Breaking waves in ocean-atmosphere interactions

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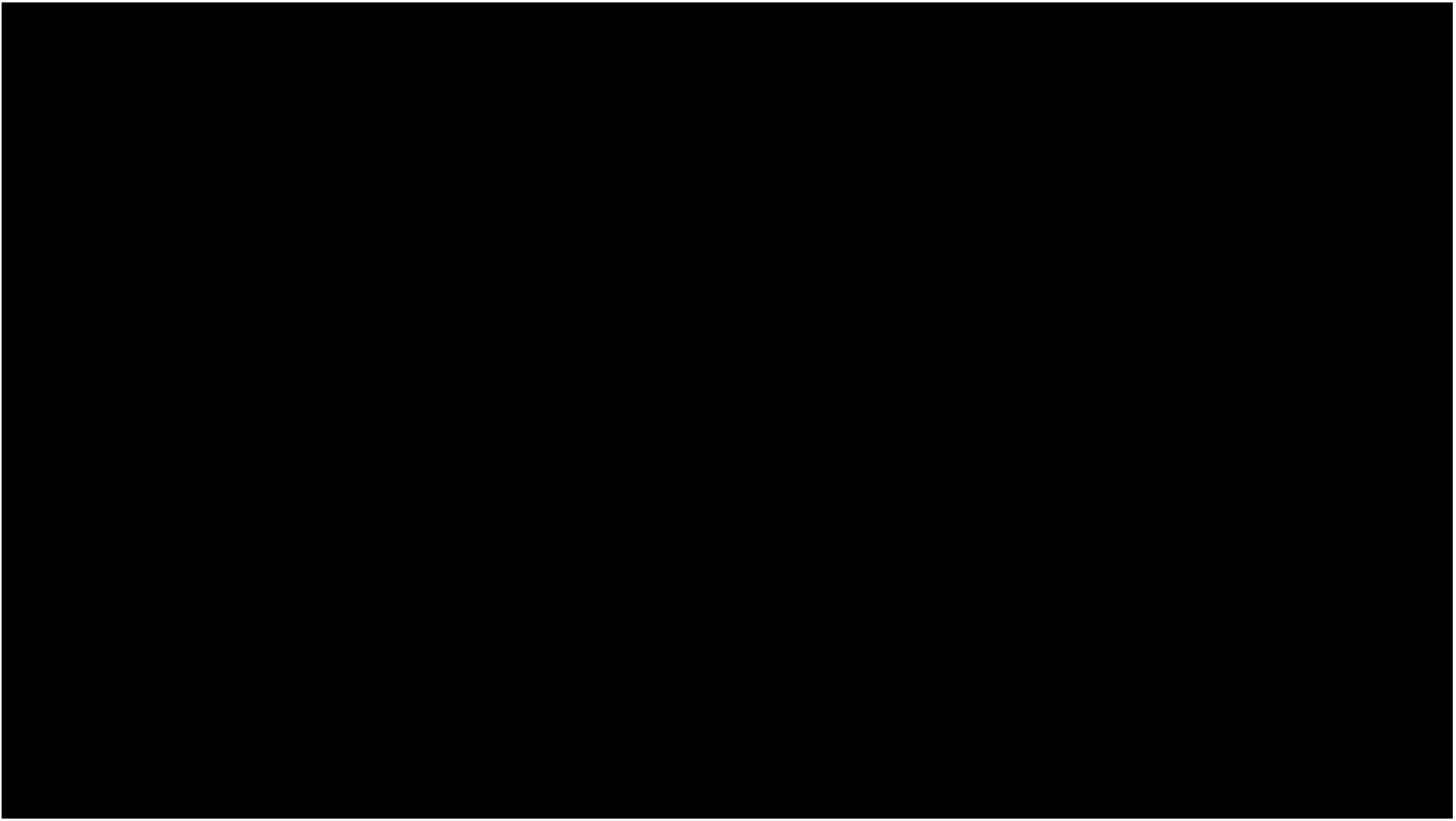
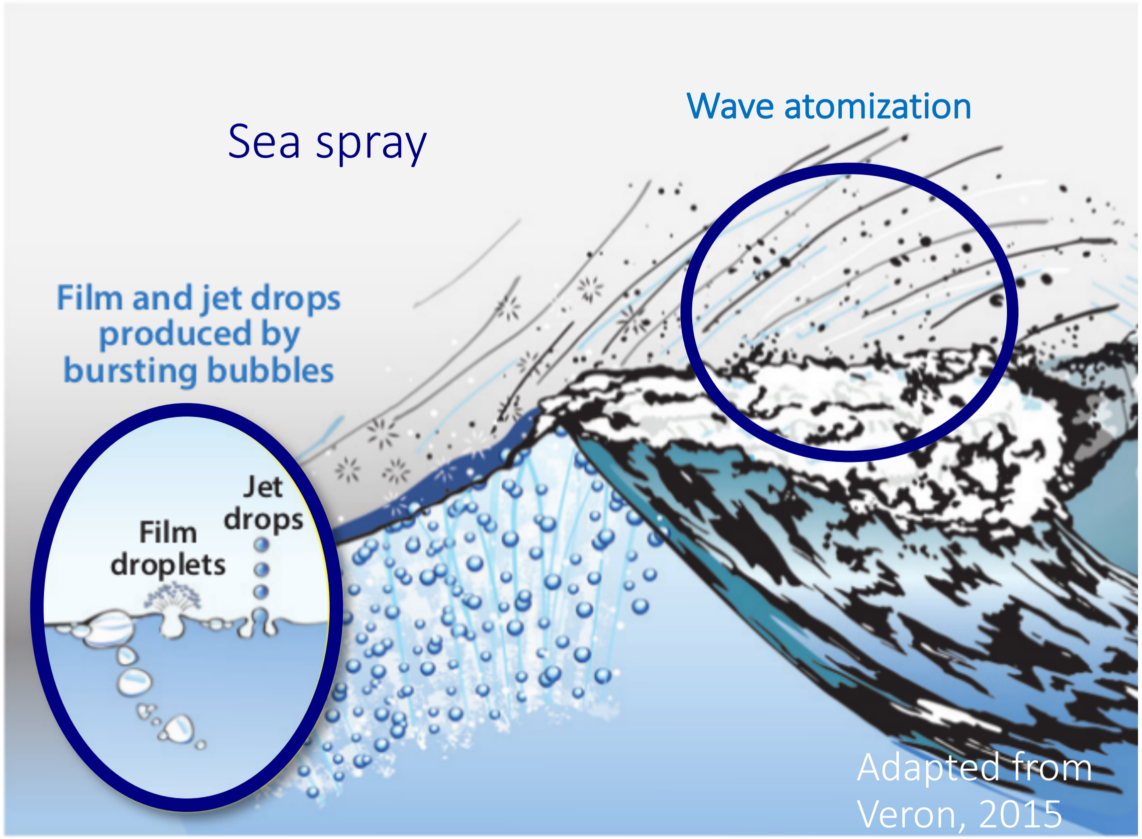
The role of wave breaking in air-sea interaction



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

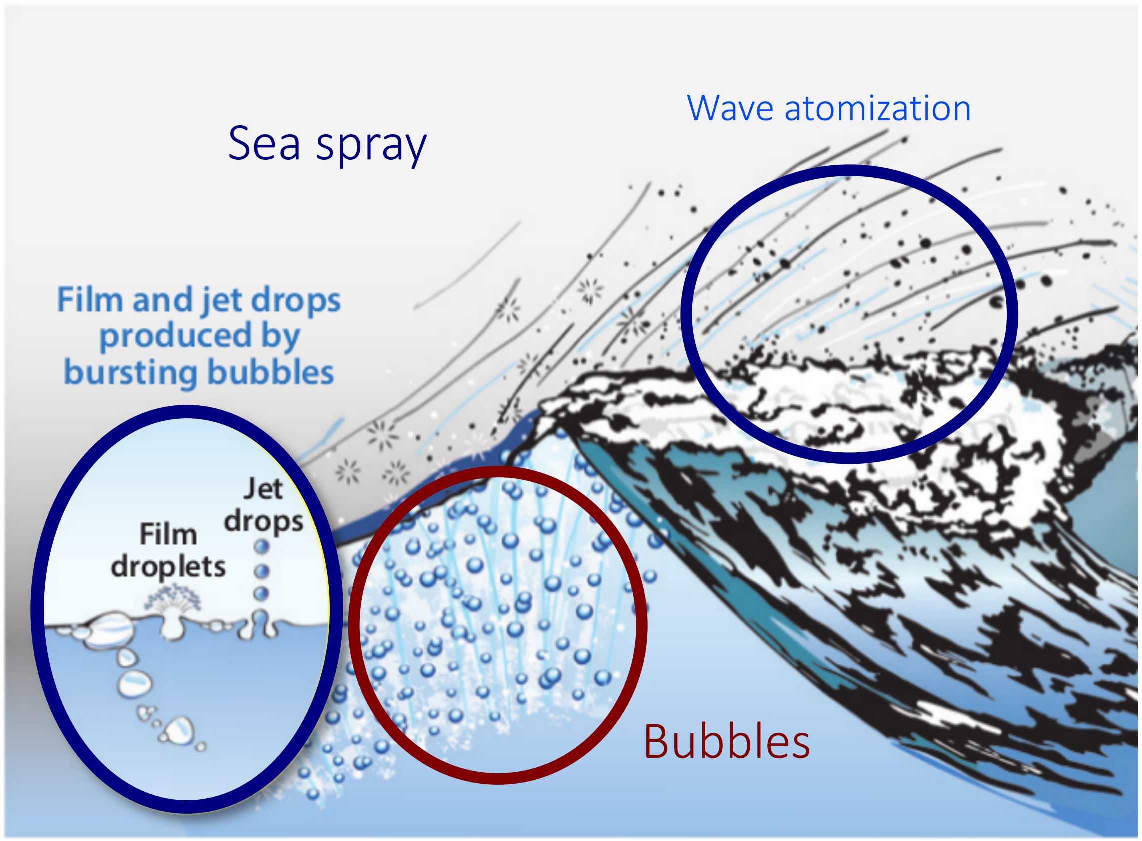


From water to air: Transfer of momentum, heat, moisture

Production of aerosols (sea salt, biological particles)

→climate impact (cloud nucleation & radiative balance)

Mass transfers and climate impacts

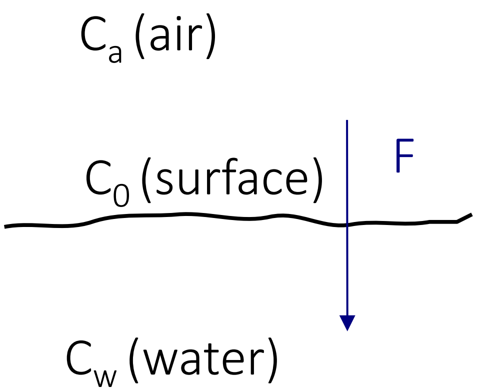


Adapted from Veron, 2015

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)

How is gas transfer physically modeled?



