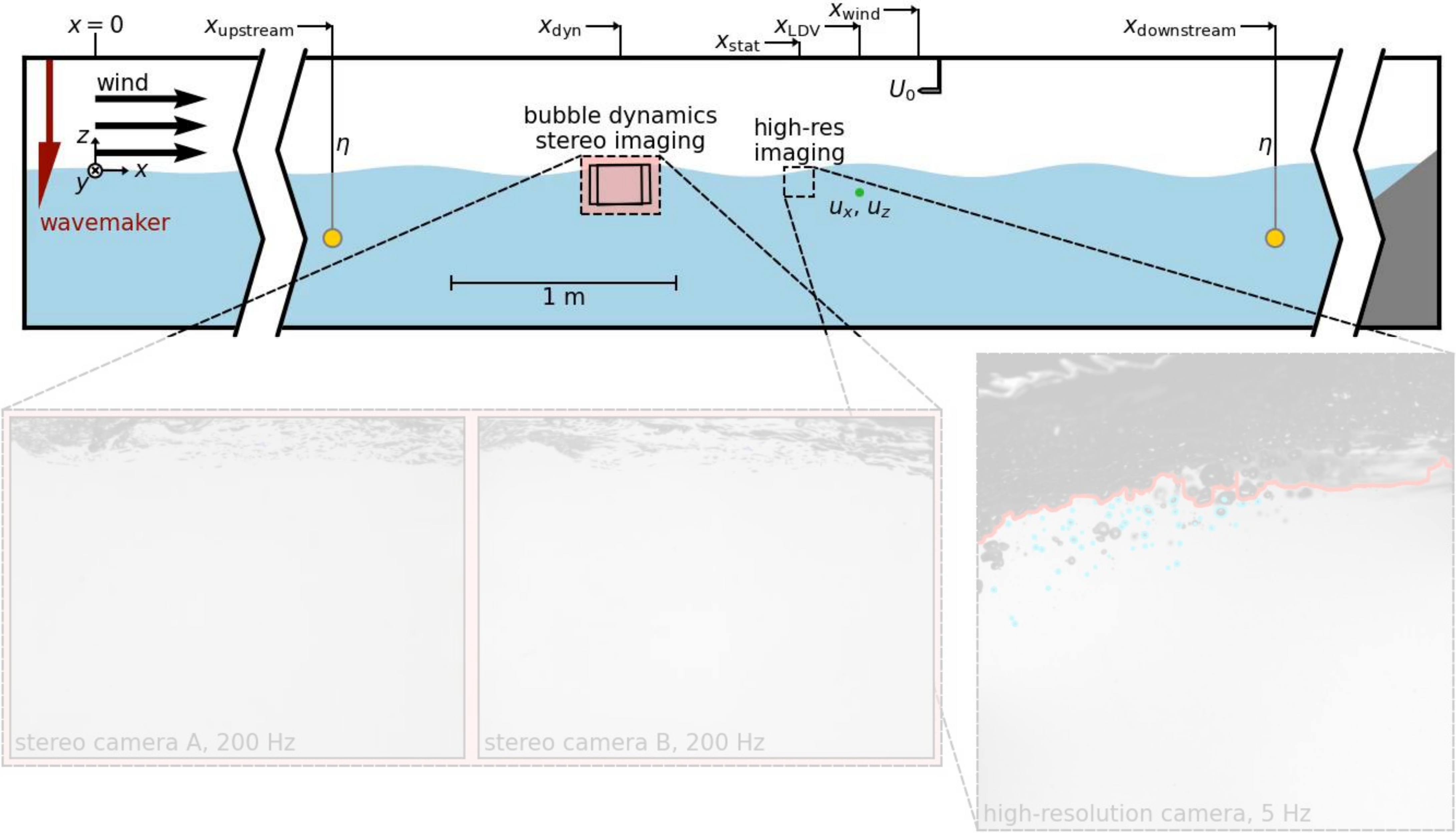


How do bubbles **break up** in turbulence?

