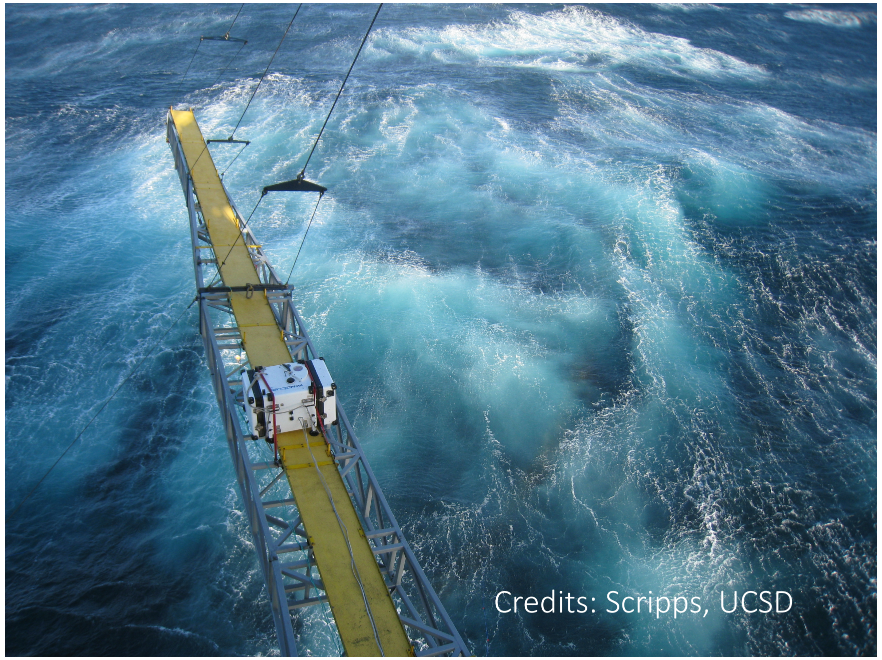
Waves and breaking waves in Gerris



Luc Deike (Princeton University)

PRINCETON
School of Engineering and Applied Science

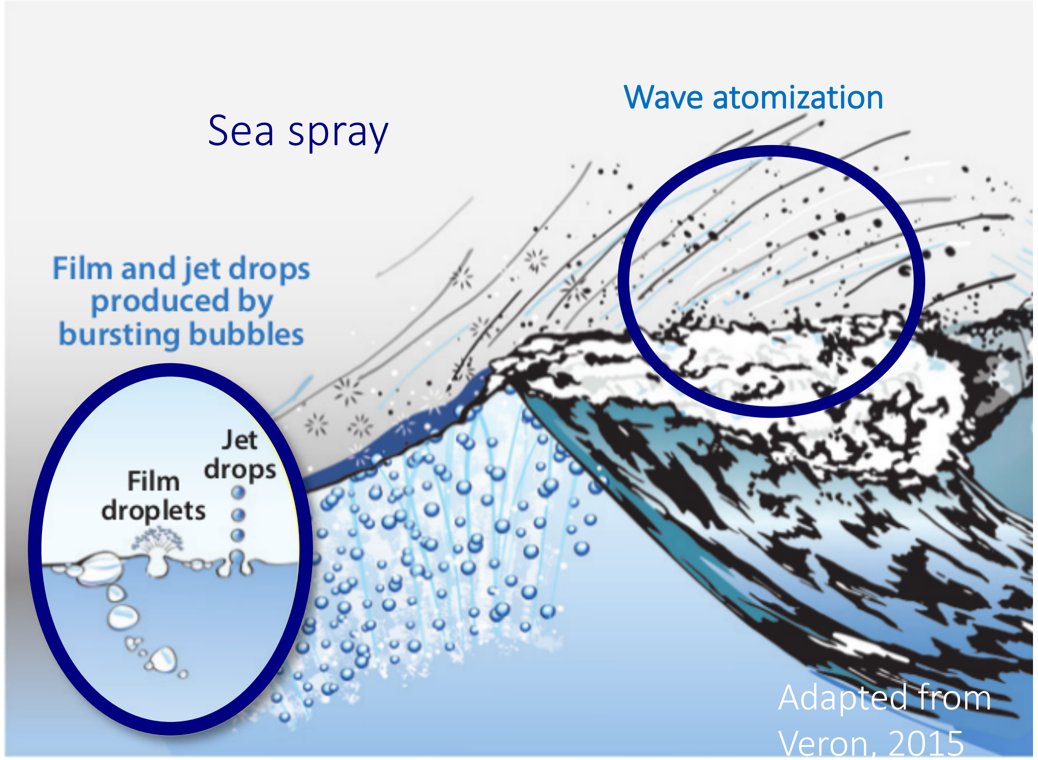
PEI
PRINCETON ENVIRONMENTAL INSTITUTE
The center for environmental research, education and outreach

Motivations: The role of wave breaking in air-sea interaction

U_{10}=16 m/s,
H_s=4.6m
Credits F. Veron
(U. Delaware)

Wave breaking: dissipates energy
transfers momentum and generates currents
transfers mass

Mass transfers and climate impacts

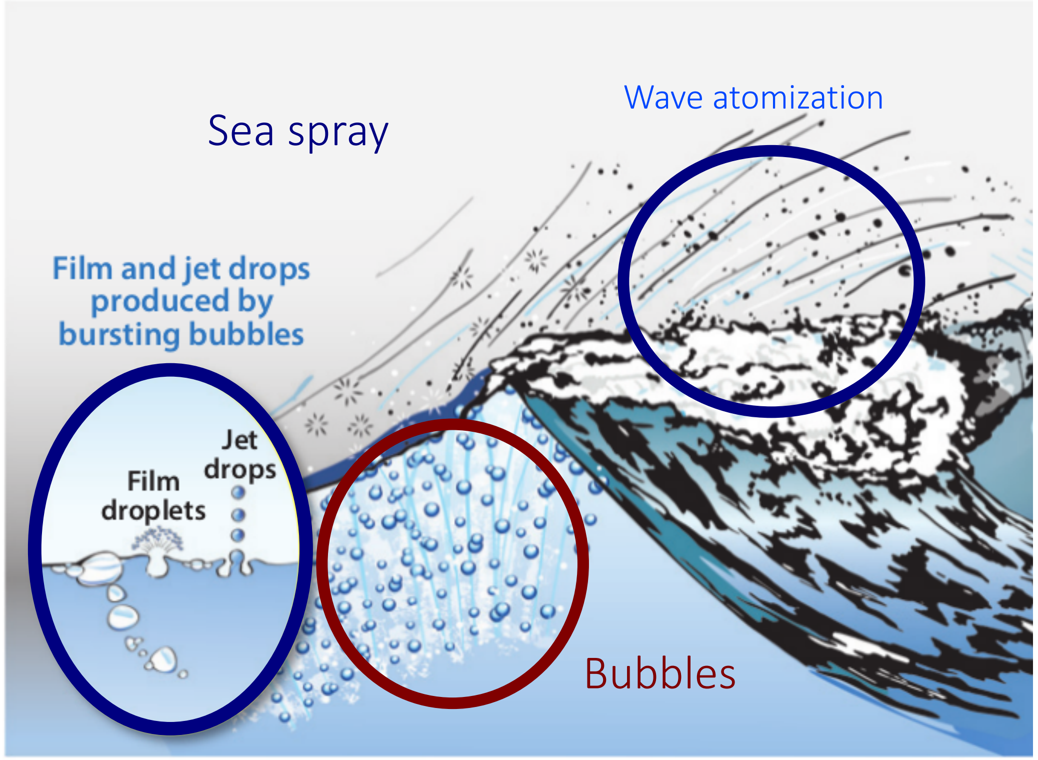


From water to air: Transfer of momentum, heat, moisture

Production of aerosols (sea salt, biological particles)

→climate impact (cloud nucleation & radiative balance)

Mass transfers and climate impacts



Adapted from Veron, 2015

From water to air: Transfer of momentum, heat, moisture
Production of aerosols (sea salt, biological particles)
→climate impact (cloud nucleation & radiative balance)

From air to water: Air entrainment & gas transfer
→climate impact (carbon uptake)

Breaking waves: lab experiments

Many papers by Duncan, Melville, Banner, Tulin, Perlin, …

Waves and breaking waves in Gerris: two-dimensional waves, shape and dissipation

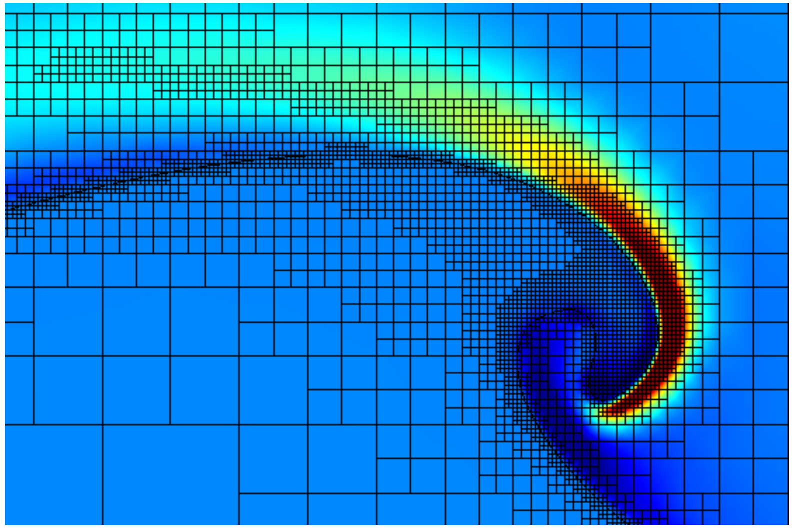
Direct Numerical Simulations of waves

Deike, Popinet and Melville, 2015, JFM

Incompressible variable-density Navier-Stokes equations, with surface tension

Gerris Flow Solver
(Open source, http://gfs.sourceforge.net)

Adpative two-phase flow,
Geometrical Volume-of-Fluid
S. Popinet, 2003, 2008,
Journal of Computational Physics



Highly efficient tool:
Wide exploration of the parameter space

Non-breaking gravity waves (high Bond number, low slope)