Solubility

$$F = -kw\,(C_0 - Cw) = -kw\,S(Ca - Cw)$$

Transfer velocity: $k_w \propto Sc^{-n}\boxed{U_{10}^{m}}$

Schmidt number

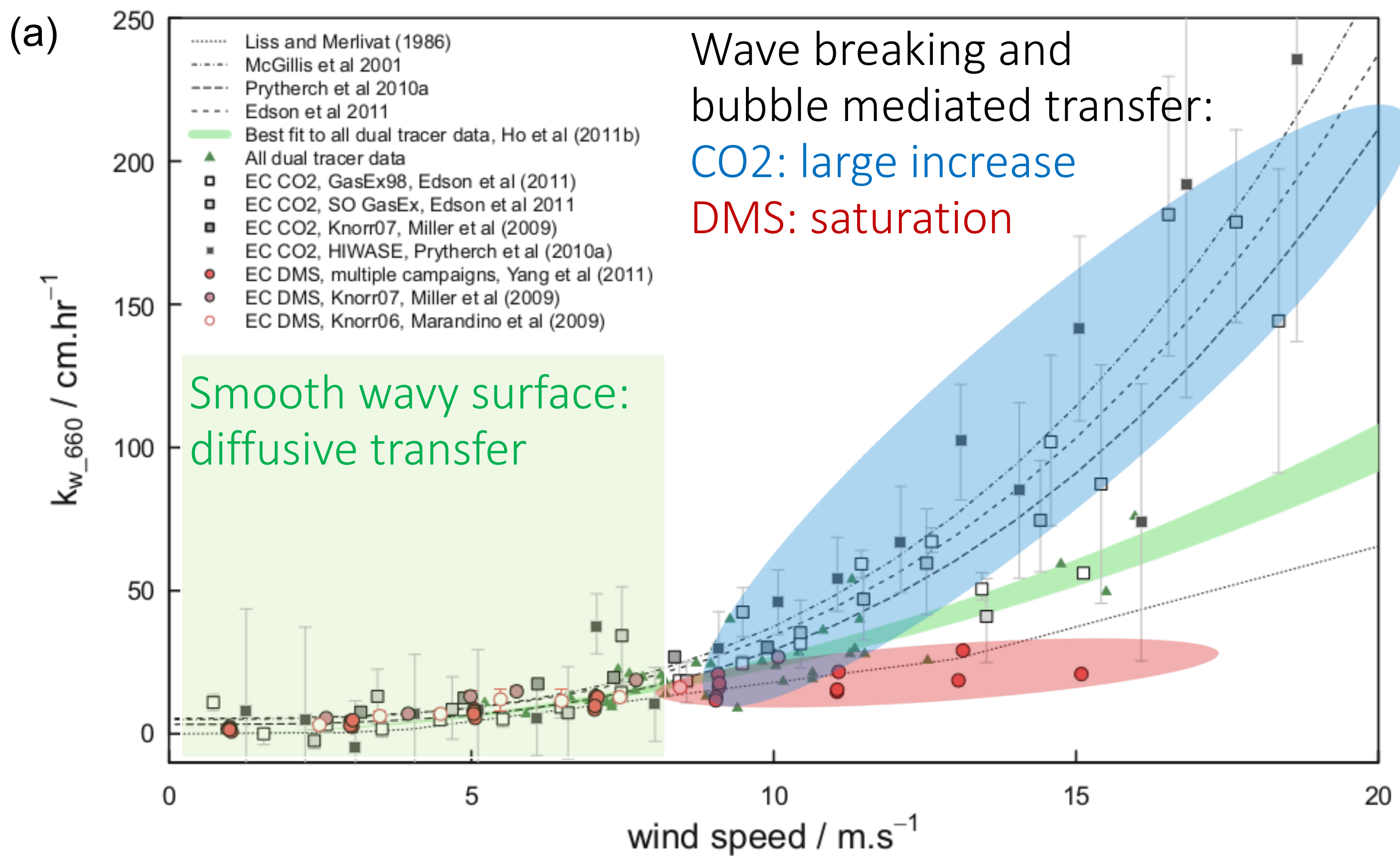
Wind speed U

$$Sc = \nu/D$$

Wanninkhov et al 2009
Garbe et al 2014

Is the wind speed the good parameter
to describe wave breaking transfer?

Field measurement of the transfer velocity



- - Various parameterizations

$$k_w \propto Sc^{-n} U_{10}^{m}$$

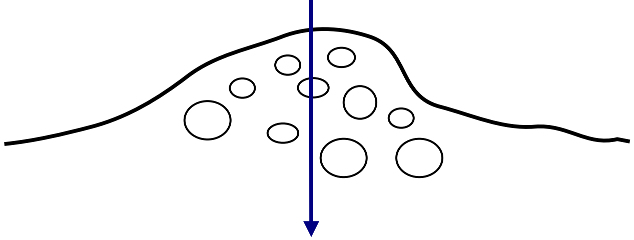
$$1 \leq m \leq 4$$

Garbe et al 2014

Wind speed is not enough to describe the transfer of gas
Need for an understanding of bubbles in breaking waves

Large uncertainties on the role of bubbles

$$F_t = F + Fb$$



$$F_b = \int j(r, wb, D, S, \ldots)n(r,z)drdz$$

bubble size/velocity

gas diffusivity/ solubility

bubble size distribution

Woolf & Thorpe 1991
Keeling 1993

Bubble resolving models,
Ocean bubble transfer from 0 to 40% of the total gas flux

Thorpe et al 2003, Zhang 2012, Liang et al 2011, 2012, 2013

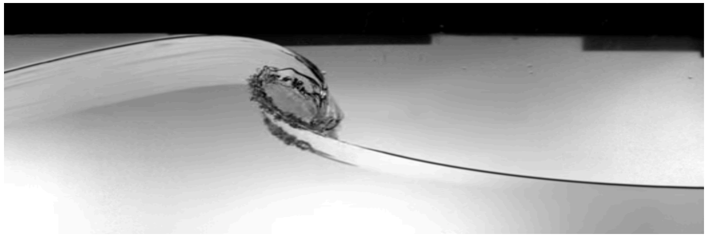
Need to constrain the bubble size distribution n(r,z)

A multiple scale problem

O(1km) to O(1m)

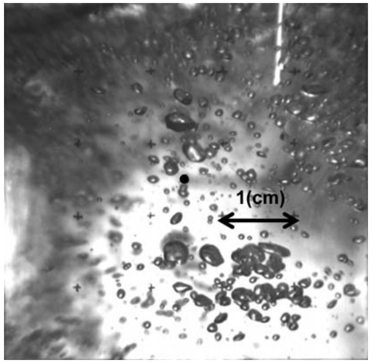
Waves and
wave breaking statistics

O(10m) to O(1m)



Breaking event

O(1cm) to O(1μm)



Bubbles in a turbulent flow

Quantify air entrainment and bubble statistics in the turbulent two-phase flow associated with breaking for a single breaker

Upscale to the field using the wave and wave breaking statistics

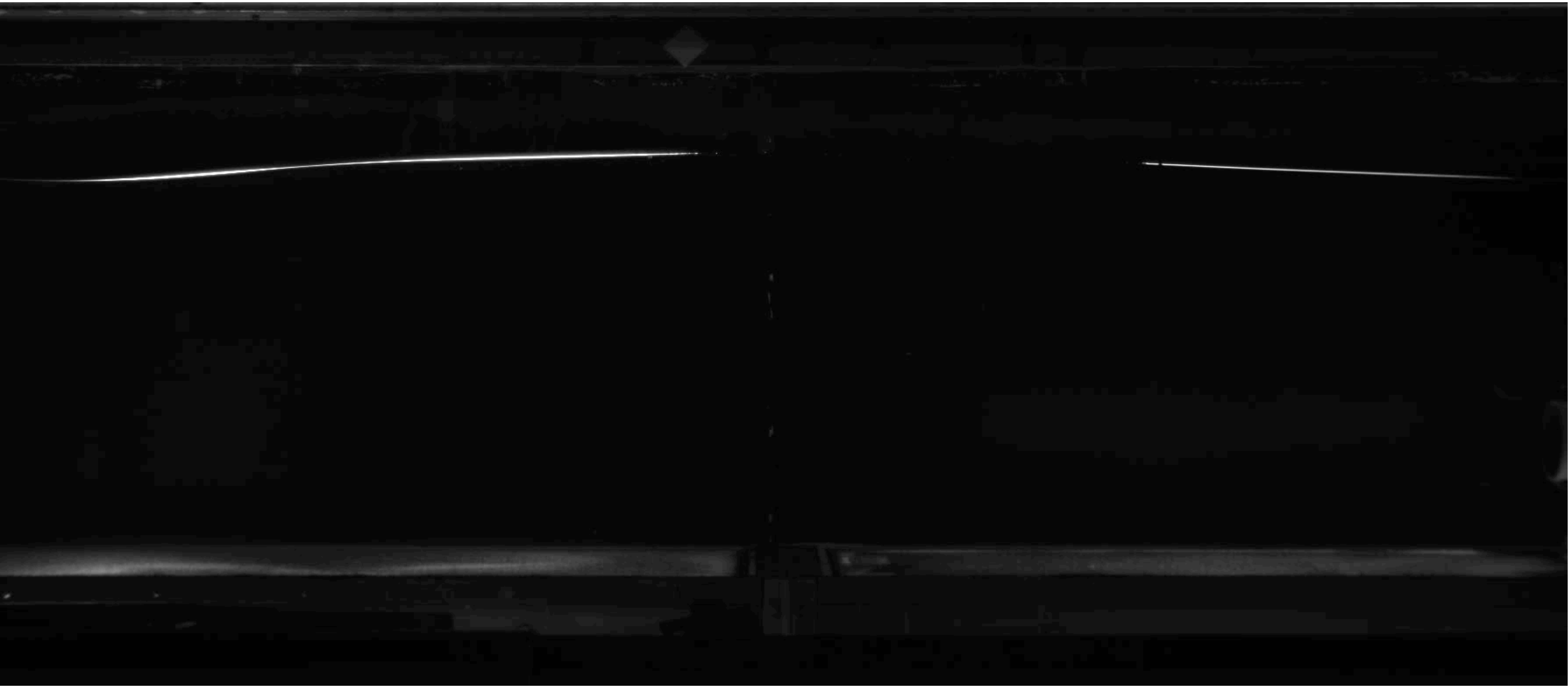
1. Simulations and labs of breaking waves