→ ∝ $(d/d_H)^{-3/2}$ scaling for the small bubble size distribution results from **capillary instabilities** during the break-up of **large bubbles in turbulence**



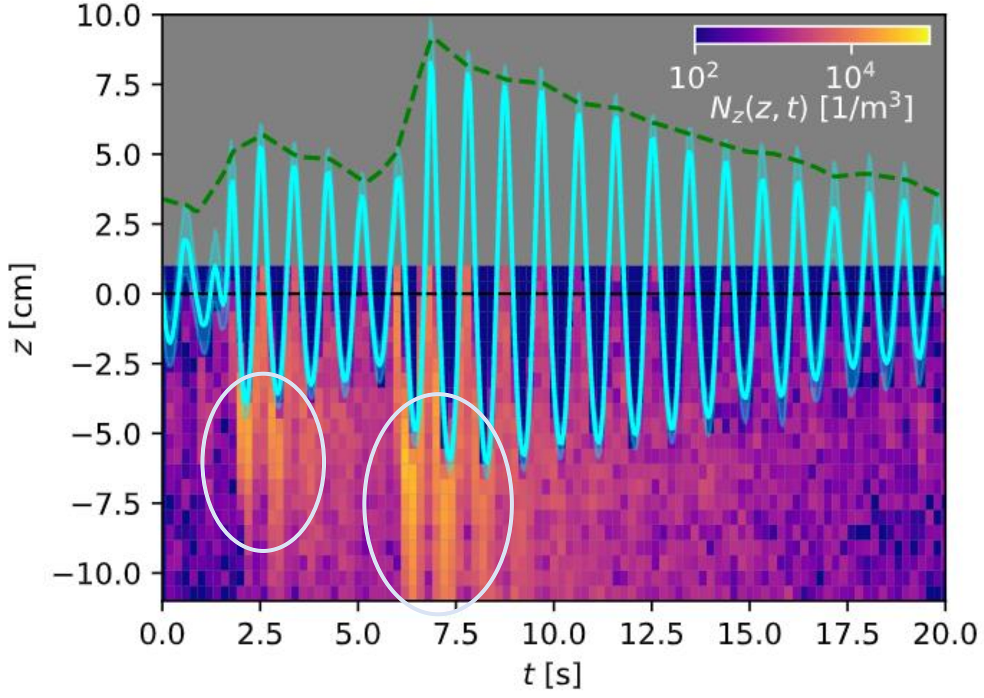
How are bubbles **entrained** and **transported** by **breaking waves**?



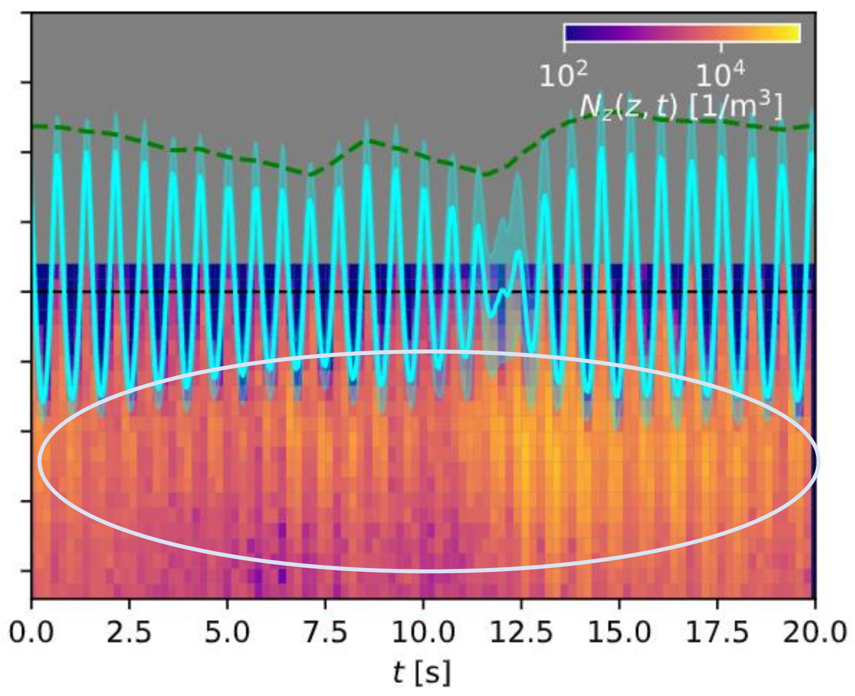
$x = 0$
x_{upstream}
x_{dyn}
x_{stat}
x_{LDV}
x_{wind}
$x_{\text{downstream}}$
wind
U_0
z
x
y
wavemaker
bubble dynamics stereo imaging
high-res imaging
η
η
u_x, u_z
1 m
stereo camera A, 200 Hz
stereo camera B, 200 Hz
high-resolution camera, 5 Hz