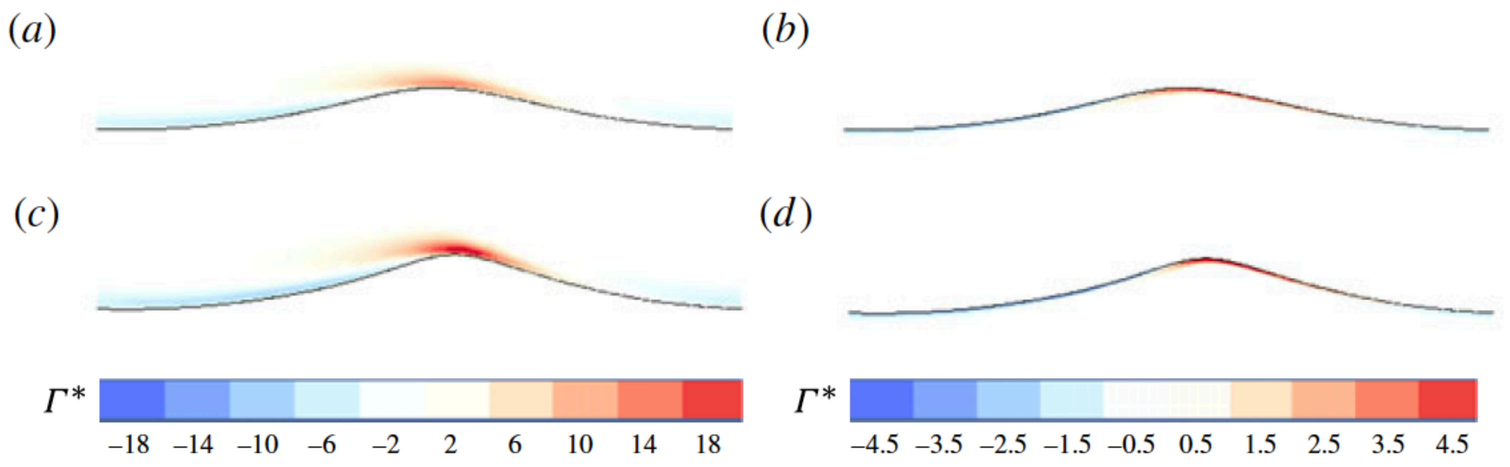
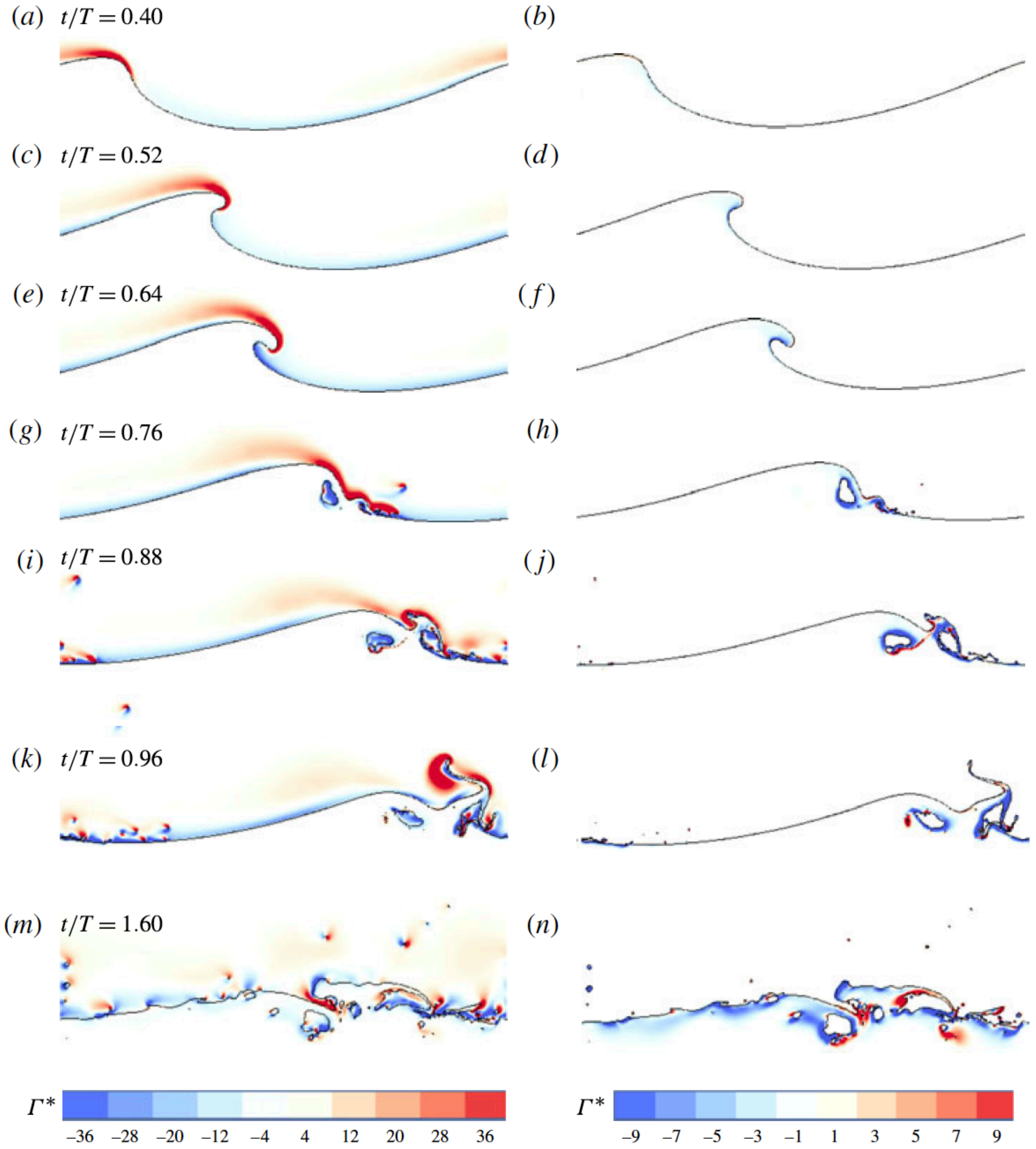
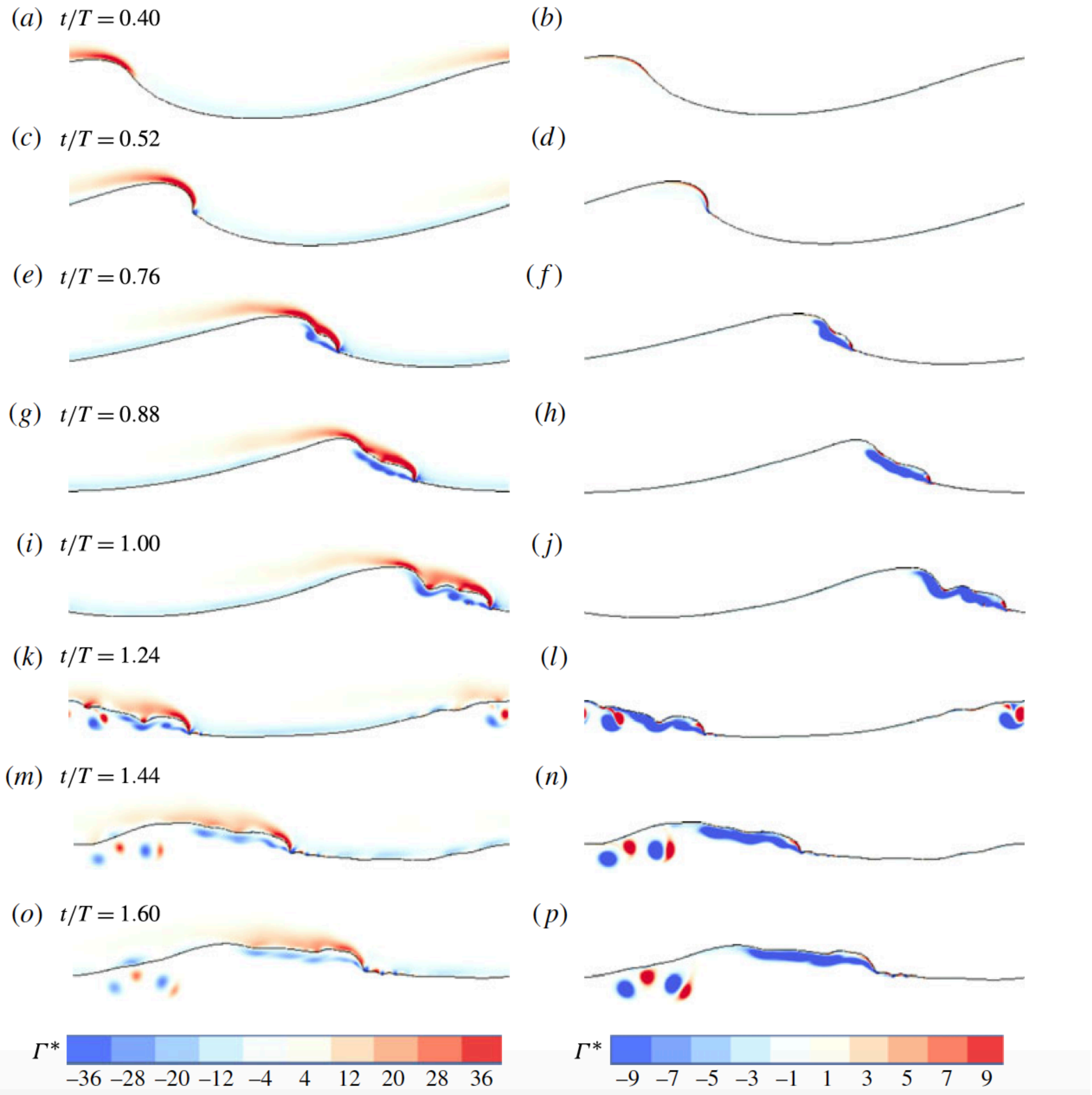


FIGURE 1. Non-breaking gravity waves propagating to the right and the vorticity field $\Gamma^* = \Gamma/\Gamma_0$ at $t/T = 1$, for two different steepness: 0.2 (*a*,*b*) and 0.25 (*c*,*d*). The vorticity field is displayed both in the air and water (*a*,*c*) and only in the water (*b*,*d*) with a different colour scale. Here $Re = 4 \times 10^4$, $Bo = 1000$. We can see that the wave is more asymmetric for $\epsilon = 0.25$, due to stronger nonlinear effects.

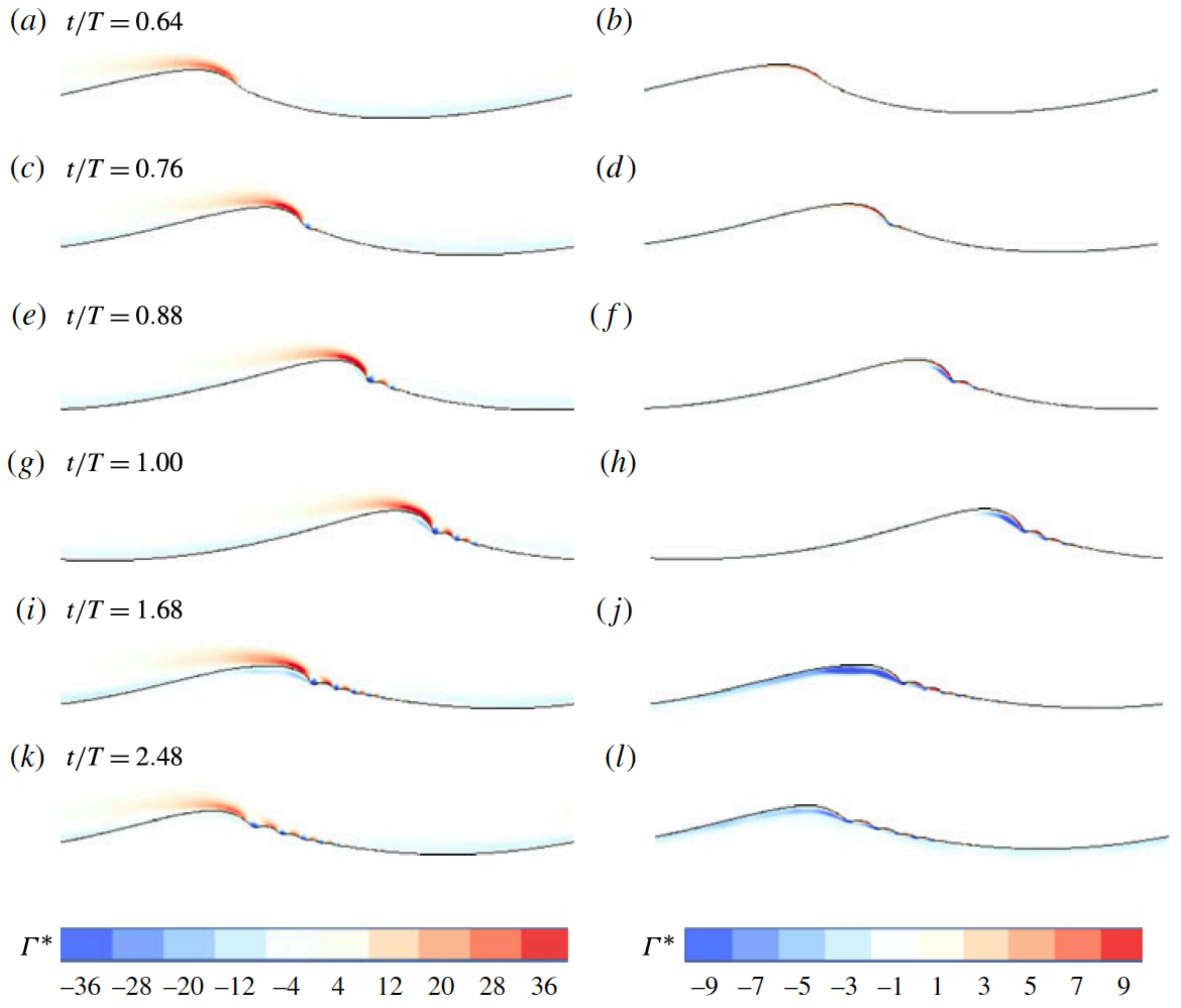
Plunging breaking waves (low Bond number, high slope)