2. Quantify wave breaking dissipation

3. From dissipation to air entrainment and bubble statistics

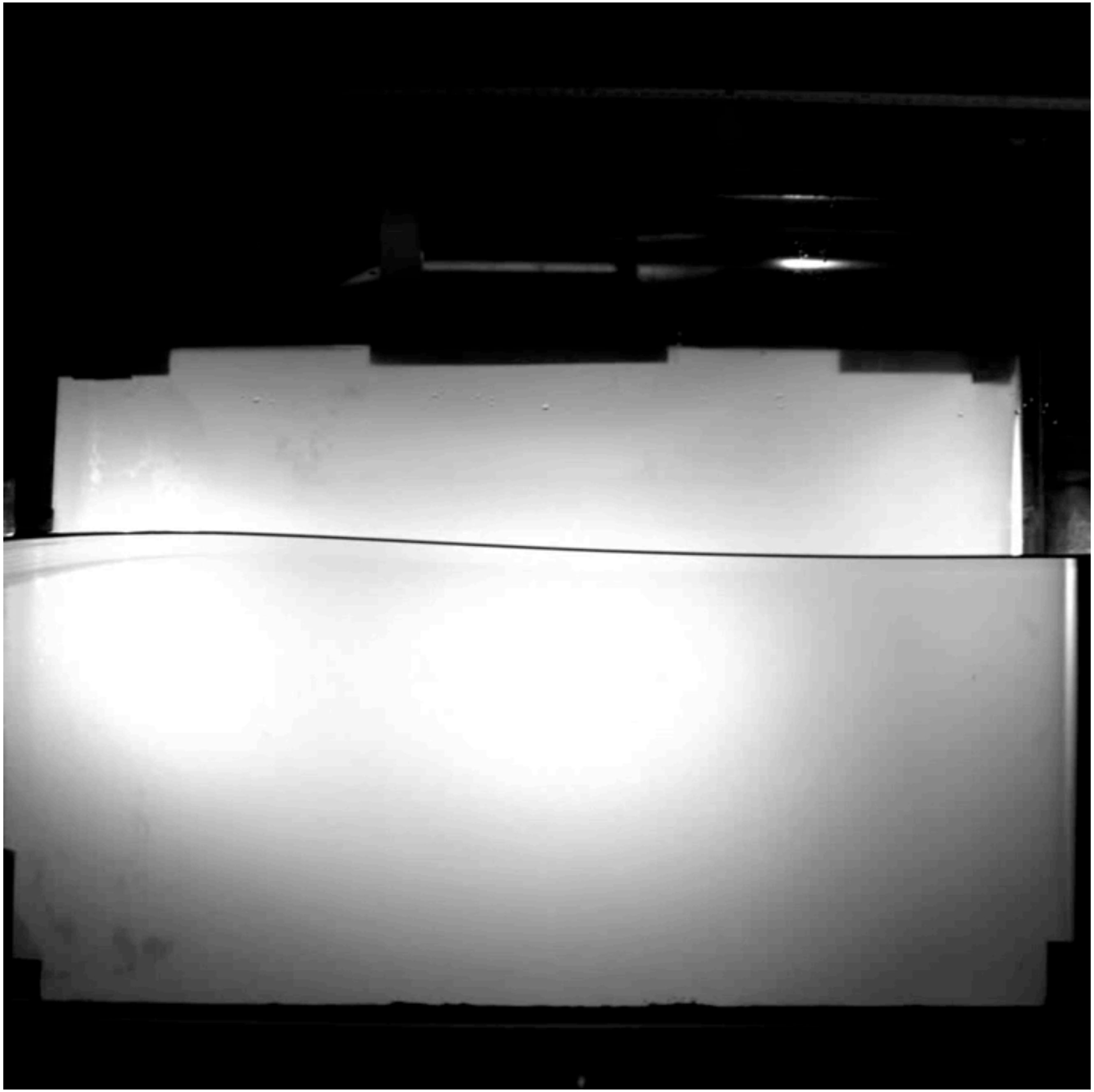
4. Upscaling to the field

Breaking waves: lab experiments



Scripps Institution of Oceanography wave channel

Breaking waves: lab experiments

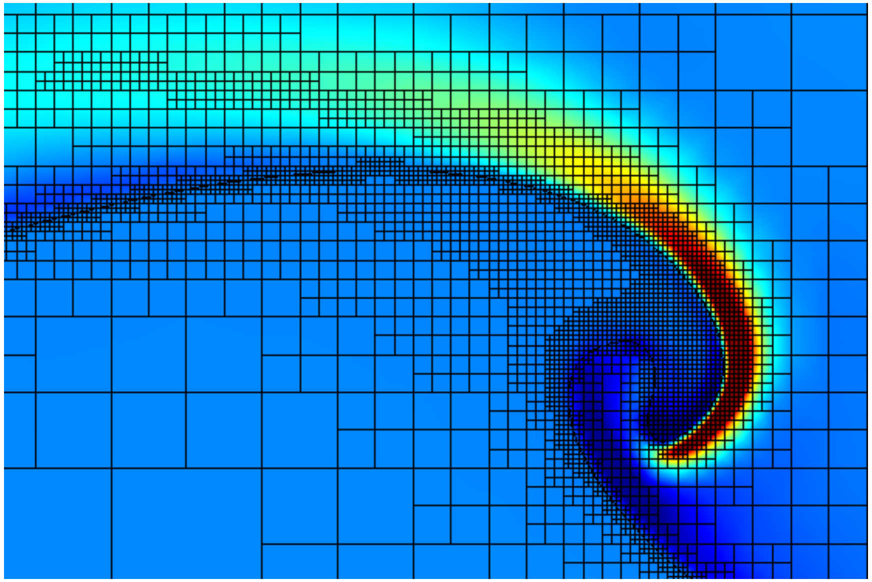


Breaking waves:
Direct Numerical Simulations (DNS)

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



Deike et al, 2015, JFM

Highly efficient tool:
Wide exploration of the parameter space

DNS of three-dimensional breaking waves

High Reynolds number

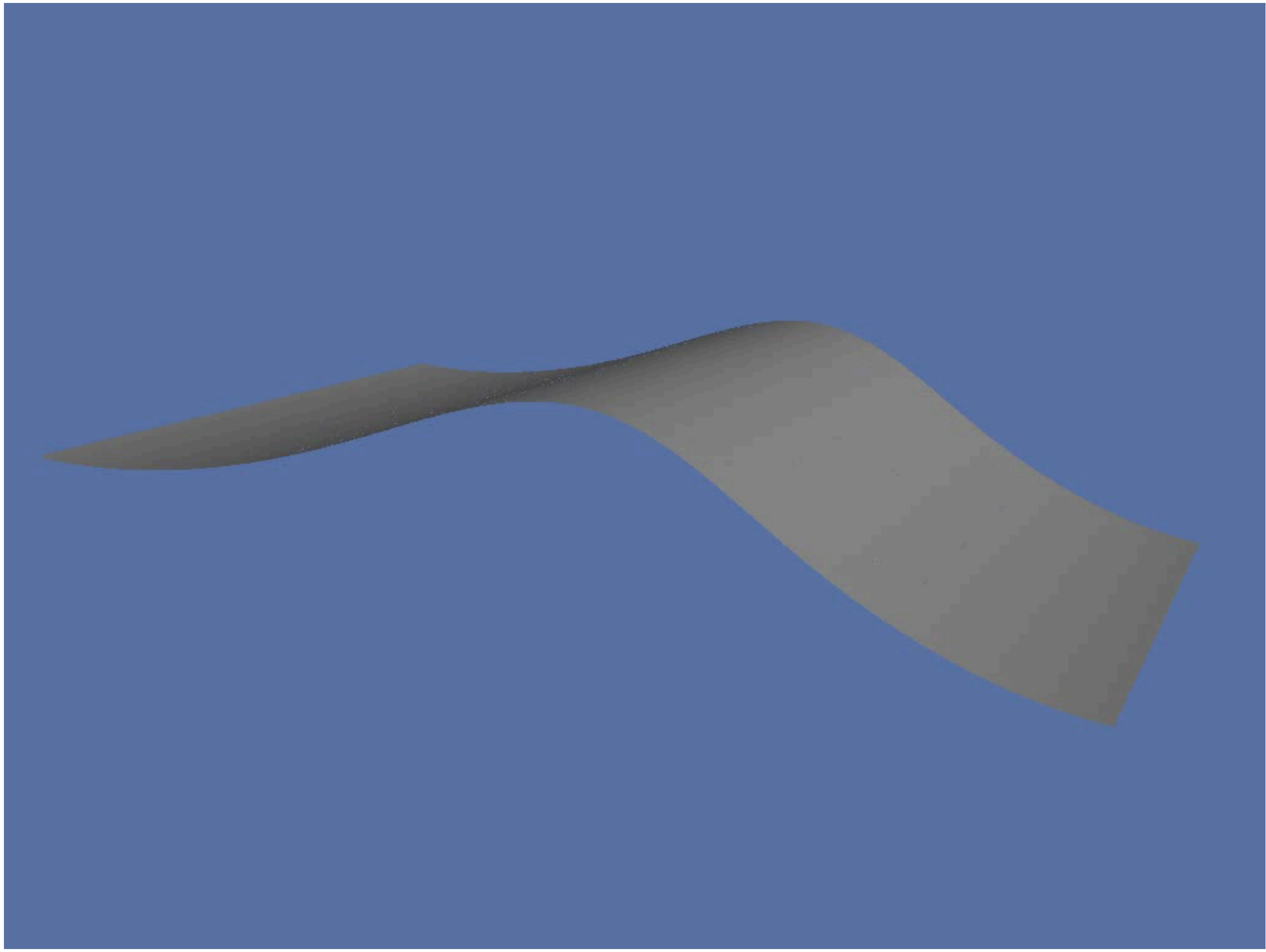
$$\mathrm{Re} = \frac{c\,\lambda}{\nu} = 40000$$

Intermediate Bond number

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

Mesh size: up to 0.22 mm

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



Deike et al, 2016, JFM

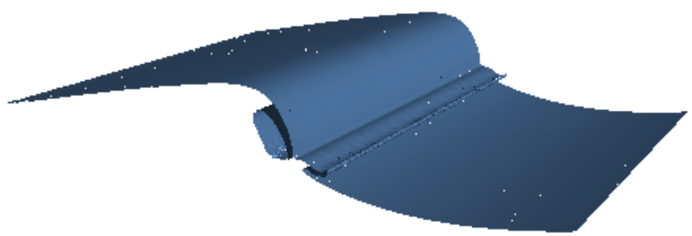
Solves accurately the dissipative
and bubbles generation length scale

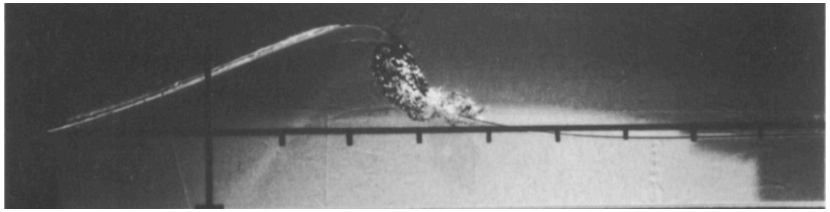
Waves of increasing slopes

DNS, Stokes waves

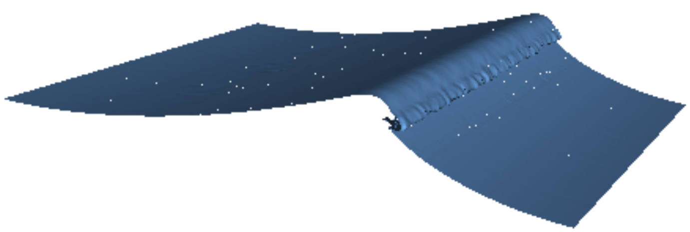
Lab, focusing wave packet

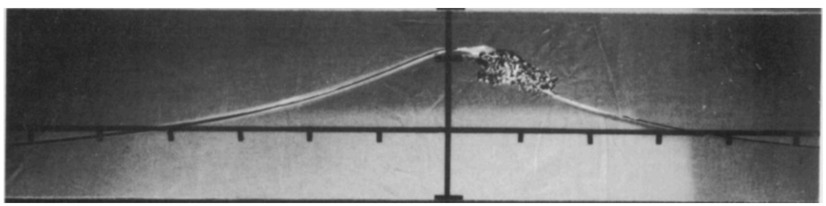
Plunging breaker, S=0.5





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

2. Quantify wave breaking dissipation

Dissipation due to wave breaking

Kinetic equation: describes the wave field evolution (Phillips 1985)

$$\frac{\partial N_k}{\partial t} = S_{input} + S_{nl} + S_{diss}$$

Dissipation due to wave breaking

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$$\frac{\partial N_k}{\partial t} = S_{input} + S_{nl} + S_{diss}$$

Dissipation due to breaking (Phillips 1985)

$$S_{diss} = \int \boxed{\epsilon_l} \boxed{\Lambda(c)dc}$$

Dissipation by a single breaking event

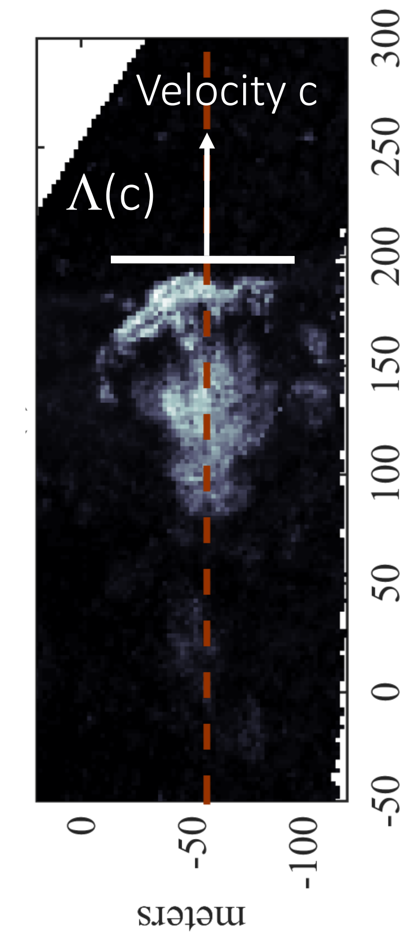
$$\boxed{\epsilon_l = b\rho c^5/g}$$

Lab (Duncan 1981)