Bubble concentration under the forced wave field

characteristic **wave slope** = 0.23

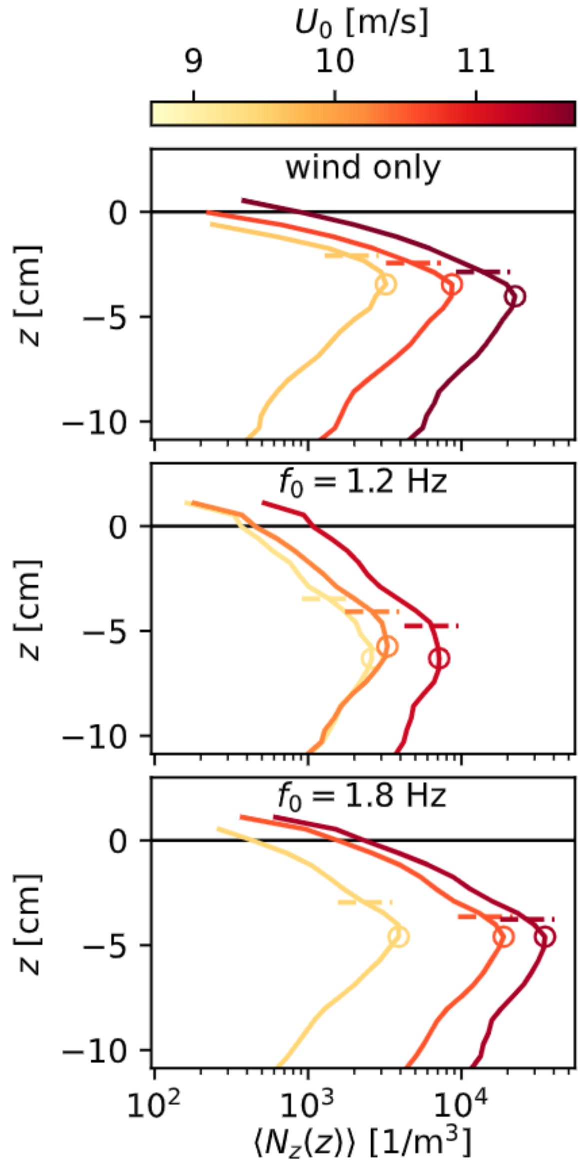


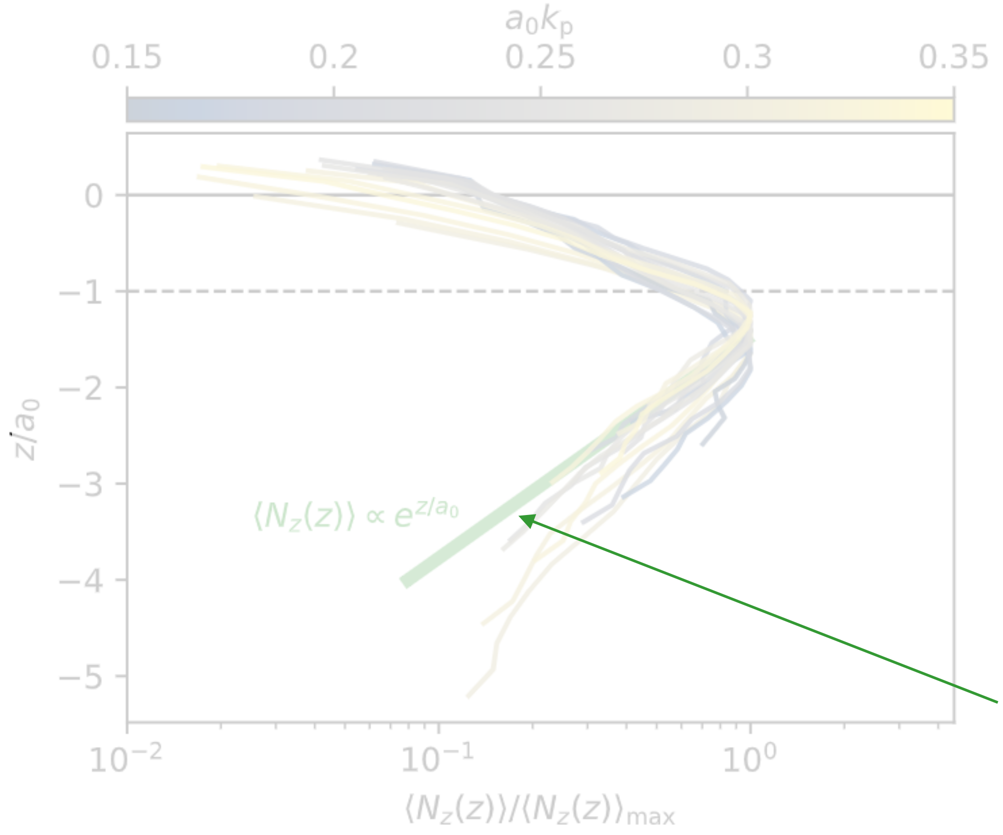
characteristic **wave slope** = 0.32