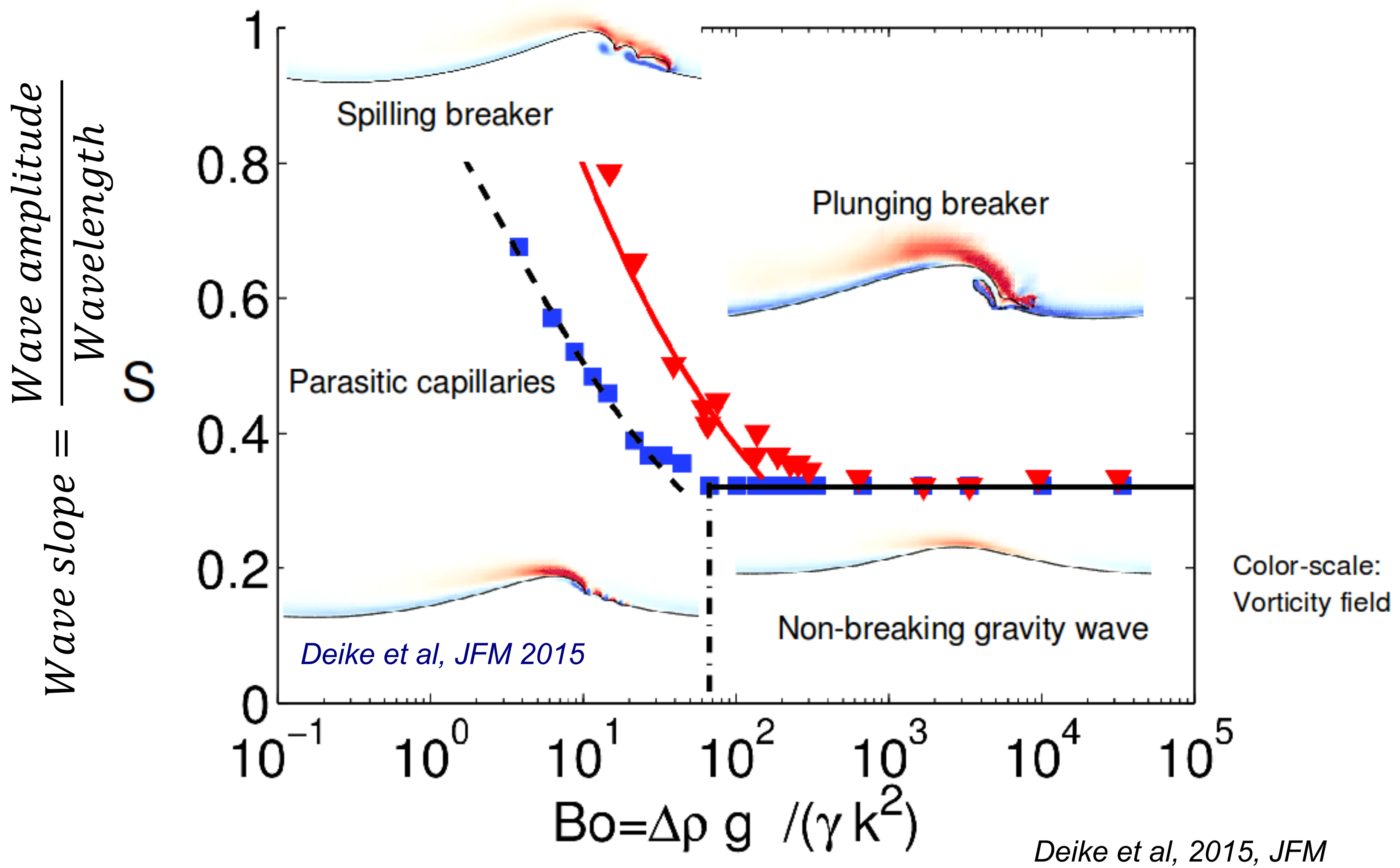
Spilling breaking waves (low Bond number, high slope)



Parasitic capillary waves (low Bond number, low slope)



Wave patterns



Deike et al, 2015, JFM

How do these waves dissipate energy?

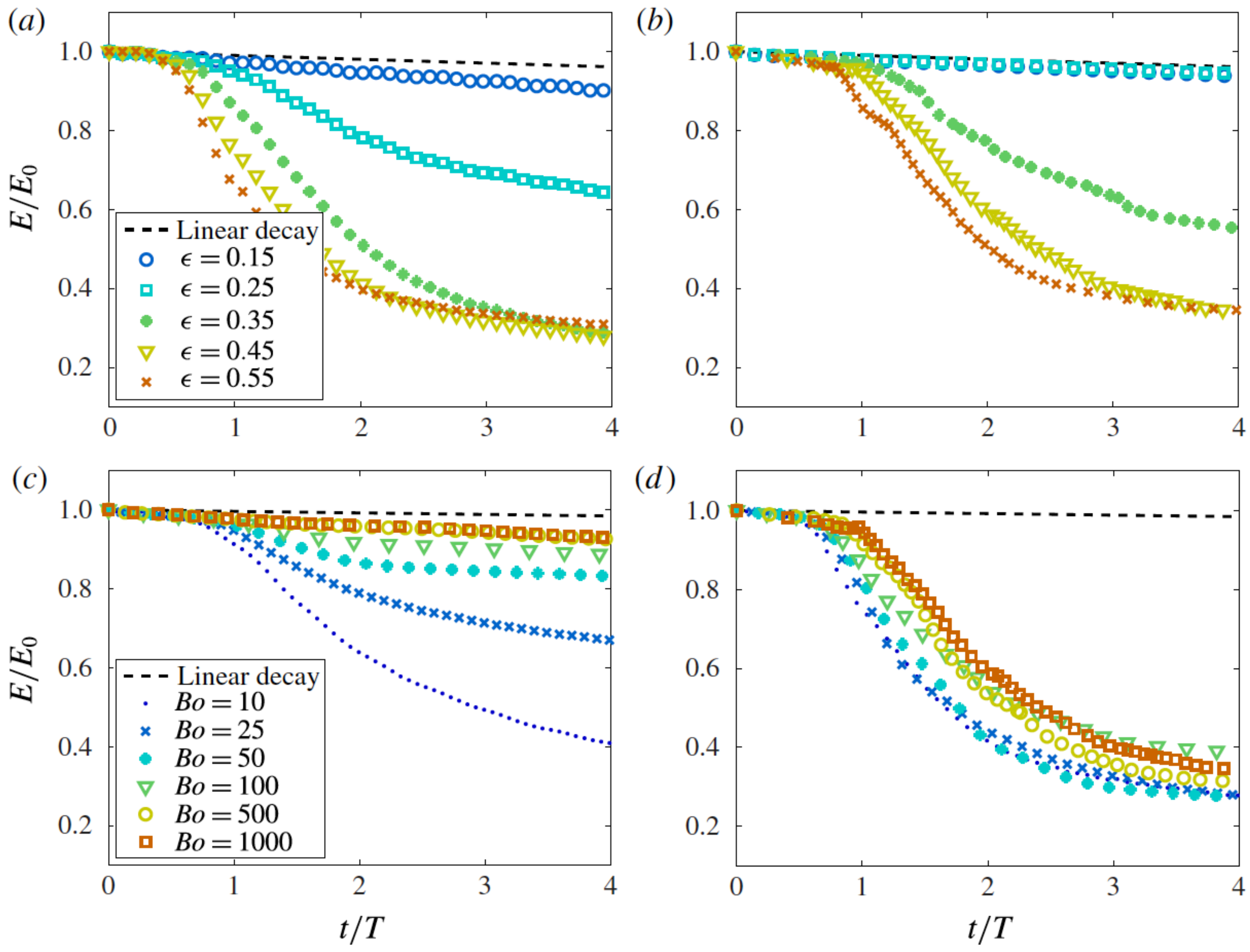


FIGURE 9. (Colour online) Normalized wave energy E/E_0 as a function of time t/T. (*a,b*) Effect of increasing steepness for (*a*) $Bo = 10$ and (*b*) $Bo = 1000$. From top to bottom $\epsilon = 0.15, 0.25, 0.35, 0.45$ and 0.55. (*c,d*) Effect of increasing surface tension at a given steepness, (*c*) $\epsilon = 0.3$ and (*d*) $\epsilon = 0.45$. From bottom to top $Bo = 2, 5, 10, 20$ and 100. Black dashed line is the theoretical linear viscous dissipation $E/E_0 = \exp(-4\nu k^2 t)$.

Three-dimensional breaking waves:
dissipation, air entrainment and bubble statistics

Direct Numerical Simulations of breaking waves

High Reynolds number

$$Re = \frac{c\,\lambda}{\nu} = 40000$$

Intermediate Bond number

$$Bo = \frac{\rho\, g}{\gamma\, k^2} = 200 \ \ (\lambda = 24\ cm)$$

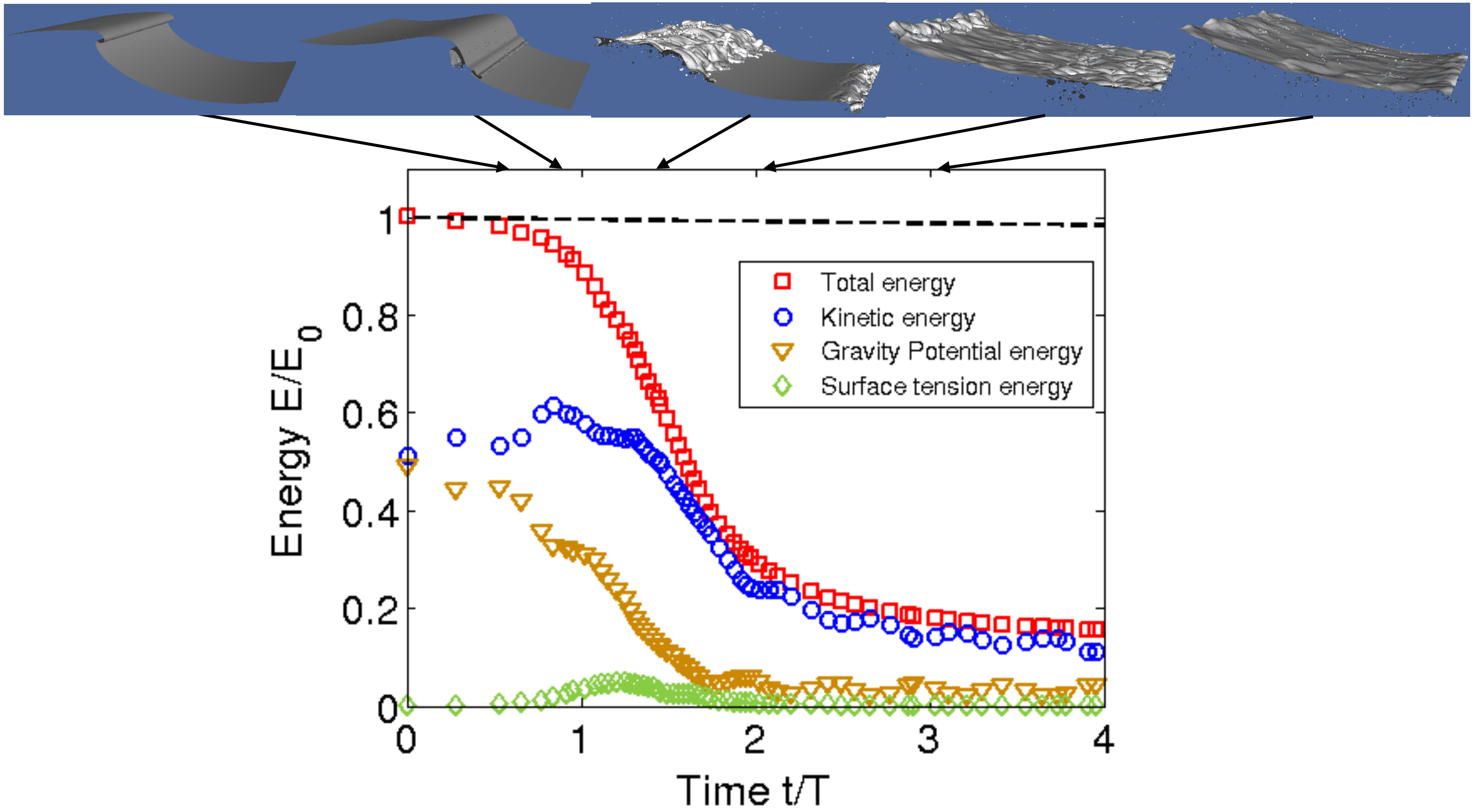
Mesh size: up to 0.22 mm
(52 days on 64 cores!)