Integration over all breaking events

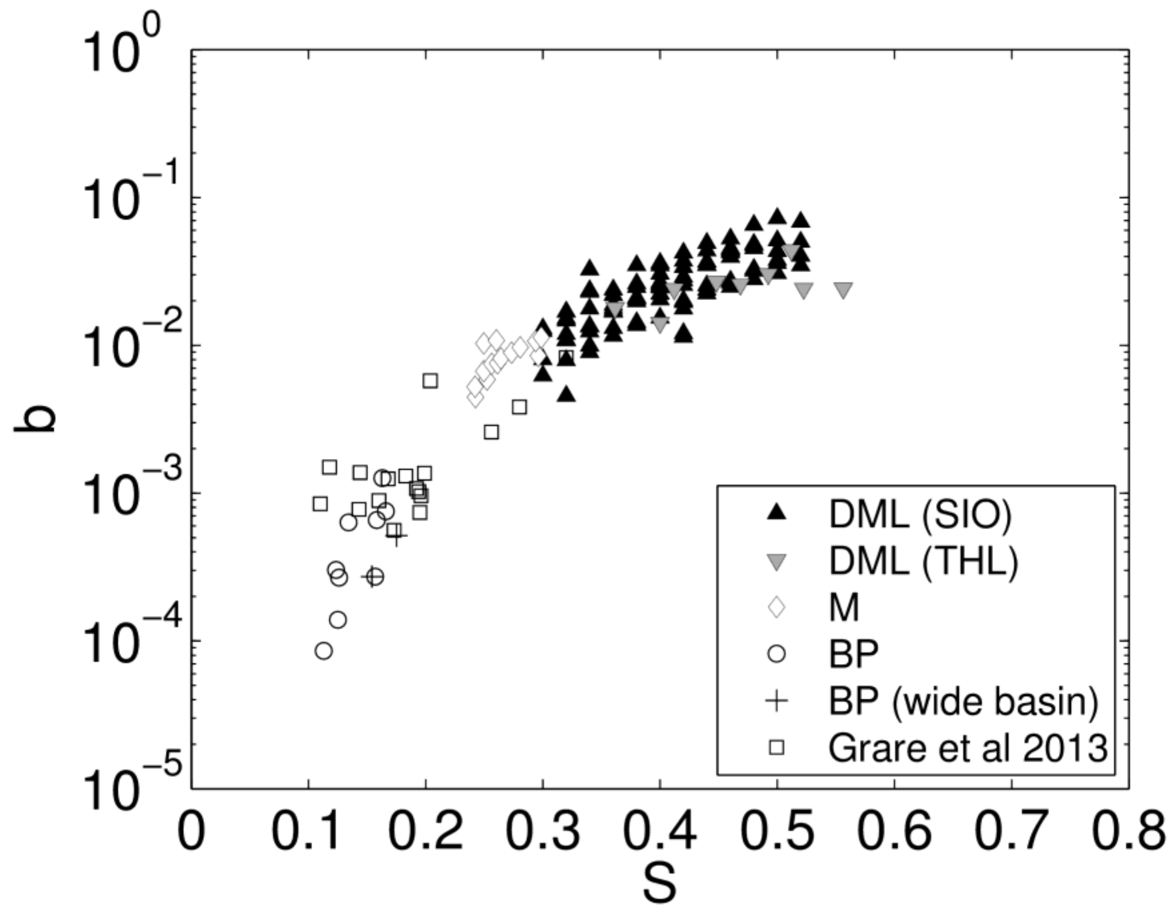
Field measurement

Melville et al 2016



What is the breaking parameter b and is it really a constant?

Experimentally the breaking parameter b varies over several orders of magnitude



Lab data from Melville 1994, Banner and Pierson 2007, Drazen et al 2008, Grare et al 2013

How do we account for the dependence of b on the wave slope?

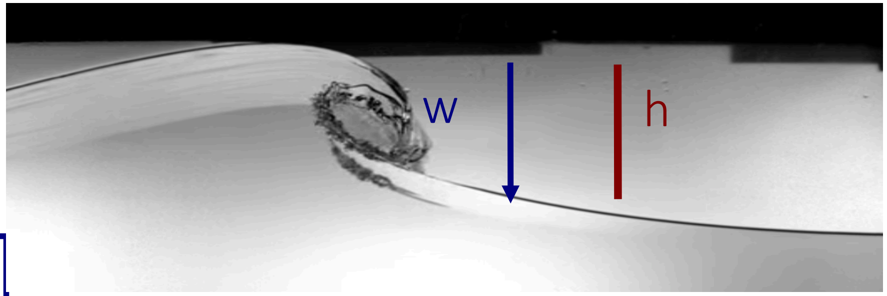
Dissipation by a single breaking event: The dimensionless breaking parameter b

Inertial argument for plunging breaking:

Taylor 1935: $\boxed{\varepsilon \propto w^3/h}$

Drazen et al 2008, Ballistic velocity w

$\boxed{w \propto (gh)^{1/2}} \rightarrow \boxed{\varepsilon \propto g^{3/2}h^{1/2}}$



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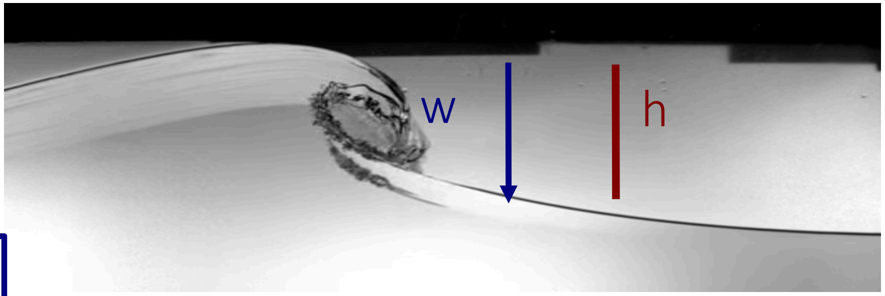
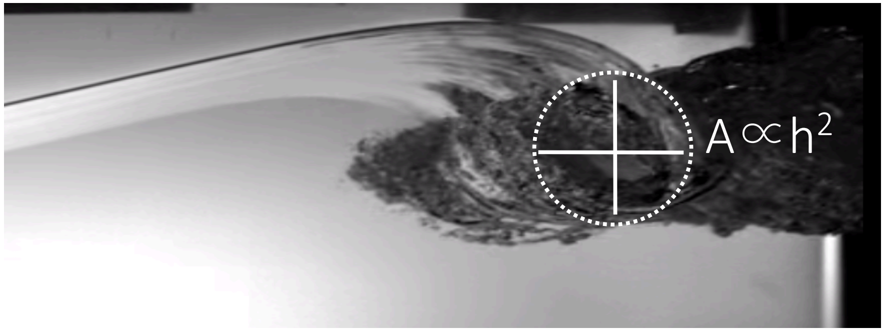


Dissipation per unit length of breaking crest ϵ_l

$$\epsilon_l = \rho A \varepsilon \,;\, A \propto h^2$$

$$\boxed{\epsilon_l \propto g^{3/2}h^{5/2}}$$



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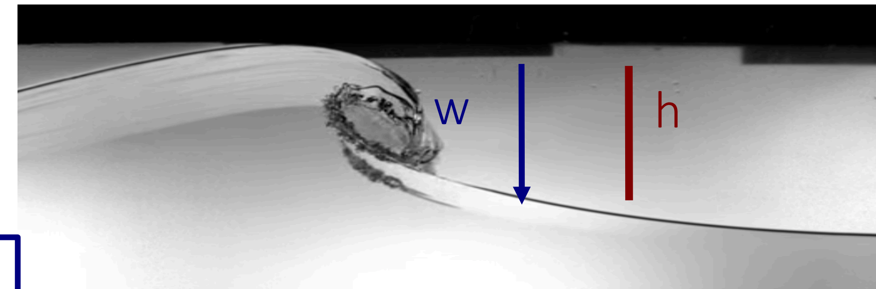

Drazen et al 2008, Ballistic velocity w

$$\boxed{w \propto (gh)^{1/2}} \rightarrow \boxed{\varepsilon \propto g^{3/2}h^{1/2}}$$

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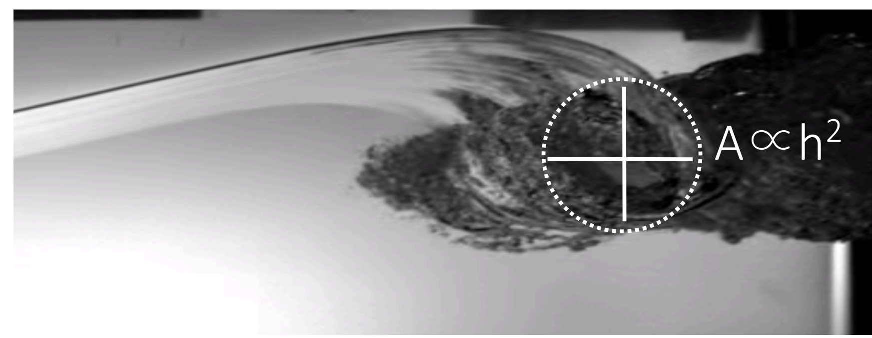


Phase velocity: $c = \frac{\omega}{k} = \sqrt{g/k}$ and the wave slope: $S = hk$

$$\boxed{\epsilon_l \propto S^{5/2}\rho c^5/g}$$

Breaking parameter b: non dimensional measure of the dissipation

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

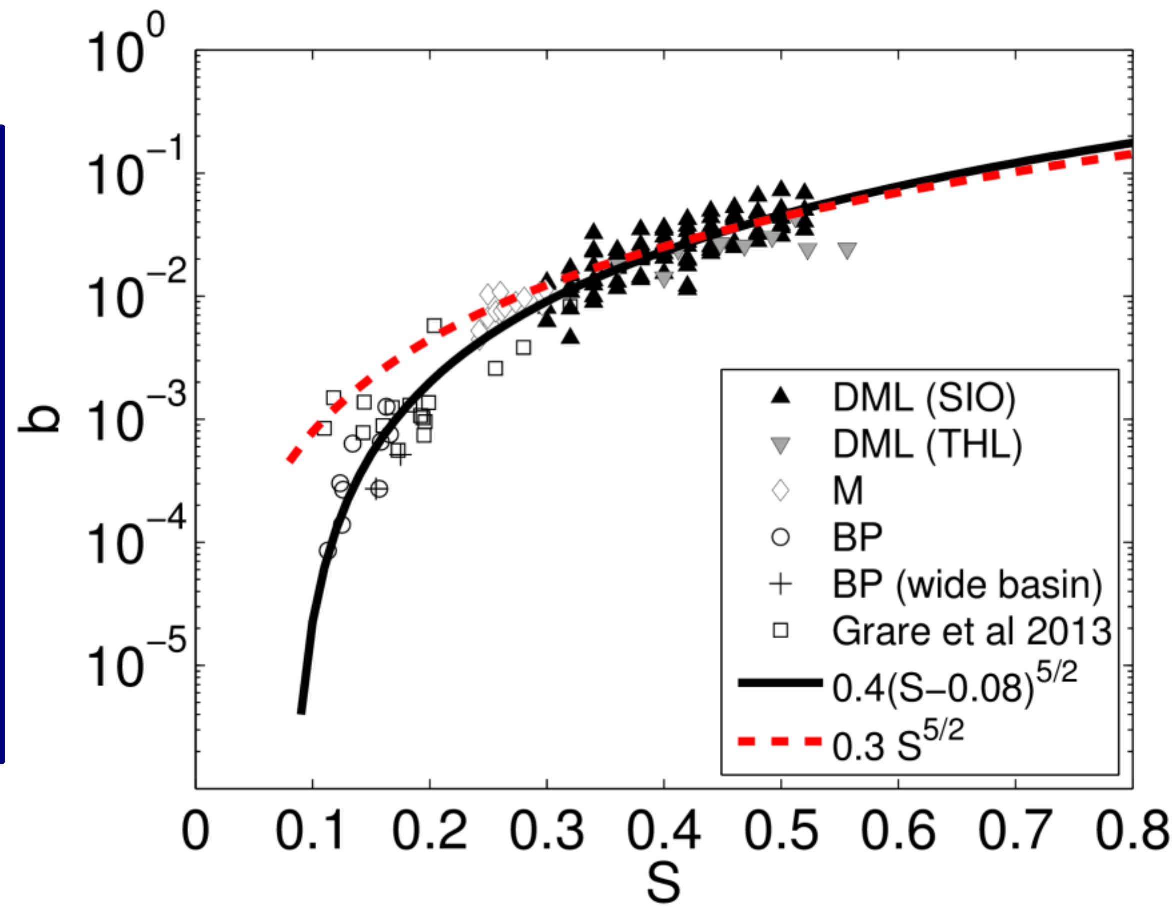
The breaking parameter b: non-dimensional measure of the breaking intensity

Inertial scaling arguments:
(Drazen et al 2008)