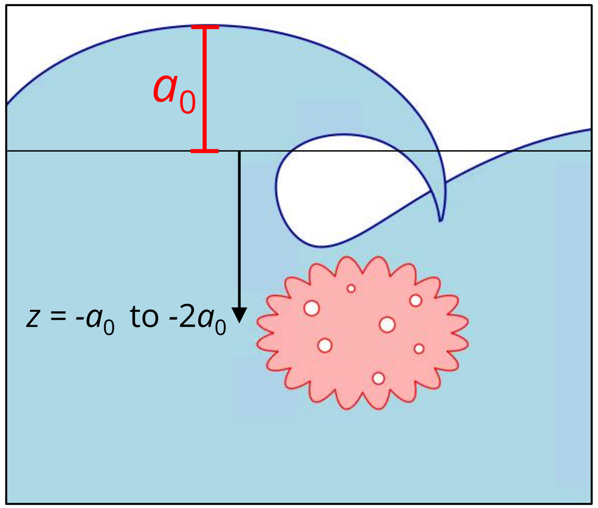


→ now, consider **time-averaged** bubble concentrations

Bubble concentration under the forced wave field



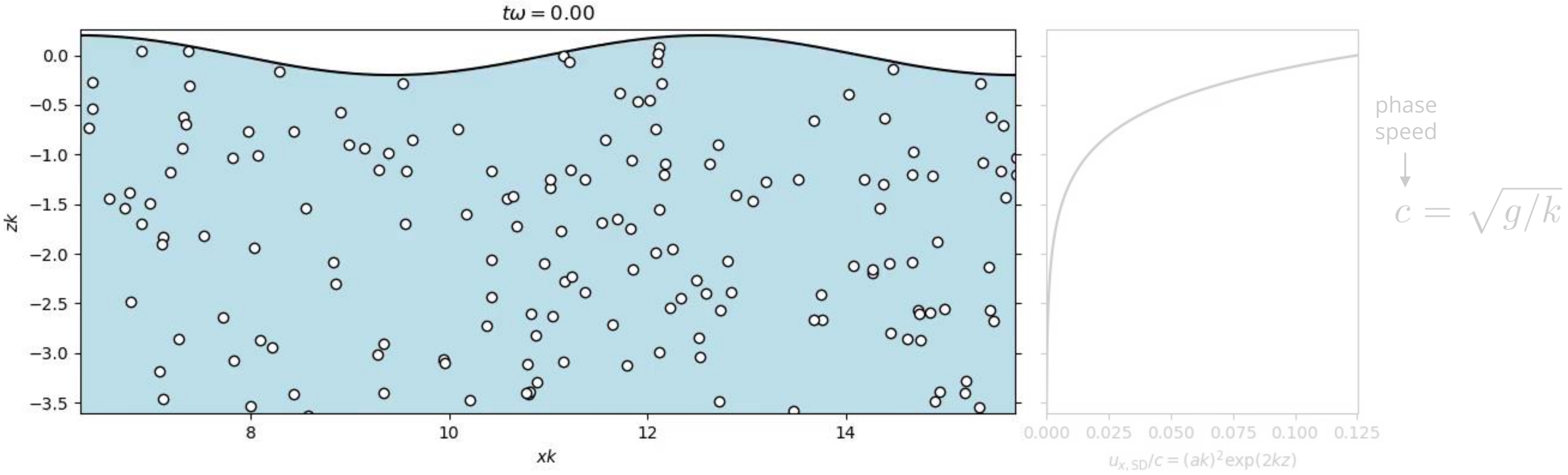




Exponential decay in bubble concentration with depth, as was found by [1]