Initial slope S from 0.3 to 0.65,
from incipient breaker
to highly plunging wave

Deike, Melville and Popinet, 2016, JFM

Solves accurately the dissipative
and bubbles generation length scale

Dissipation during breaking



Strong dissipation

Measure of the dissipation rate and breaking parameter b

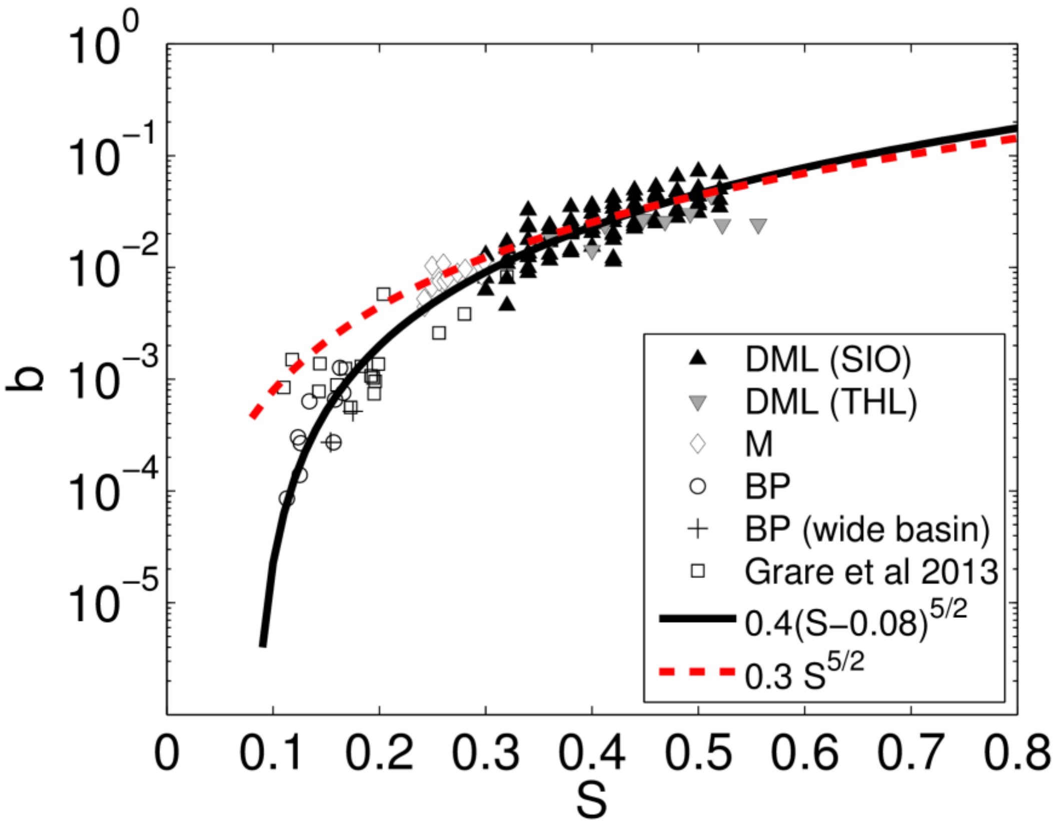
The breaking parameter b:
non-dimensional measure of the breaking intensity

Inertial scaling arguments:
(Drazen et al 2008)

$$b \propto S^{5/2}$$

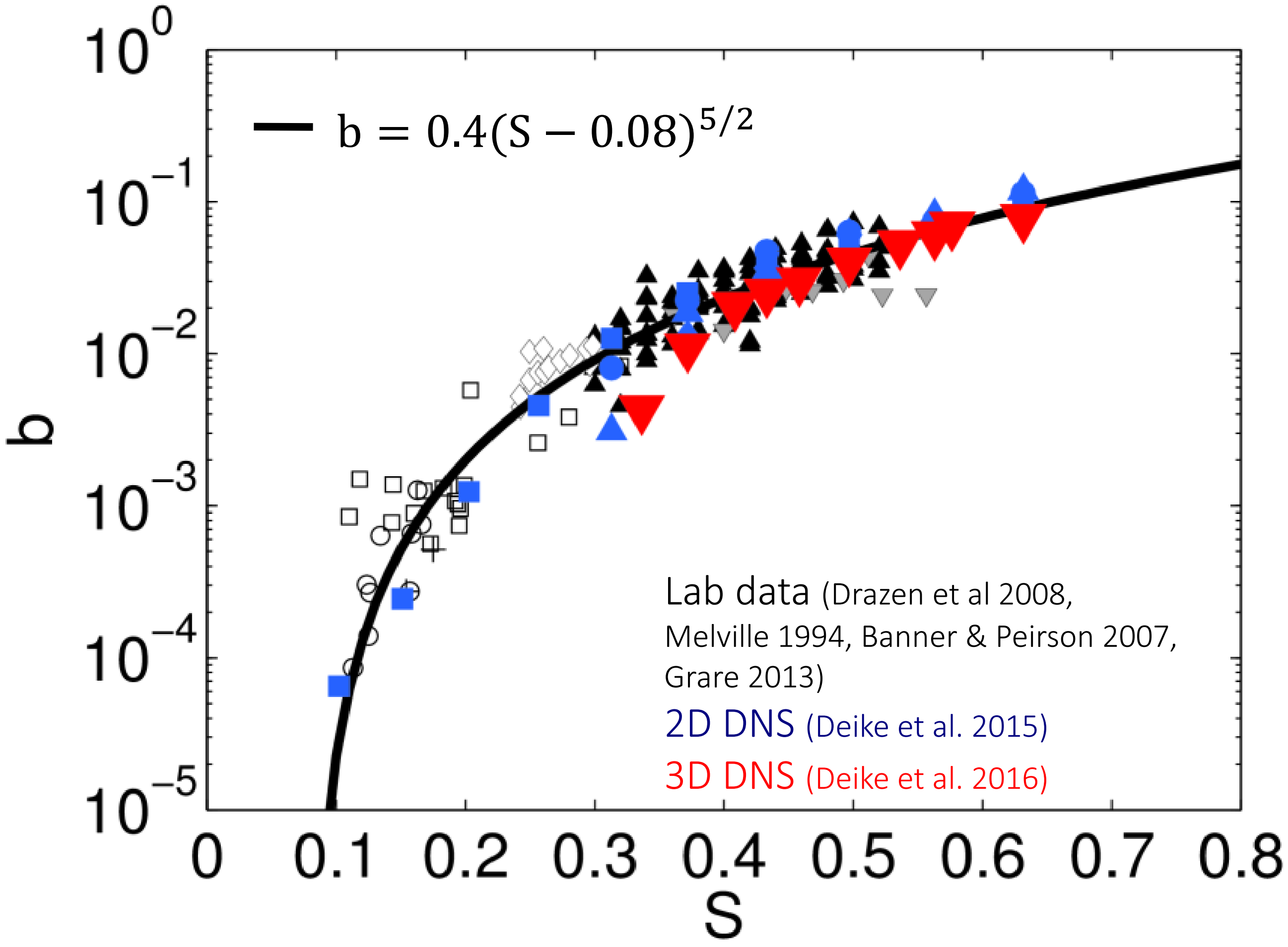
Introducing a breaking threshol
(Romero et al 2012)

$$b = 0.4(S - 0.08)^{5/2}$$



Adapted from Romero et al 2012,
Grare et al 2013

Simulations correctly capture small turbulent scales



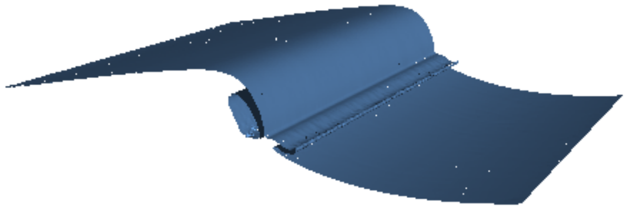
Deike, Popinet and Melville, 2015, JFM
Deike, Melville and Popinet, 2016, JFM

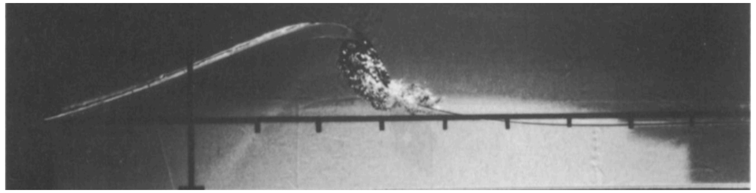
Waves of increasing slopes

DNS, Stokes waves

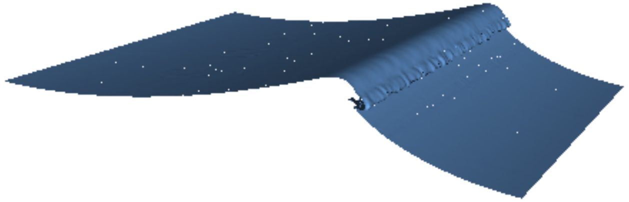
Lab, focusing wave packet

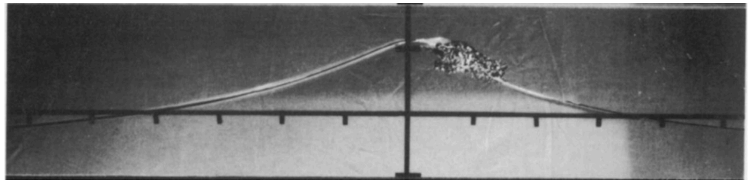
Plunging breaker, S=0.5





Spilling breaker, S=0.35





Deike et al, 2016, JFM

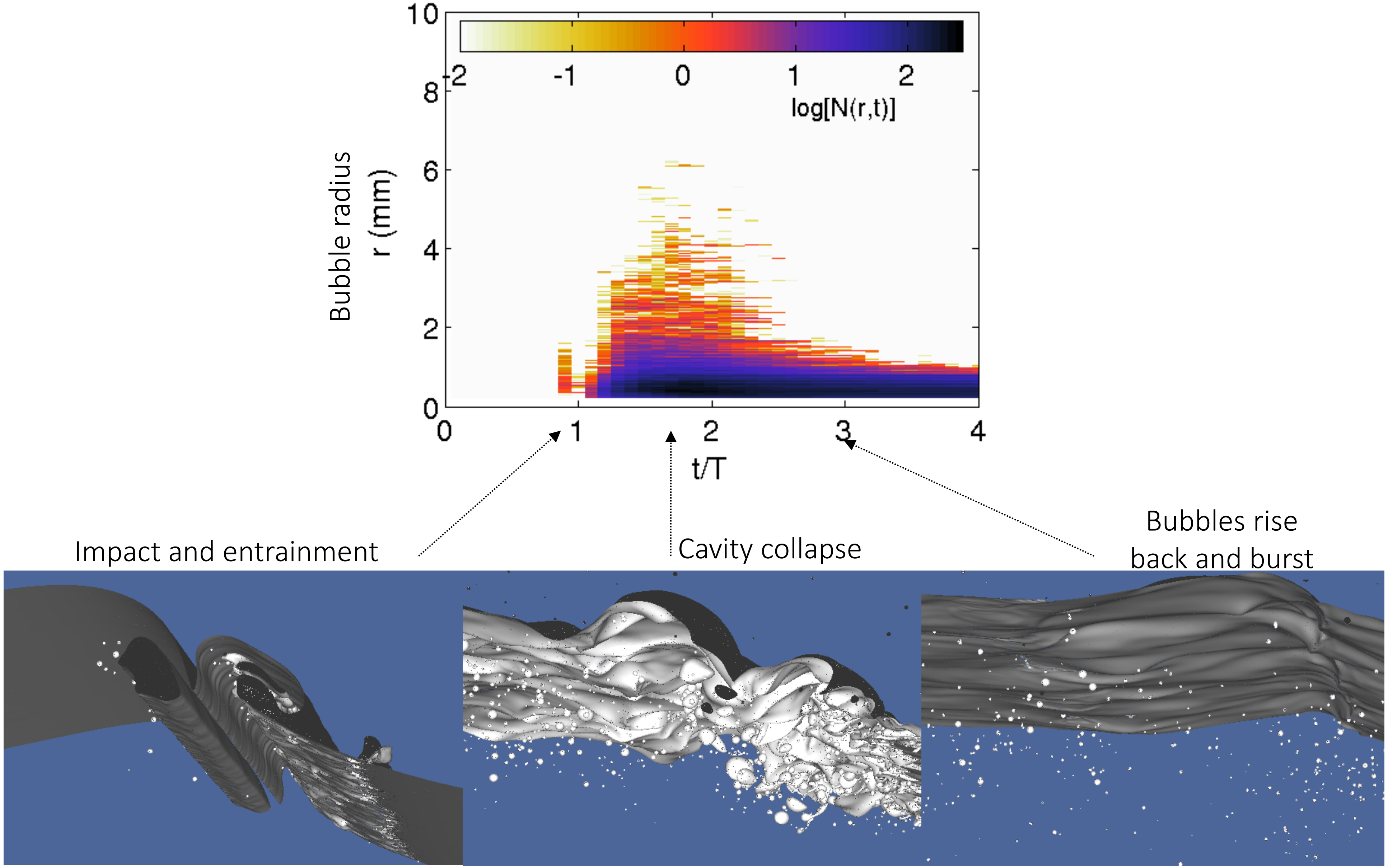
Rapp and Melville (1990)