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

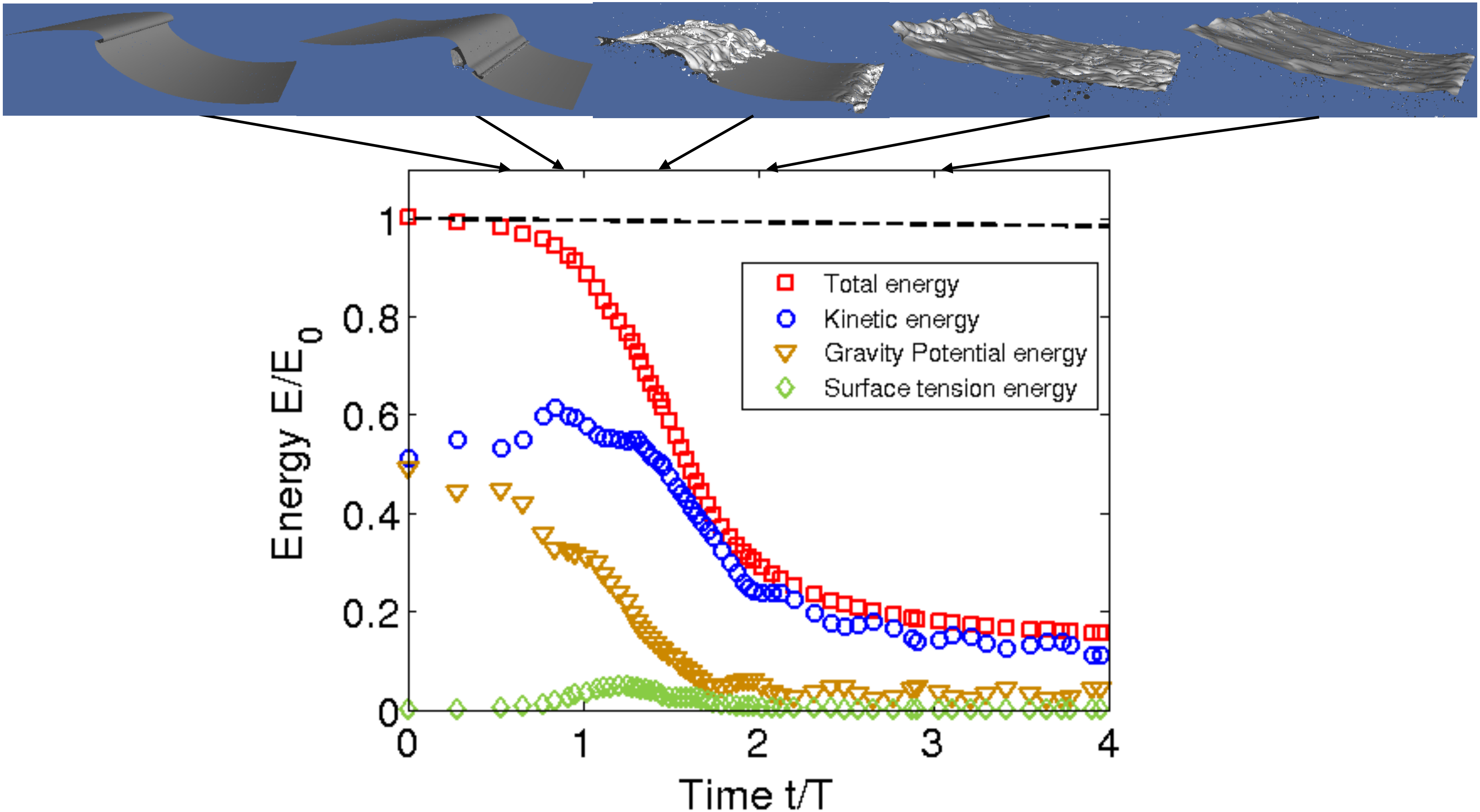
Introducing a breaking threshold:
(Romero et al 2012)

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



Adapted from Romero et al 2012,
Grare et al 2013

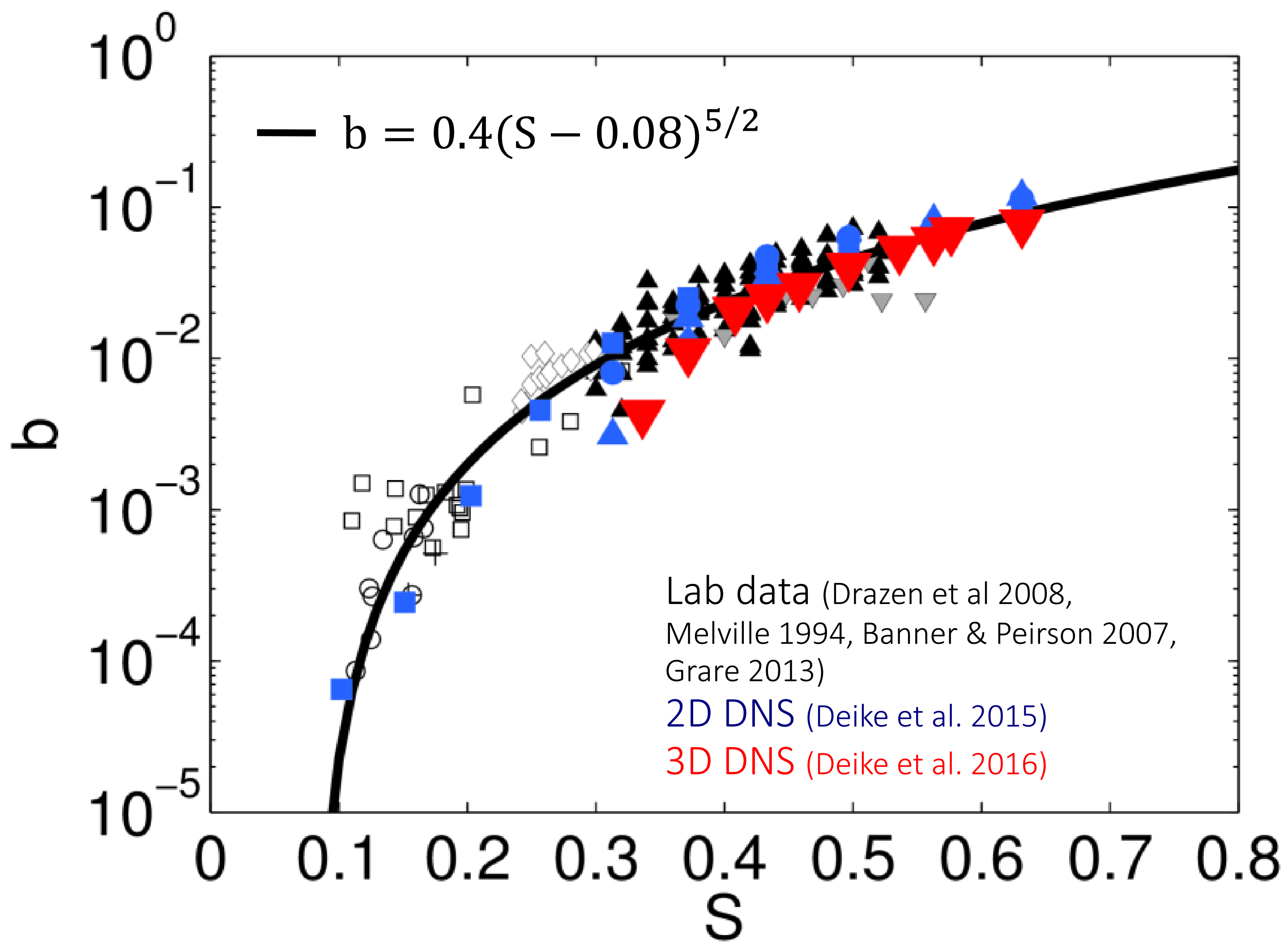
Dissipation during breaking



Strong dissipation

Measure of the dissipation rate ε_l and breaking parameter b

Simulations correctly capture small turbulent scales



Discussion

Dissipation due to breaking described by inertial model (Drazen et al 2008, Romero et al 2012, Deike et al 2015, 2016)

Dissipation by breaking in 2D and 3D simulations agrees with experimental data

Small dissipative scales are correctly resolved Deike et al 2015, 2016.

→ Air entrainment and bubble statistics using 3D DNS

3. From dissipation to air entrainment and bubble statistics

A framework for air entrainment and gas transfer

Dissipation $S_{diss} = \int \boxed{\epsilon_l} \boxed{\Lambda(c)dc}$

Single breaking event

Integration over all breaking events

Volume of entrained air $V_A = \int \boxed{v_l(\epsilon l, c, \dots)} \boxed{\Lambda(c)dc}$

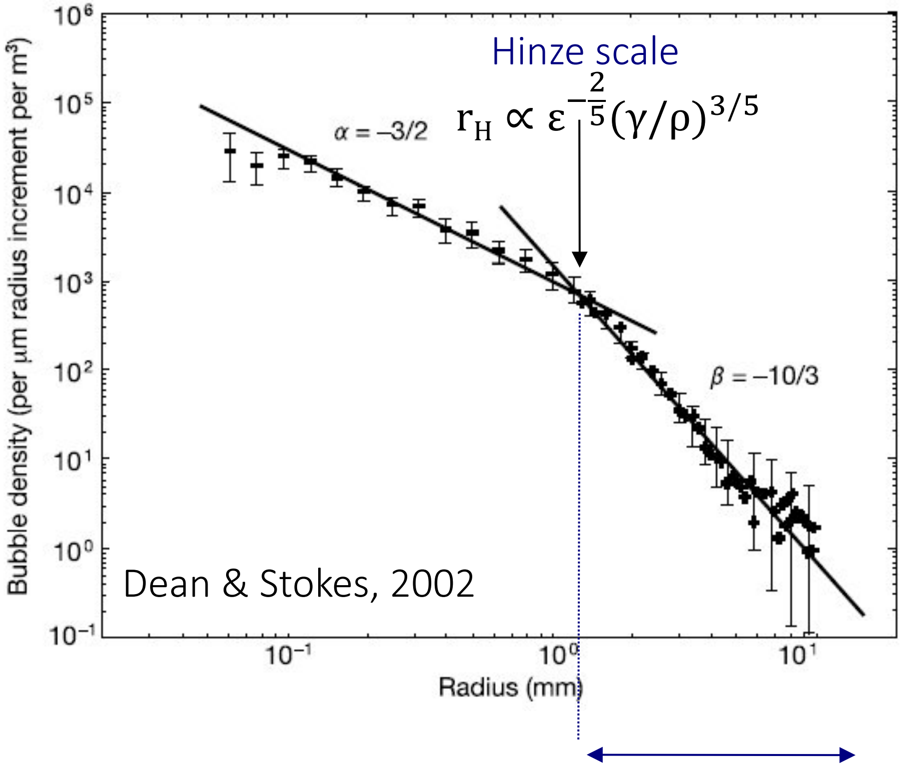
And then the gas flux $F_b = \int \boxed{f_l(vl, S, Sc)} \boxed{\Lambda(c)dc}$

But first we need to understand a single breaking event

$$\boxed{v_l(\epsilon_l, c, \dots) = \frac{4\pi}{3} \int r^3 n(r, c, \epsilon l, \dots) dr}$$

Bubble size distribution: State of the art

<u>Lab data:</u>
Bubble size distribution n(r)
[per unit volume, per unit radius]



Bubble break-up:
turbulent cascade

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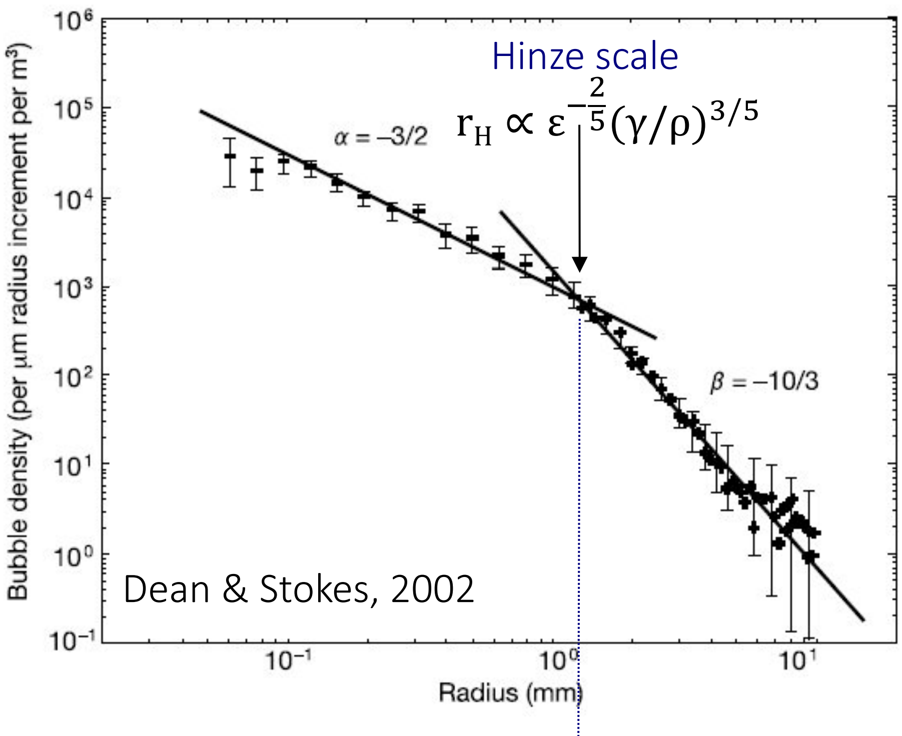