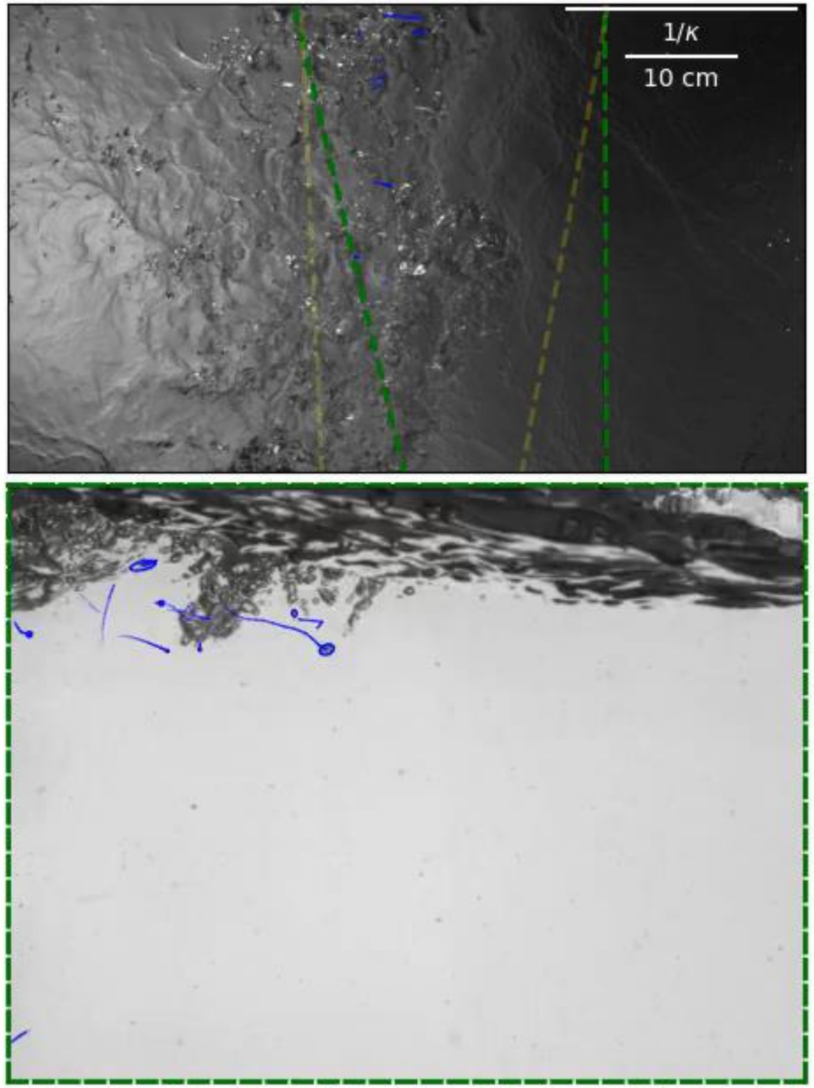
[1] Hwang, P. A., Hsu, Y. L., & Wu, J. (1990). Air bubbles produced by breaking wind waves: A laboratory study. *Journal of physical oceanography*, *20*(1), 19-28.