Wave slope increases → turbulence generation increases

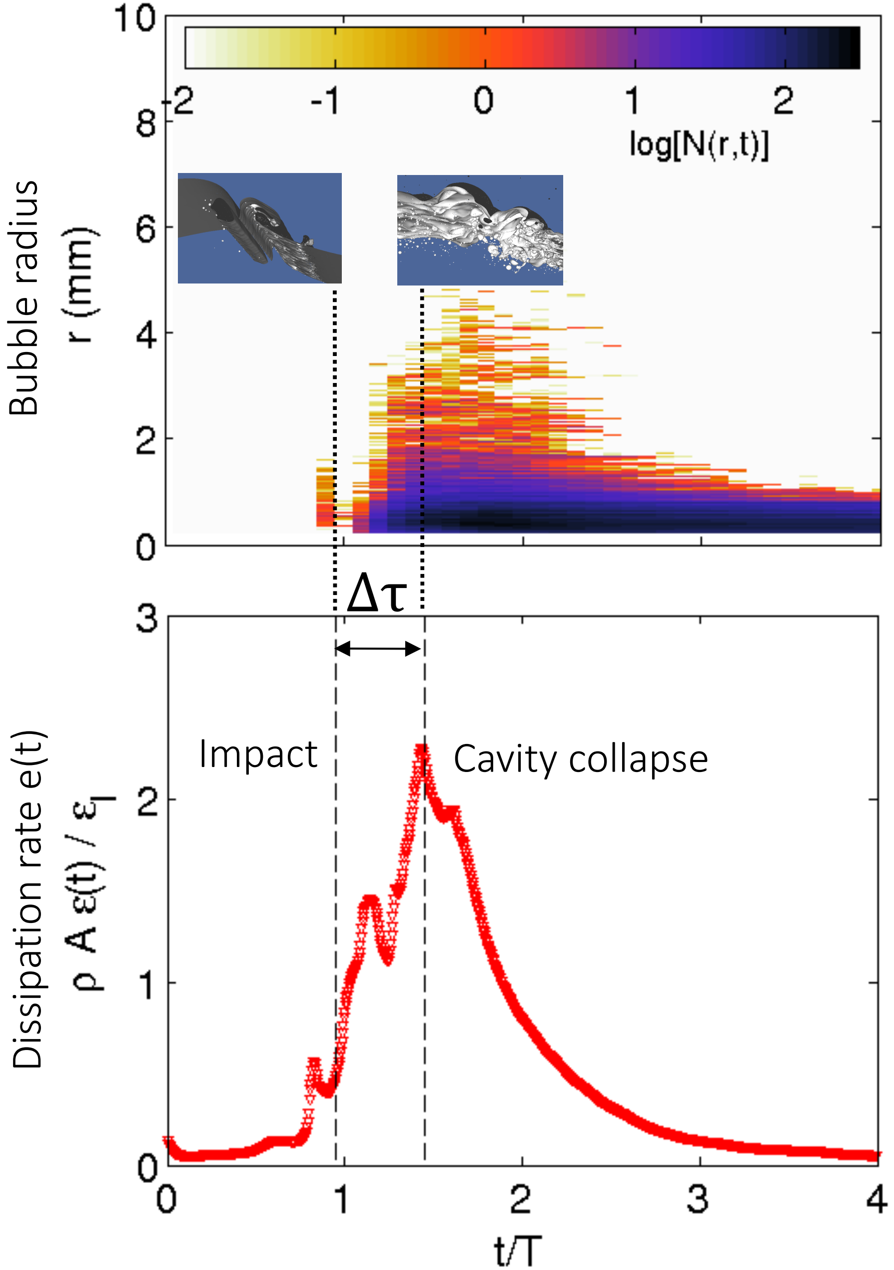
→ dissipation due to breaking increases

→ air entrainment increases

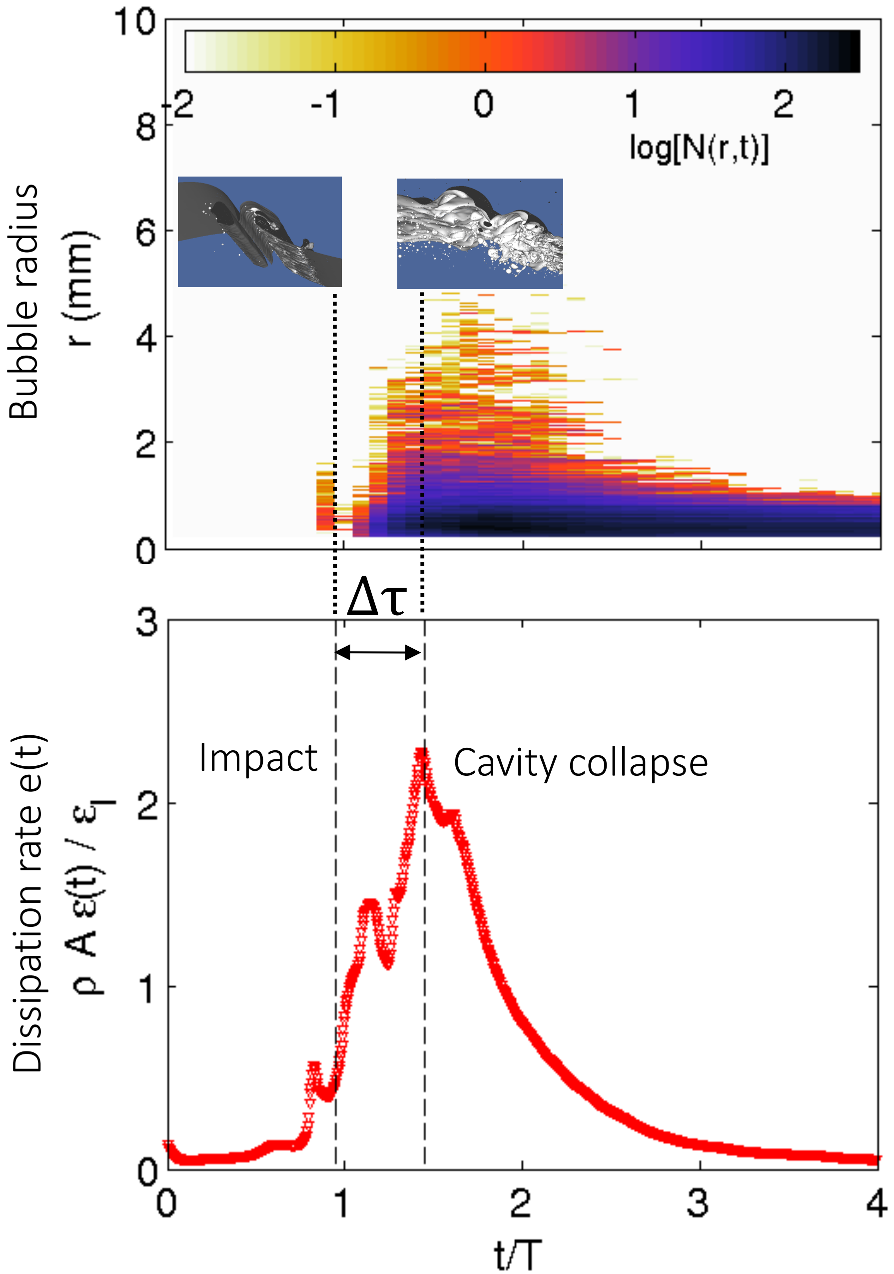
Time evolution of the bubble size distribution

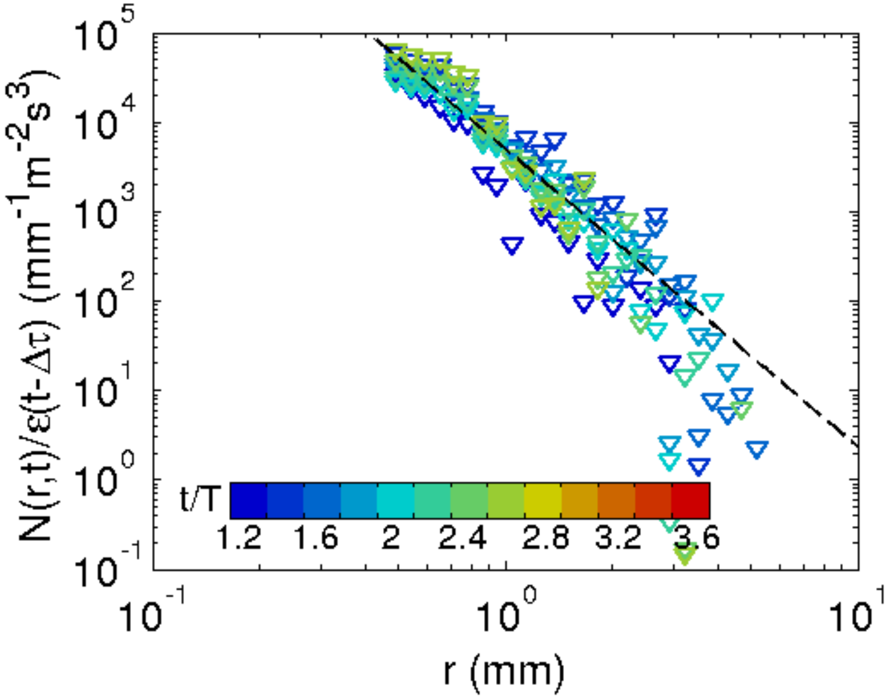


Bubbles and dissipation have similar time evolution



Number of bubbles scales with dissipation





$$n(r,x,t) \sim r^{-\frac{10}{3}}\varepsilon(t')$$

A predictive model for the bubble phase

i. Globally, the work done against buoyancy forces in entraining the bubbles is proportional to the mechanical dissipated energy

$$\frac{V_a}{V_w} \propto \frac{\varepsilon(x,t')}{gW}$$

ii. Turbulent break-up model adapted from Garrett et al 2000:

$$n(r) \propto \frac{V_a}{V_w} r^{-10/3} {r_m}^{-2/3}$$

→ Local bubble size distribution

$$n(r,x,t) = \frac{B}{2\pi} \boxed{r^{-10/3} {r_m}^{-2/3}} \boxed{\frac{\varepsilon(x,t')}{gW}}$$