Bubble break-up:
turbulent cascade

<u>Model:</u>
Garrett et al, JPO 2000
Turbulent break-up steady model

r > Hinze scale, n(r) depends
- linearly on the constant air flow rate Q
- on bubble radius r
- on turbulent dissipation rate ε

Dimensional analysis → $\boxed{n(r) \sim Q\, \varepsilon^{-1/3} r^{-10/3}}$

Bubble size distribution: Questions

Model from Garrett et al 2000: $n(r) \sim Q\ \varepsilon^{-1/3} r^{-10/3}$

observed experimentally

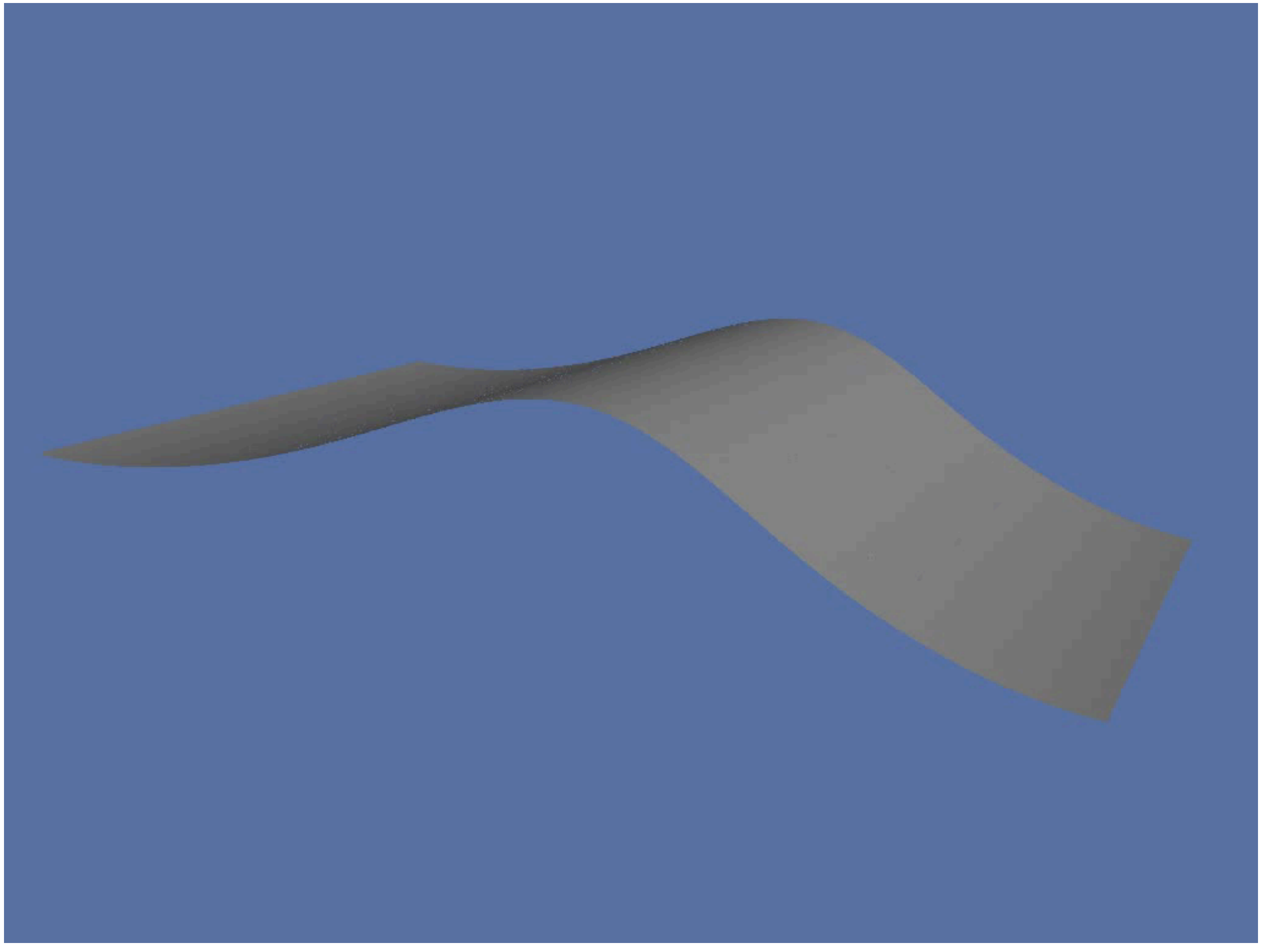
- What is the “mean” air flow rate Q?

- The variables Q and e are likely to be related
→ what is the final scaling in ε ?

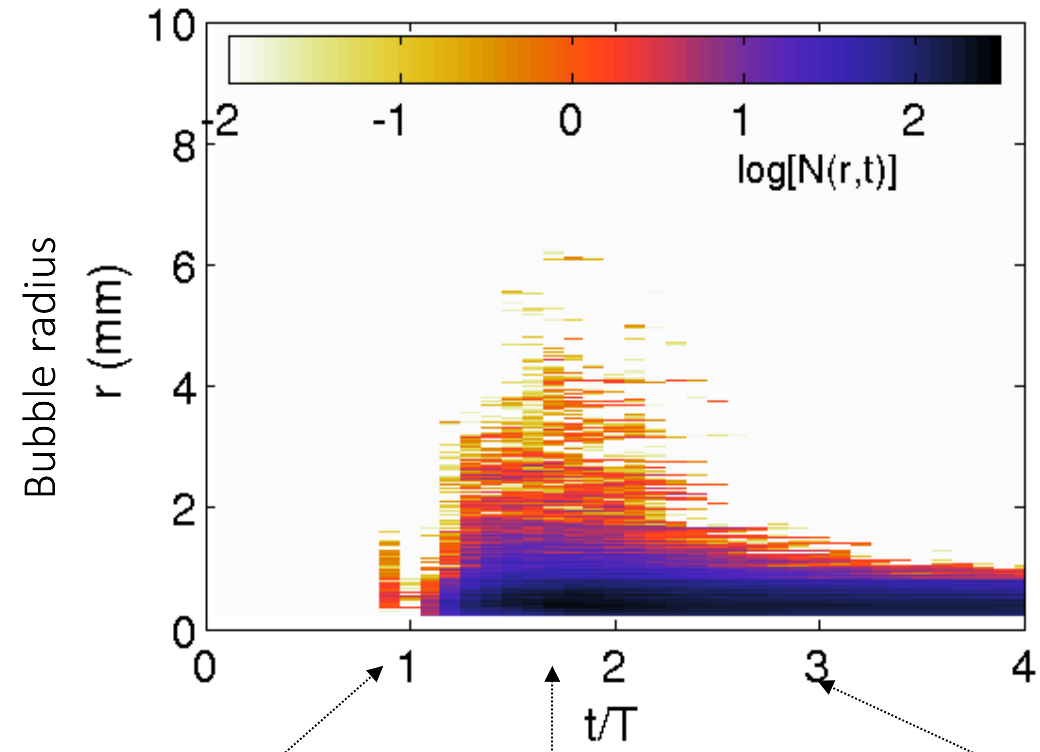
- Time evolution of n(r,t) and the volume of entrained air V(t)?

Direct Numerical Simulation of 3D breaking waves

DNS of 3D breaking waves



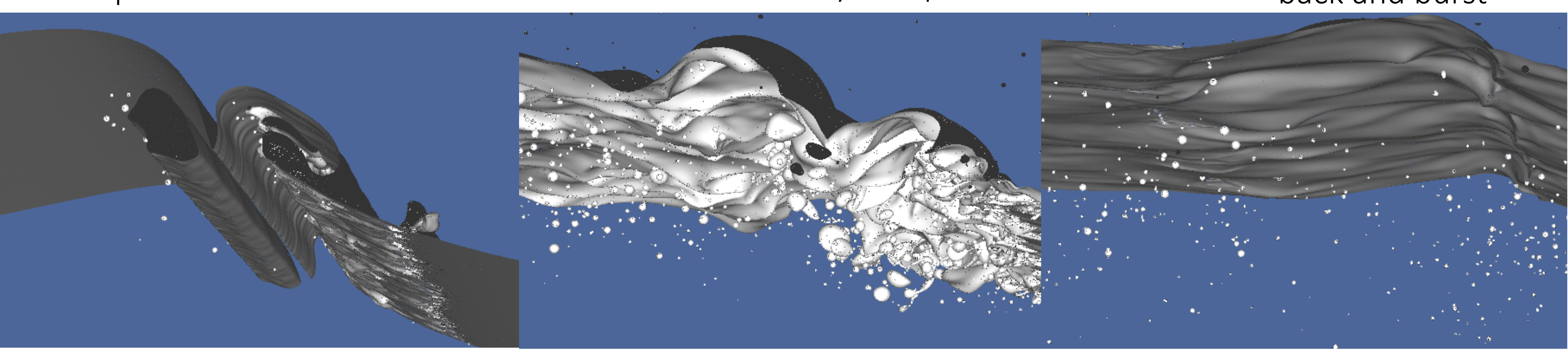
Time evolution of the bubble size distribution