The ***Stokes drift***[1] transports fluid particles near the surface of a wavy flow



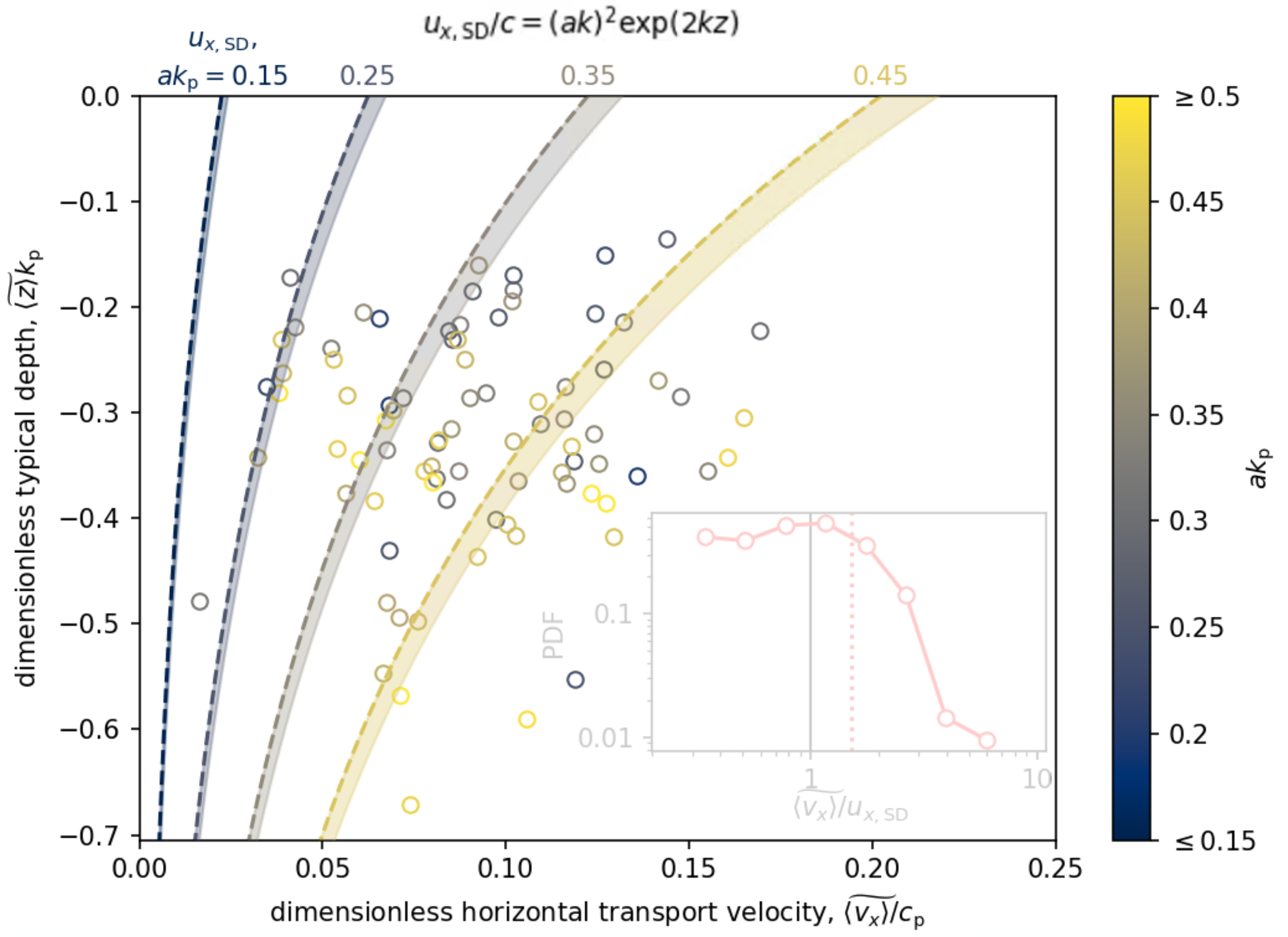
[1] van den Bremer, T. S., & Breivik, Ø. (2018). **Stokes drift.** *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *376*(2111), 20170104.