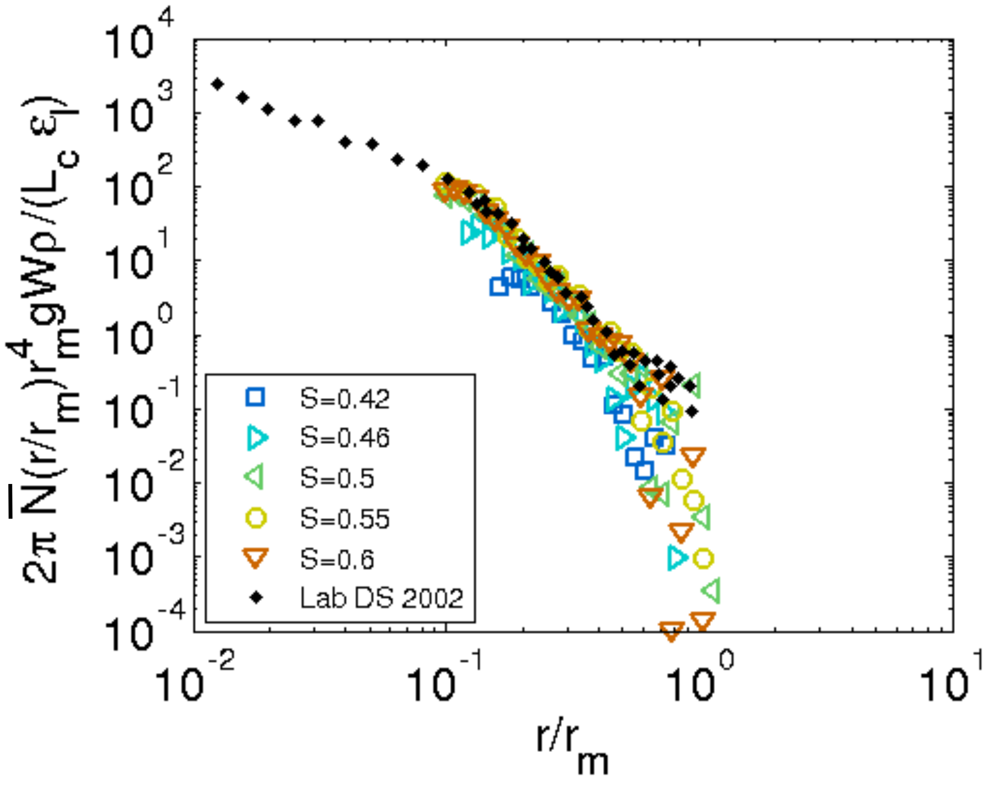
Turbulent fragmentation

Balance between buoyancy and dissipation

How does it compare to lab data?
Experimental data from Dean and Stokes 2002

Model explains observed bubble size distribution for breaking waves at various scales, lab and DNS

Rescaled bubble size distribution



Rescaled radius

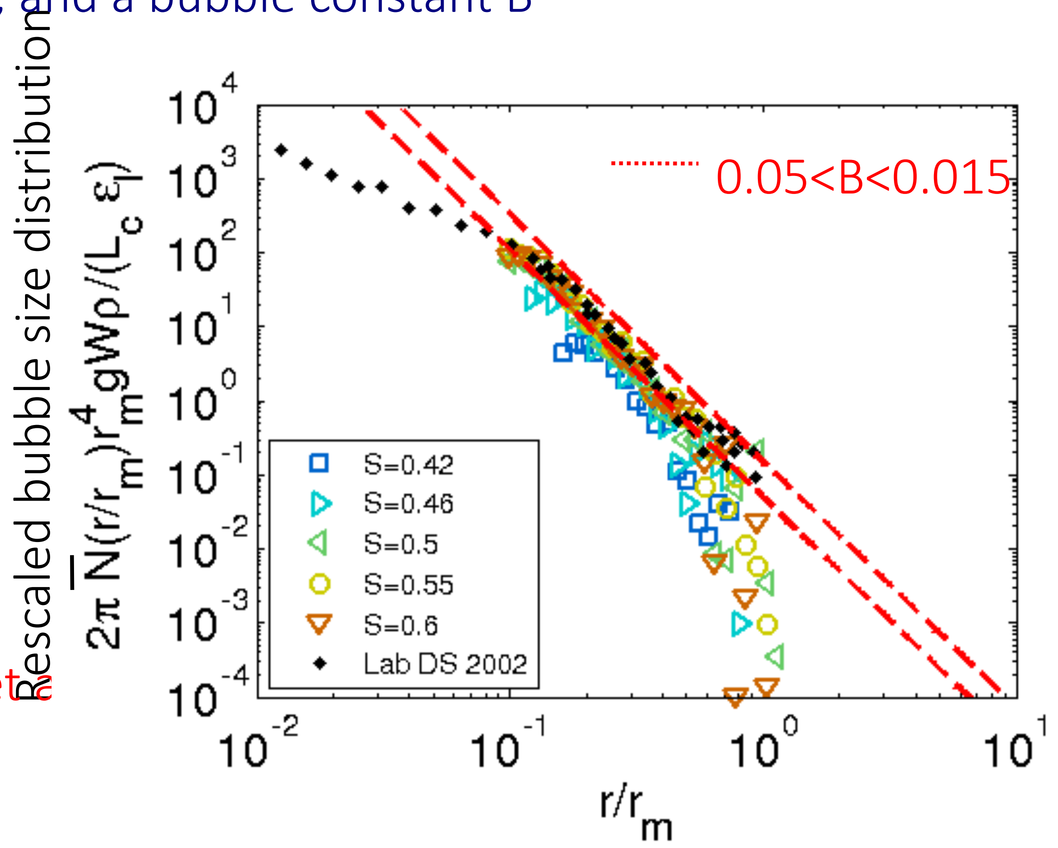
A predictive model for the bubble phase

Model depends on wave variables, and a bubble constant B

$$\overline{N(r)} = \frac{B}{2\pi}\frac{\epsilon_l}{gW\rho} r^{-10/3} r_m^{-2/3} L_c$$

B= $\frac{\text{Energy in the bubbles}}{\text{Total Dissipated energy}}$

Lab estimation 0.05<B<0.15
(Blenkisopp & Chaplin 2007, Lim et a



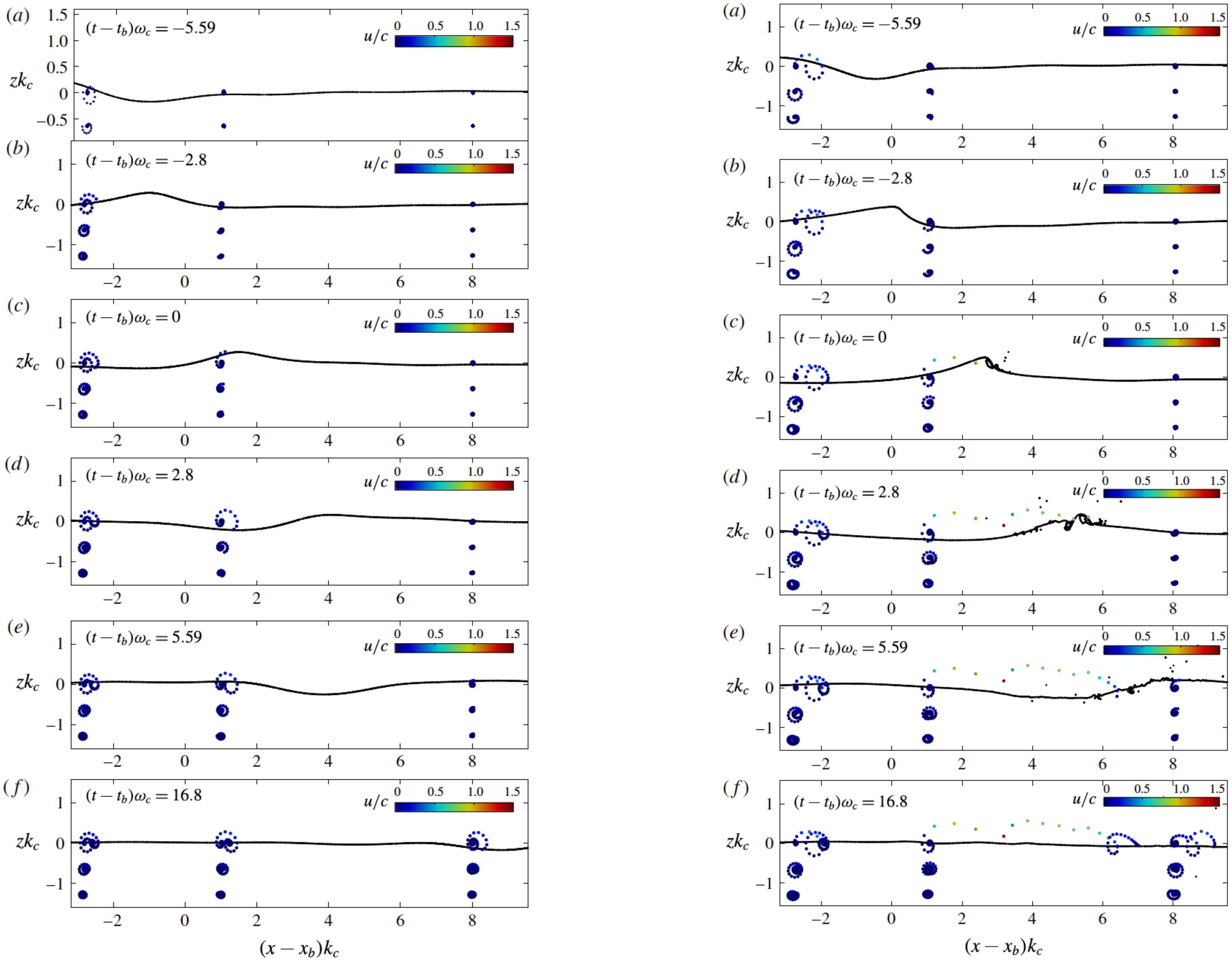
Rescaled radius

Lets apply our model to the field ...

Post-breaking flow: Lagrangian mass transport

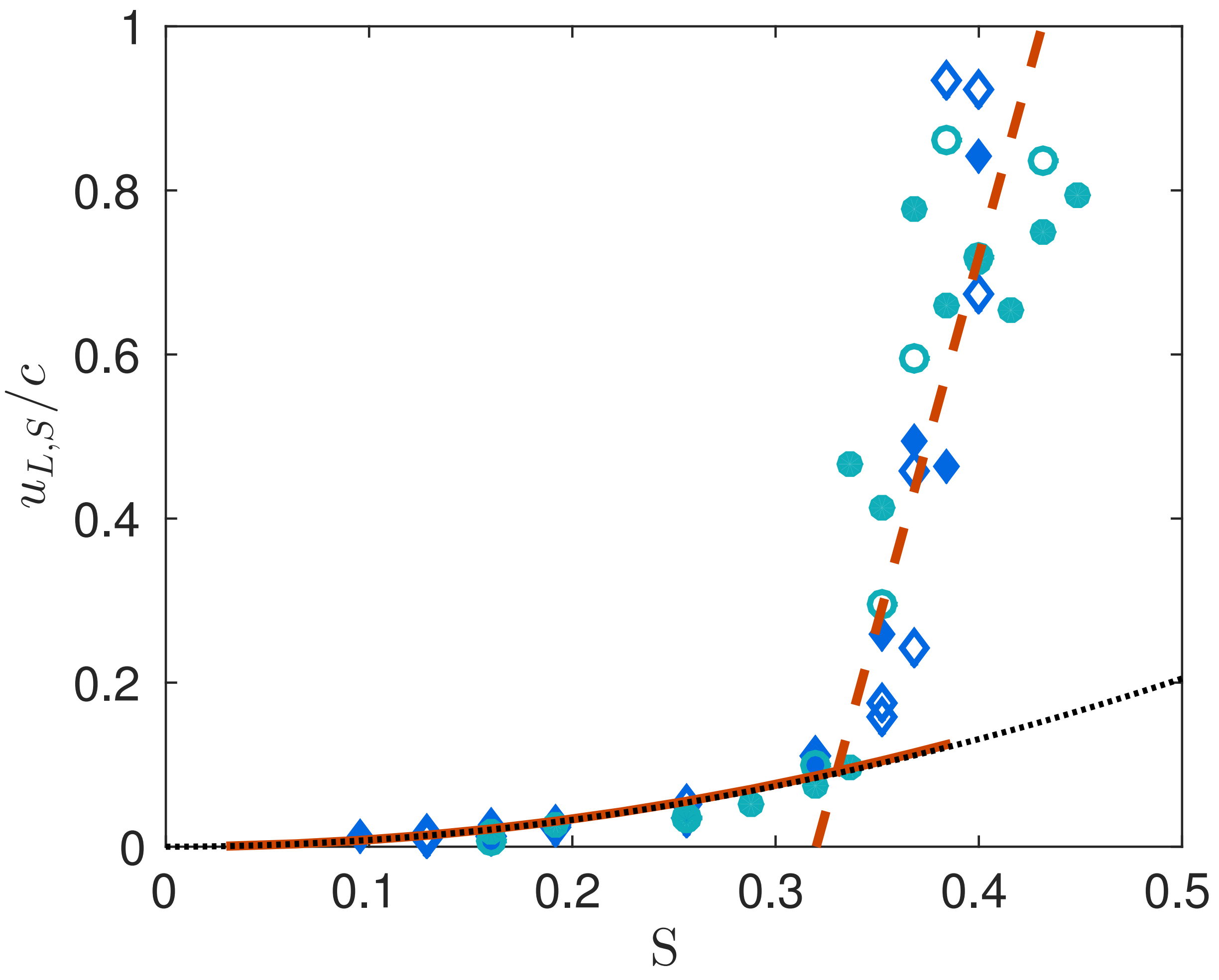
Lagrangian mass transport by breaking waves

Deike, Pizzo and Melville, 2017, J. Fluid Mech.