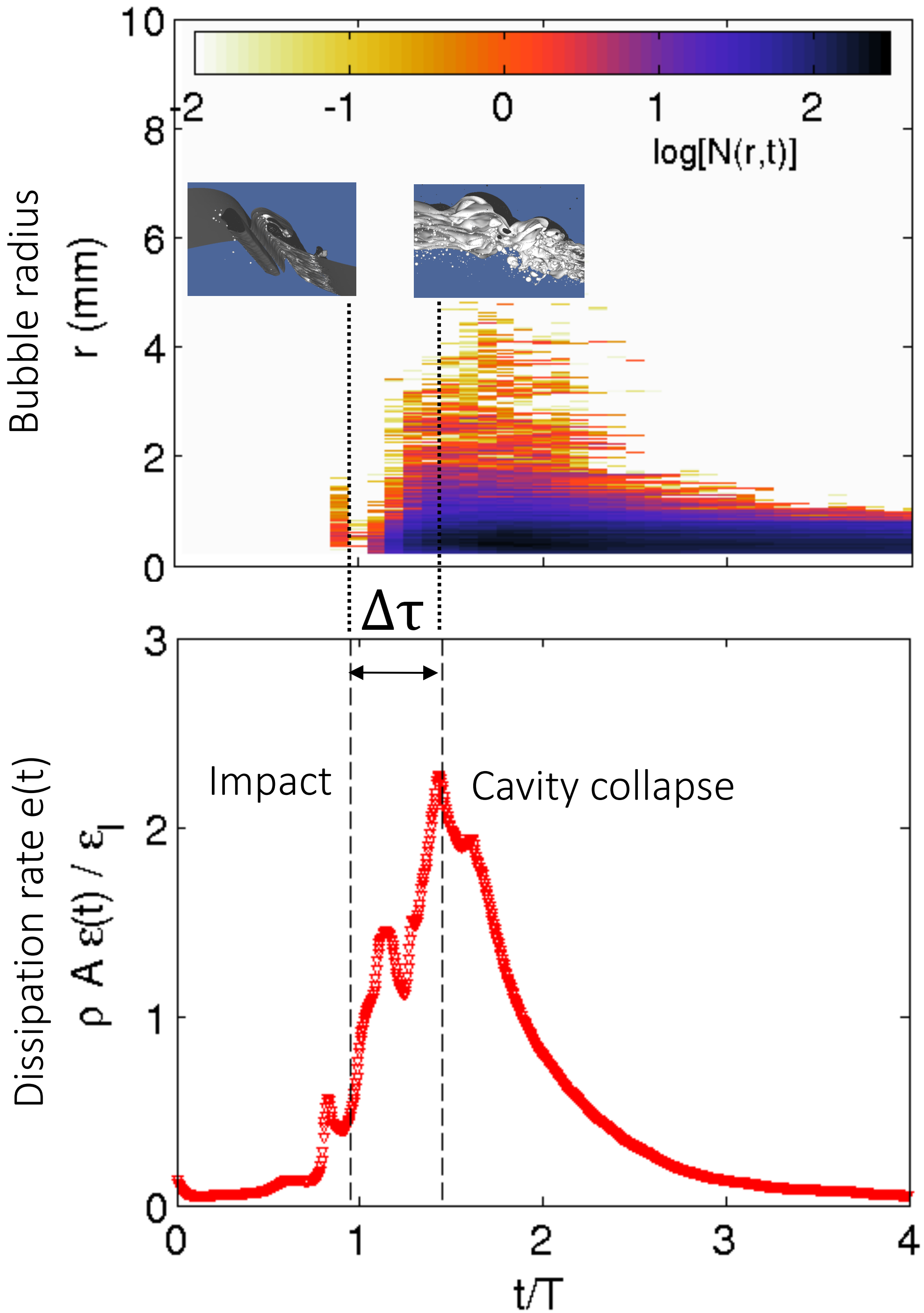
Impact and entrainment

Cavity collapse

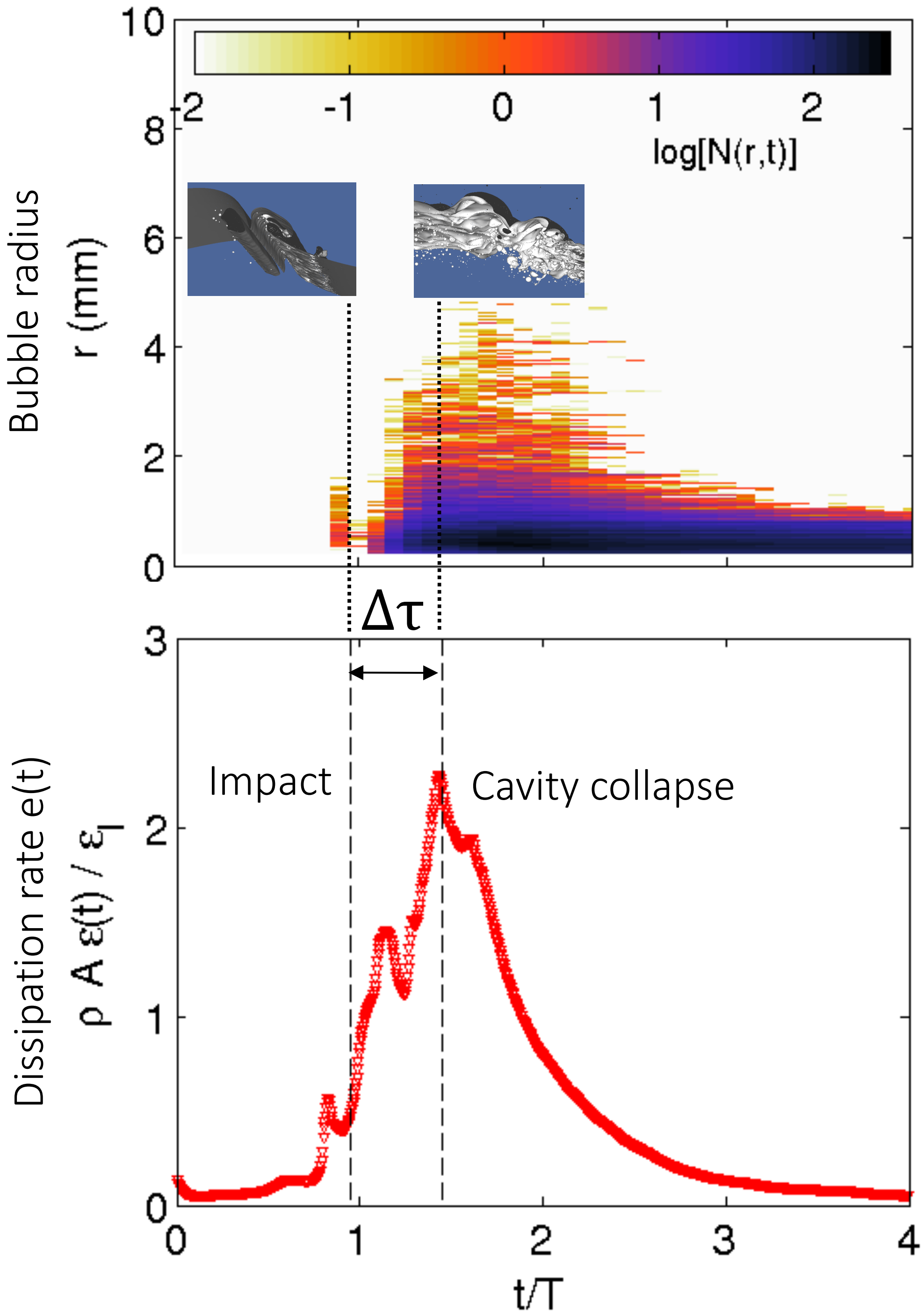
Bubbles rise back and burst

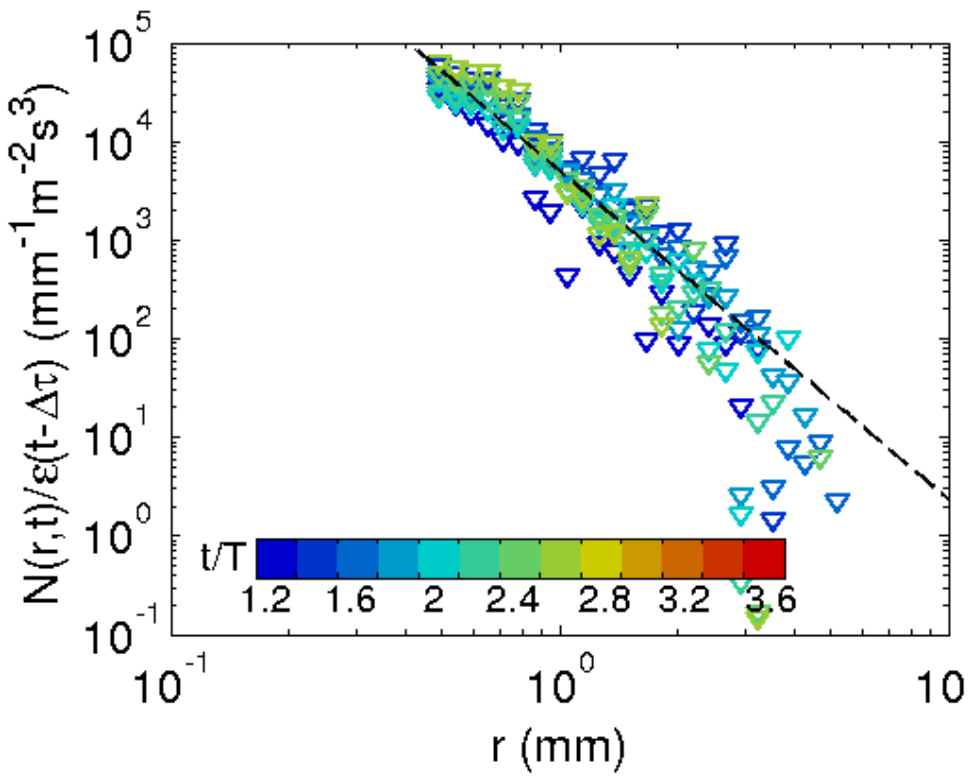


Bubbles and dissipation have similar time evolution



Number of bubbles scales with dissipation





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

Towards a predictive model of bubble phase

Work done against buoyancy forces $\sim$ Mechanical dissipated energy

Towards a predictive model of bubble phase

Work done against buoyancy forces $\sim$ Mechanical dissipated energy

Formalized by

$$\boxed{\iiint \rho g n(r,x,t)\frac{4\pi r^3}{3}\mathrm{w(x,t)drdxdt}} = B\boxed{\iint \rho\varepsilon(x,t)\big(1-\alpha(x,t)\big)dxdt}$$

Separating variables,
and introducing a weighted vertical velocity of the bubble plume W:

$$\longrightarrow \quad \underbrace{\boxed{\mathrm{V_w}\varepsilon(\mathrm{t}',\mathrm{x})}}_{\text{Dissipation}} \sim \underbrace{\boxed{\mathrm{V_a g W}}}_{\text{Buoyancy forces}} \quad \longrightarrow \quad \mathrm{V_a/V_w} \sim \varepsilon(\mathrm{t}',\mathrm{x})/(\mathrm{gW})$$

Towards a predictive model of bubble phase

Work done against buoyancy forces ~ Mechanical dissipated energy

Formalized by

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How do we reconcile this with the previous model?

Towards a predictive model of bubble phase

Garrett et al 2000: $$\boxed{n(r) \sim Q\, \varepsilon^{-1/3} r^{-10/3}}$$

How to estimate the mean air flow rate?

Towards a predictive model of bubble phase

Garrett et al 2000: $\boxed{n(r) \sim Q\,\varepsilon^{-1/3} r^{-10/3}}$

How to estimate the mean air flow rate?

$$Q = \frac{1}{\tau}\frac{V_a}{V_w}$$

Volume of air entrained

Volume of water

Break up time

Towards a predictive model of bubble phase

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Volume of air entrained

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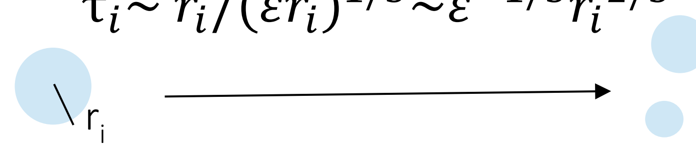
Break up time

Turbulent break-up time of a bubble:
(Taylor 1935, Martinez-Bazan et al 1999)

$$\tau_i \sim r_i/(\varepsilon r_i)^{1/3} \sim \varepsilon^{-1/3} {r_i}^{2/3}$$



Towards a predictive model of bubble phase

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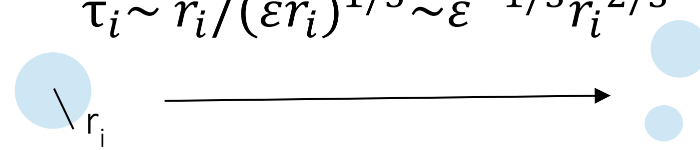
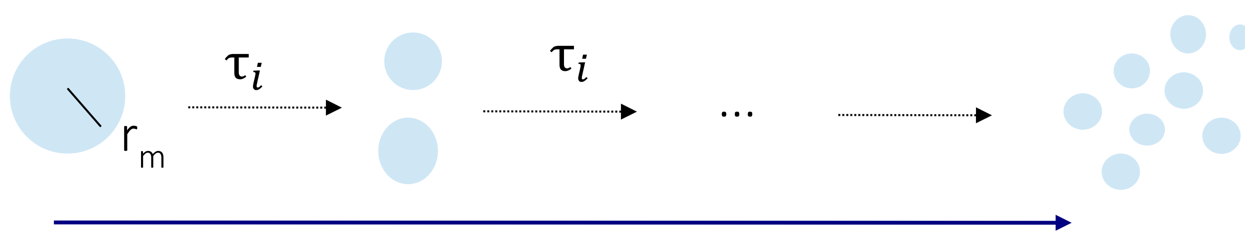


Successive break-ups:



$$\tau \sim \sum \tau_i \sim \varepsilon^{-1/3} r_m^{2/3}$$

This leads to: $\boxed{n(r) \sim \frac{V_a}{V_w} r_m^{2/3} r^{-10/3}}$

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

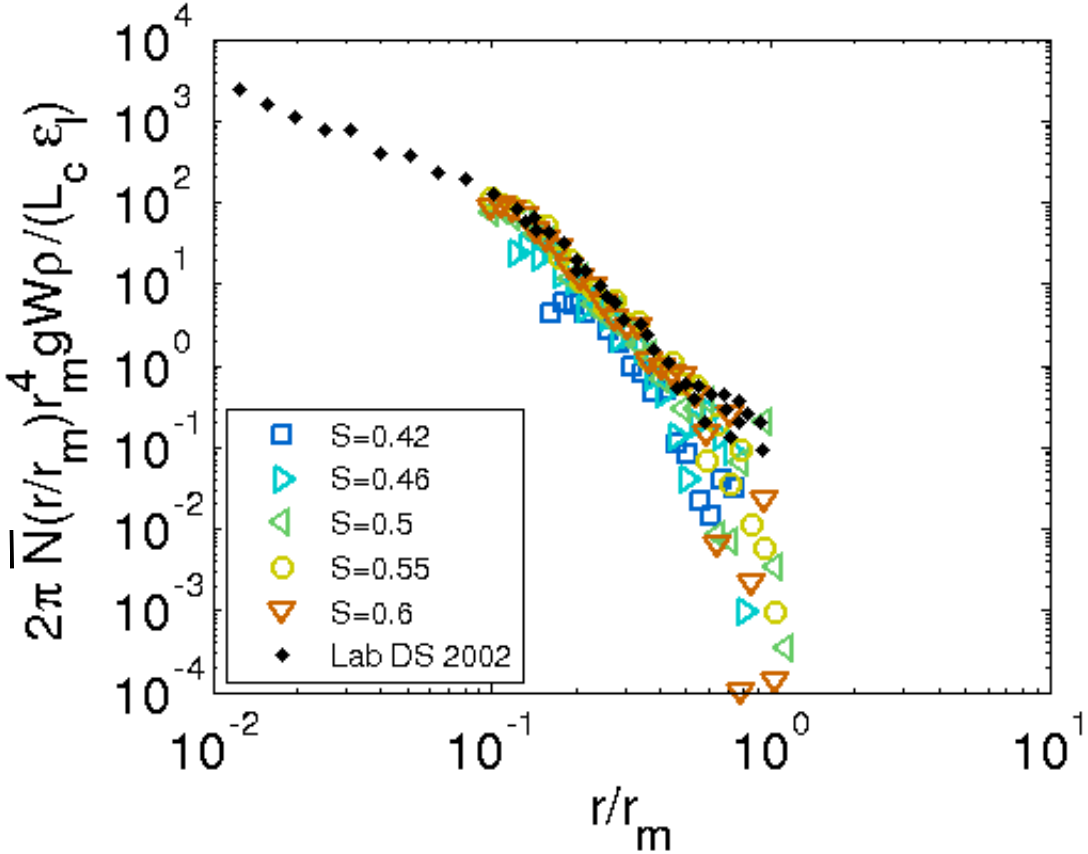
Balance between buoyancy and dissipation

How does it compare to lab data?