Enhanced bubble transport during **entrainment**



mean motion with the wave: $u_x > 0$

Enhanced bubble transport during **entrainment**



Bubbles move **faster** than the relevant Stokes drift:

- **Buoyancy/density** modifications to Lagrangian drift[1]

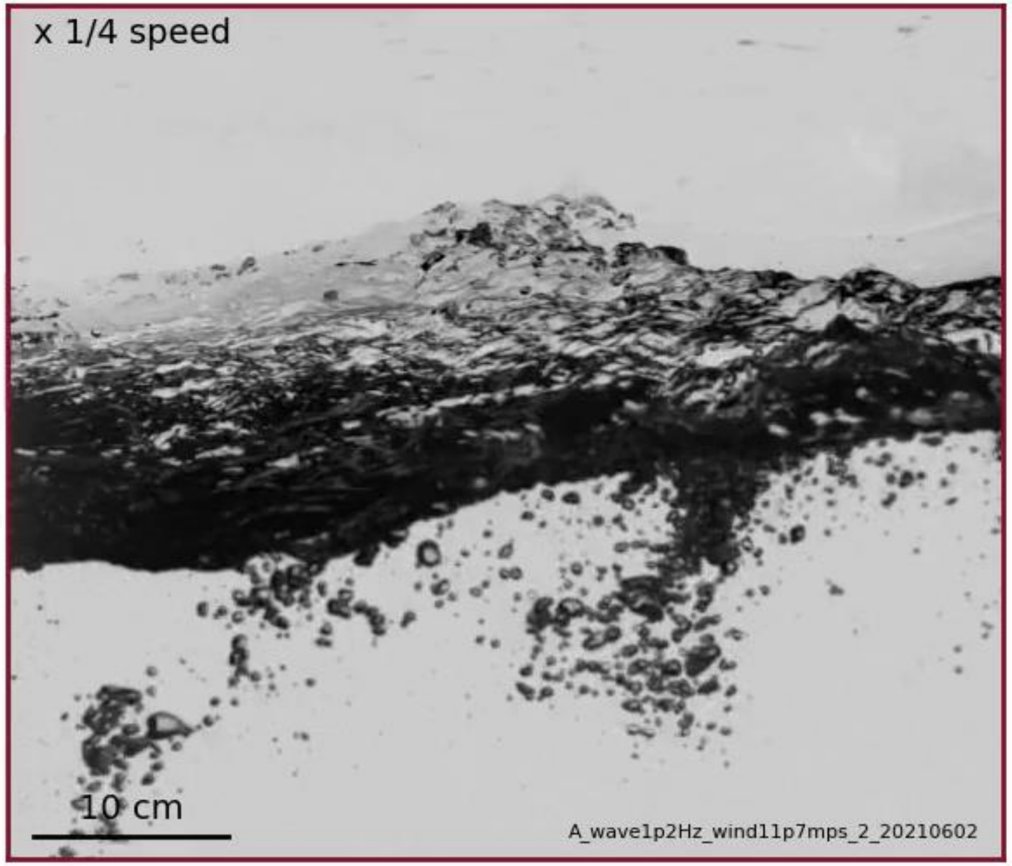
- Effects of **wave breaking**, which has been shown to **enhance the stream-wise transport** of fluid tracers and solid particles[2-3]

[1] DiBenedetto, M. H., Clark, L. K., & Pujara, N. (2022). **Enhanced settling and dispersion of inertial particles in surface waves.** Journal of Fluid Mechanics, 936.

[2] Deike, L., Pizzo, N., & Melville, W. K. (2017). **Lagrangian transport by breaking surface waves.** *Journal of Fluid Mechanics*, *829*, 364-391.

[3] Lenain, L., Pizzo, N., & Melville, W. K. (2019). **Laboratory studies of Lagrangian transport by breaking surface waves.** Journal of Fluid Mechanics, 876.

Summary of work on bubble entrainment



- Bubbles are **entrained** to a depth comparable to the **amplitude** of the wave that breaks

- The time-averaged concentration below this depth decays **exponentially**, with a **length scale** set by the breaking wave **amplitude**

- The **stream-wise transport** of bubbles during entrainment is **enhanced** relative to the Stokes drift due to the effects of **breaking**

Questions?