(a) $(t-t_b)\omega_c = -5.59$
(b) $(t-t_b)\omega_c = -2.8$
(c) $(t-t_b)\omega_c = 0$
(d) $(t-t_b)\omega_c = 2.8$
(e) $(t-t_b)\omega_c = 5.59$
(f) $(t-t_b)\omega_c = 16.8$
u/c
0 0.5 1.0 1.5
zk_c
$(x-x_b)k_c$

Lagrangian drift up to an order of magnitude larger during breaking



Deike, Pizzo and Melville, 2017, J. Fluid Mech.

Spray generation by bursting bubbles

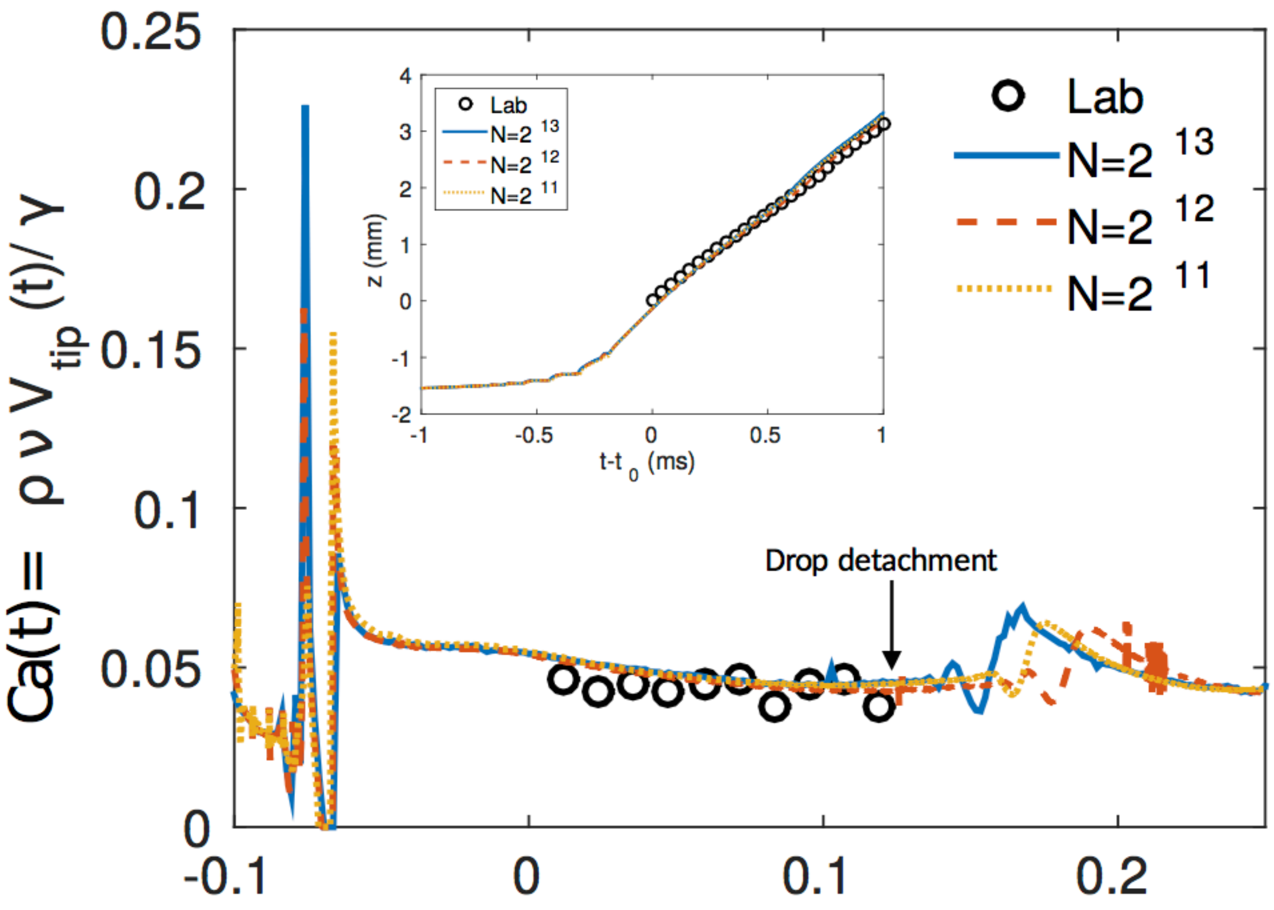
The dynamics of jets produced by bursting bubbles: Direct numerical simulations (DNS) using Gerris

The dynamics of jets produced by bursting bubbles: Cross validation between laboratory experiments and DNS

Simulations & lab (Ghabache et al 2014)

The dynamics of jets produced by bursting bubbles: Cross validation between laboratory experiments and DNS

Air bubble in water, $La = 6.7 \times 10^4$, $Bo = 0.1172$



Deike, Ghabache, Das, Liger-Belair, Zaleski, Popinet, Seon In review, Phys. Rev Fluids.

The dynamics of jets produced by bursting bubbles: Cross validation between laboratory experiments and DNS

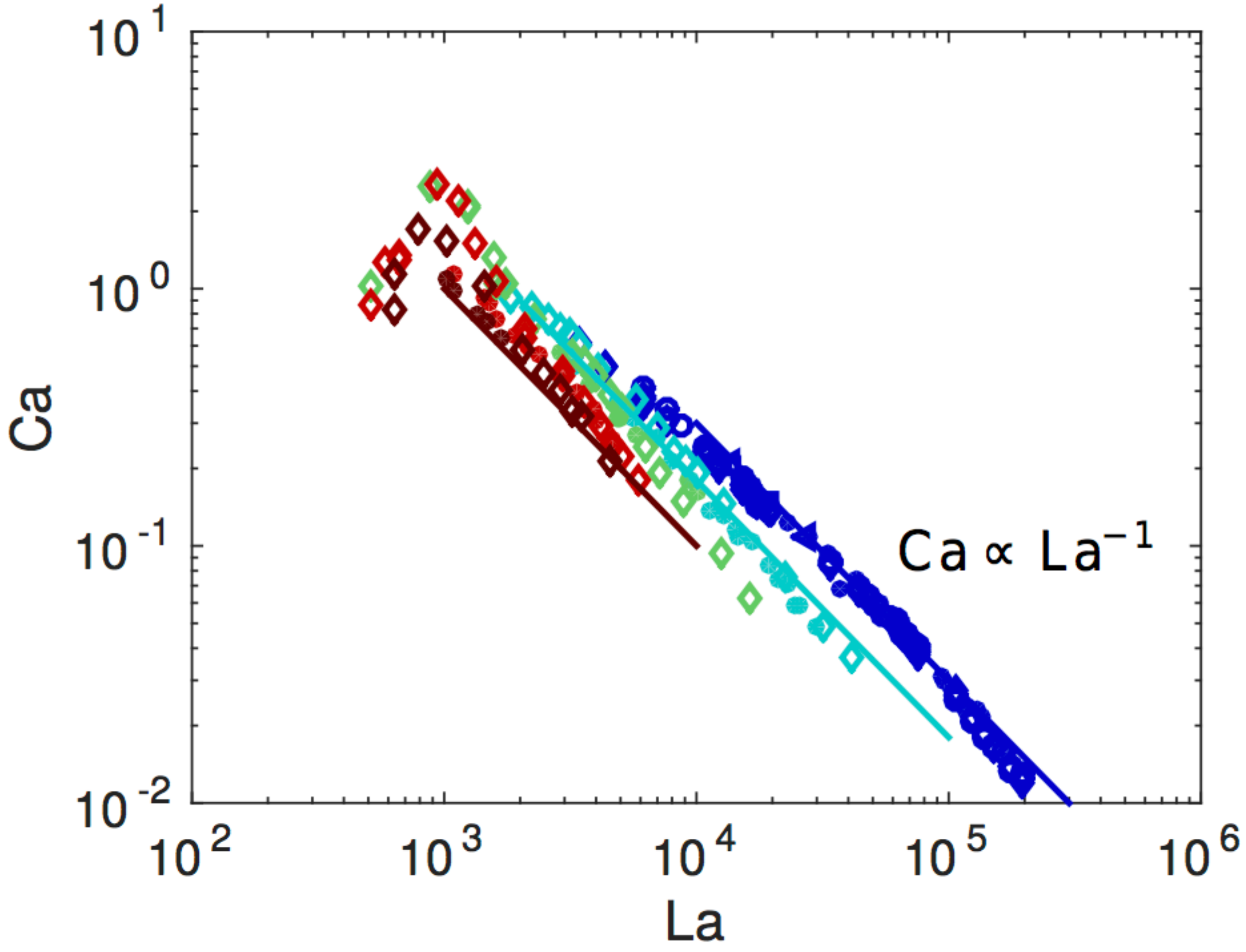
Normalized velocity

$$\mathrm{Ca} = v_{tip}\mu/\gamma$$

Dimensional number

$$La = \rho\gamma R/\mu^2$$

$$Bo = \rho g R^2/\gamma$$



Filled circles: experiments, open diamonds and triangles: numerics

Deike, Ghabache, Das, Liger-Belair, Zaleski, Popinet, Seon In review, Phys. Rev Fluids.

The dynamics of jets produced by bursting bubbles: Jet velocity v=f(La,Bo)

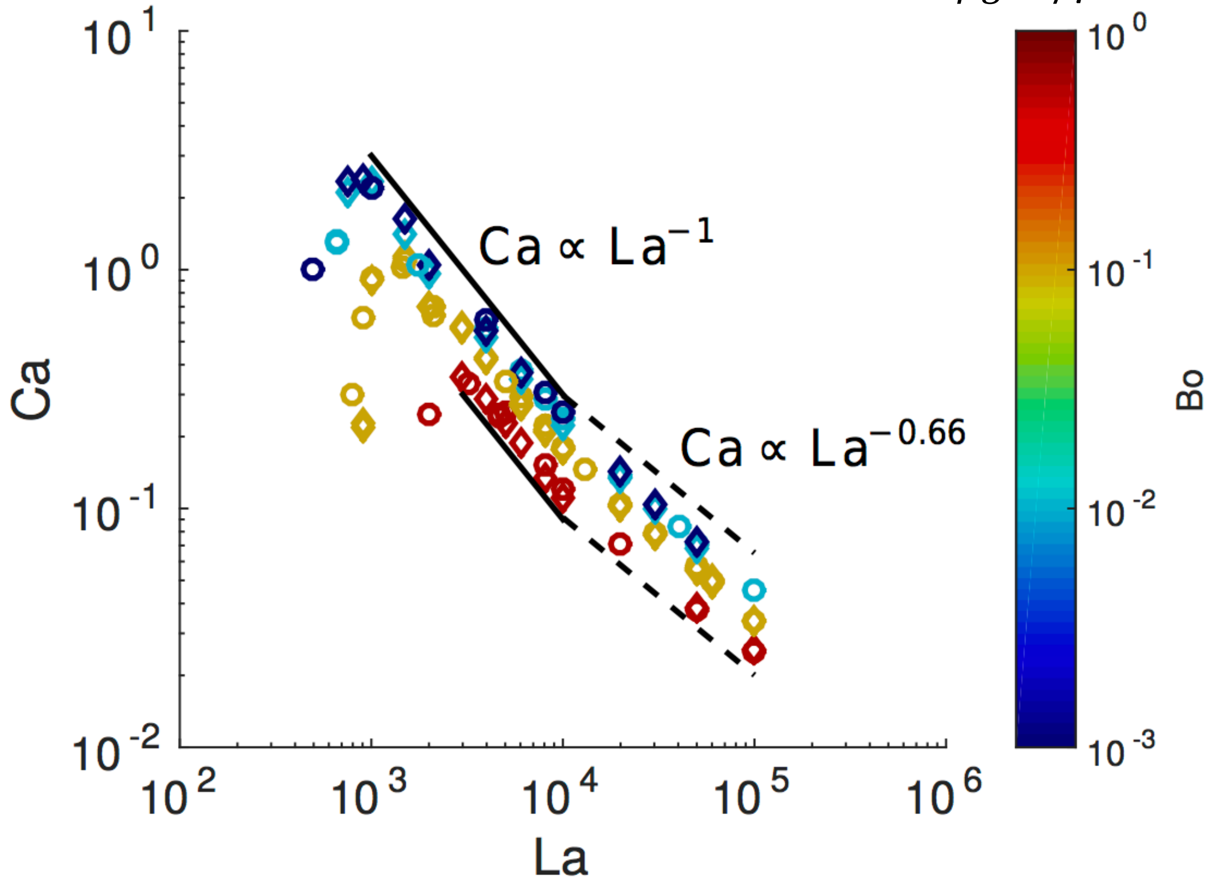
Normalized velocity

$\mathrm{Ca} = v_{tip}\mu/\gamma$

Dimensional number

$La = \rho\gamma R/\mu^2$

$Bo = \rho g R^2/\gamma$



In review, Phys. Rev Fluids.

The dynamics of jets produced by bursting bubbles: Jet velocity v=f(La,Bo)

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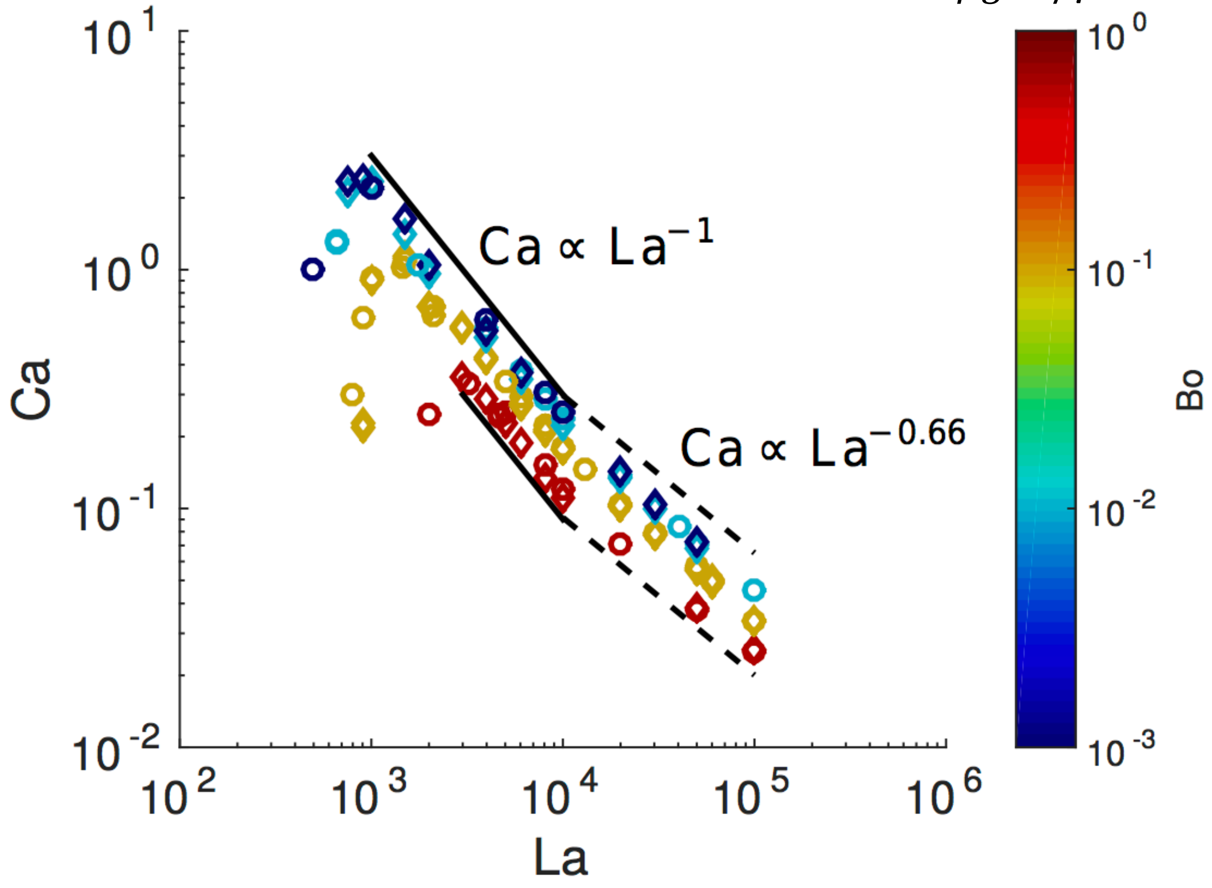
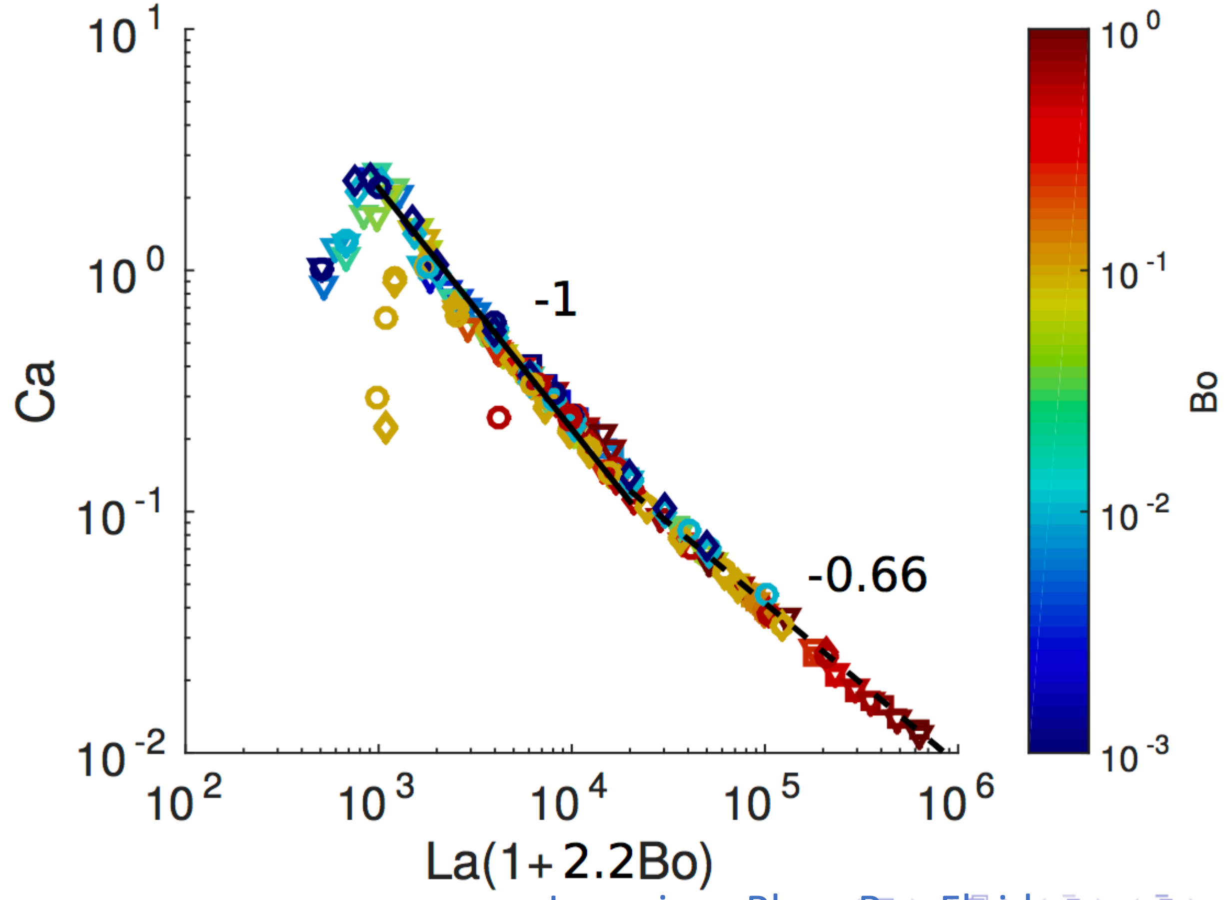
$Bo = \rho g R^2/\gamma$





In review, Phys. Rev Fluids.

Conclusions

General understanding of the two-phase flow associated with breaking

Model for dissipation and the bubble statistics under a breaking wave using lab and numerical results

Deike, Popinet and Melville 2015, J. Fluid Mech.
Deike, Melville and Popinet 2016, J. Fluid Mech.

Current Generation by breaking waves *Pizzo, Deike and Melville 2016, J. Fluid Mech.*

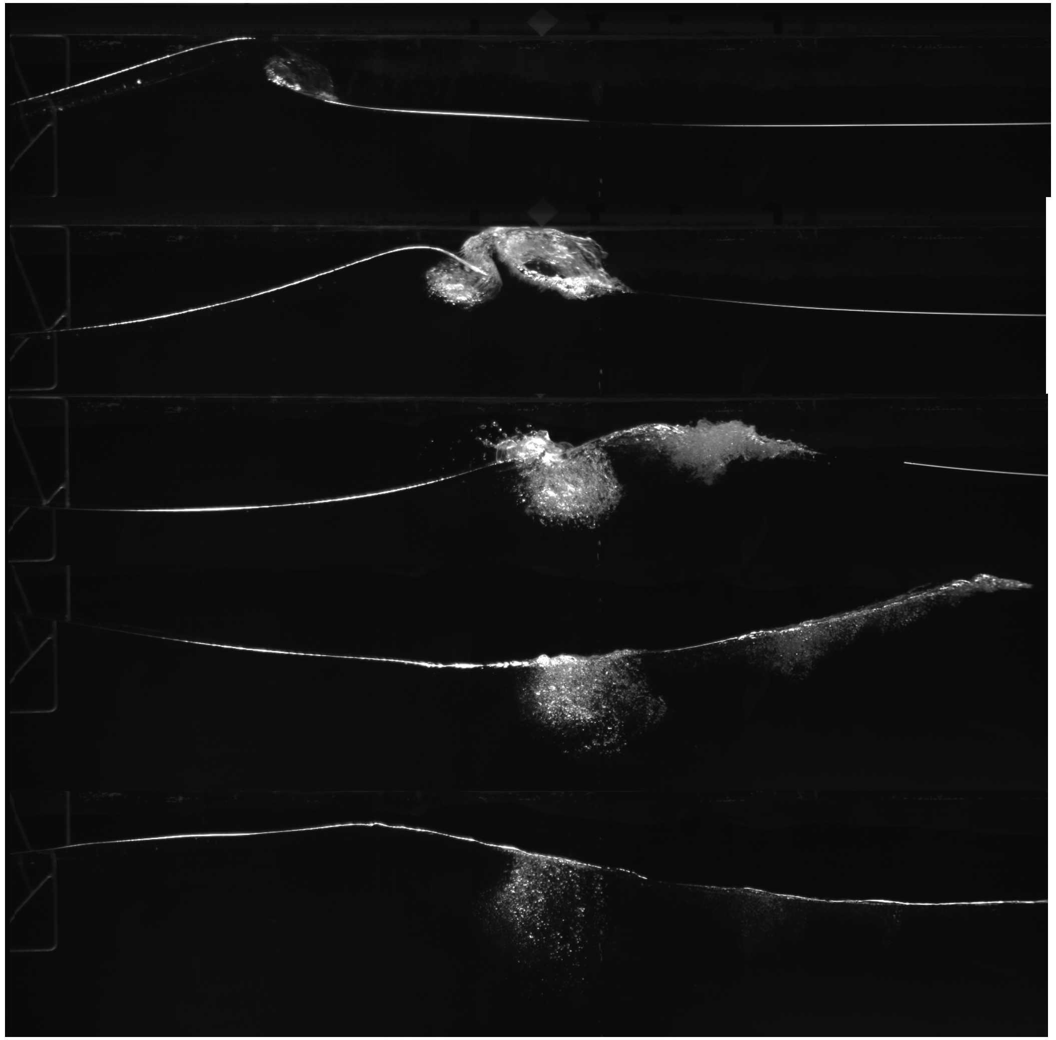
Lagrangian drift due to breaking waves *Deike, Pizzo and Melville 2017, J. Fluid Mech.*

Spray generation by bubble bursting *With A. Berny, T. Seon, S. Popinet, S. Zaleski*

Upscaling strategy to the ocean,

semi-empirical relationships between air entrainment and wind wave conditions
first step for physics based parameterization of gas transfer

Deike, Lenain and Melville 2017, GRL.
Deike and Melville, in preparation



Thank you for your attention...