Numerical data and the 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

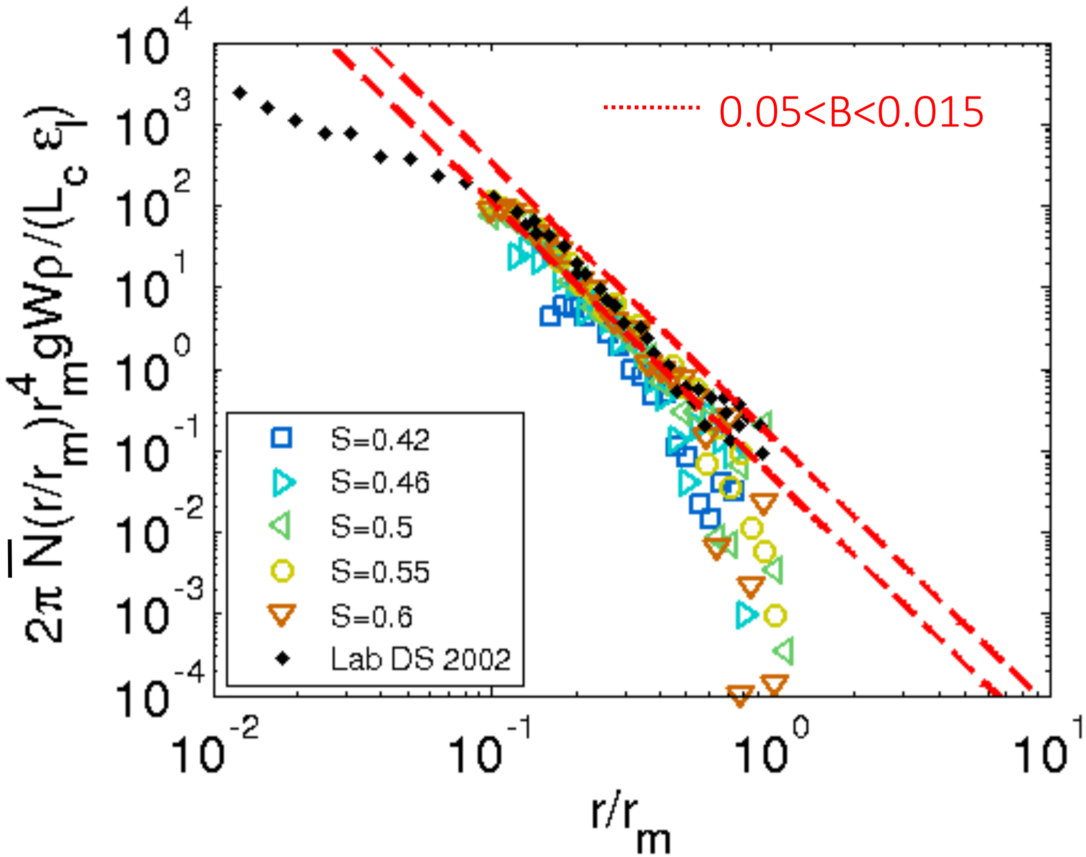
$$\overline{N(r)} = \frac{B}{2\pi}\frac{\epsilon_l}{gW\rho} r^{-10/3} r_m^{-2/3} L_c$$

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

Lab estimation 0.05<B<0.15

(Blenkisopp & Chaplin 2007, Lim et al 2015)

Rescaled bubble size distribution



Rescaled radius

Deike et al, 2016

Lets apply our model to the field ...

4. Upscaling to the field: volume flux of air

$$V_A = \int \boxed{v_l\,(c)}\ \boxed{\Lambda(c)\,dc}$$

Physical model for breaking event

Ocean breaking statistics measured in the field

From a single breaker to a statistics

Total volume of air for one breaker $\bar{V} = \int \frac{4\pi}{3} r^3 \overline{\mathrm{N(r)}} dr$

Volume of air per unit time,
per unit length of breaking crest $v_l\,(c) = \bar{V}/(\tau\, L_c)$ and $\tau \propto h/W$

Volume flux of air in the ocean: $V_A = \int \boxed{v_l\,(c)}\,\boxed{\Lambda(c)dc}$

Physical model
for breaking event

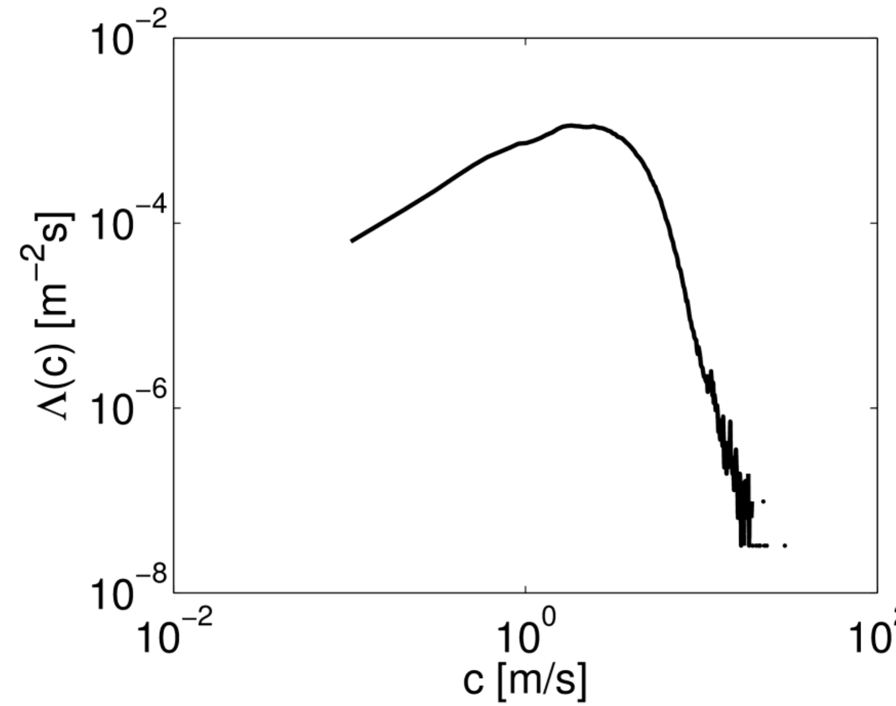
Ocean breaking
statistics measured
in the field

This leads to:

$$V_A = \int \boxed{\frac{B}{g}\frac{b}{hk}c^3}\,\Lambda(c)dc$$

Wave spectrum measurement
(following Romero et al 2012)

Measuring the ocean breaking statistics $\Lambda(c)$

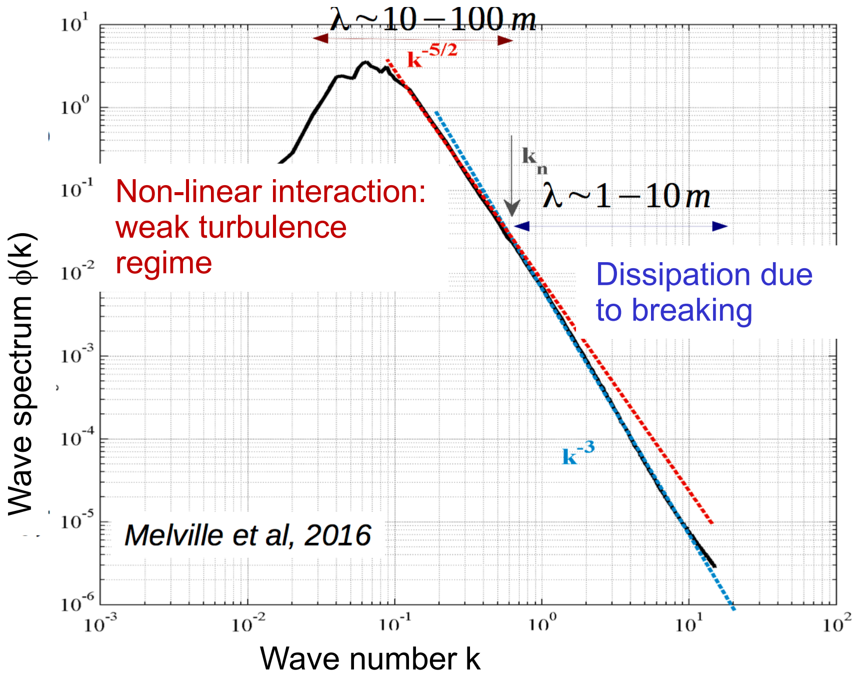


Melville et al 2016, Lenain & Melville 2017
Deike et al, 2017

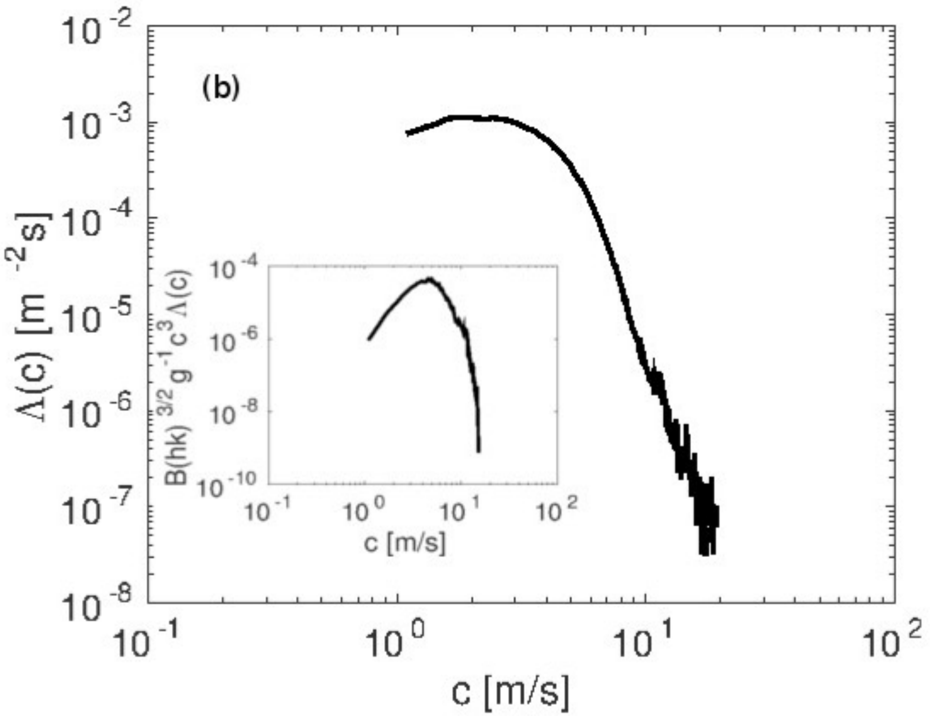
Spectral volume flux of entrained air

$$V_A = \int \frac{B}{g}\frac{b}{hk} c^3 \;\; \Lambda(c)dc = \int \frac{B}{g} (hk)^{3/2} c^3 \;\; \Lambda(c)dc$$

Wave & saturation spectrum (LIDAR measurements)



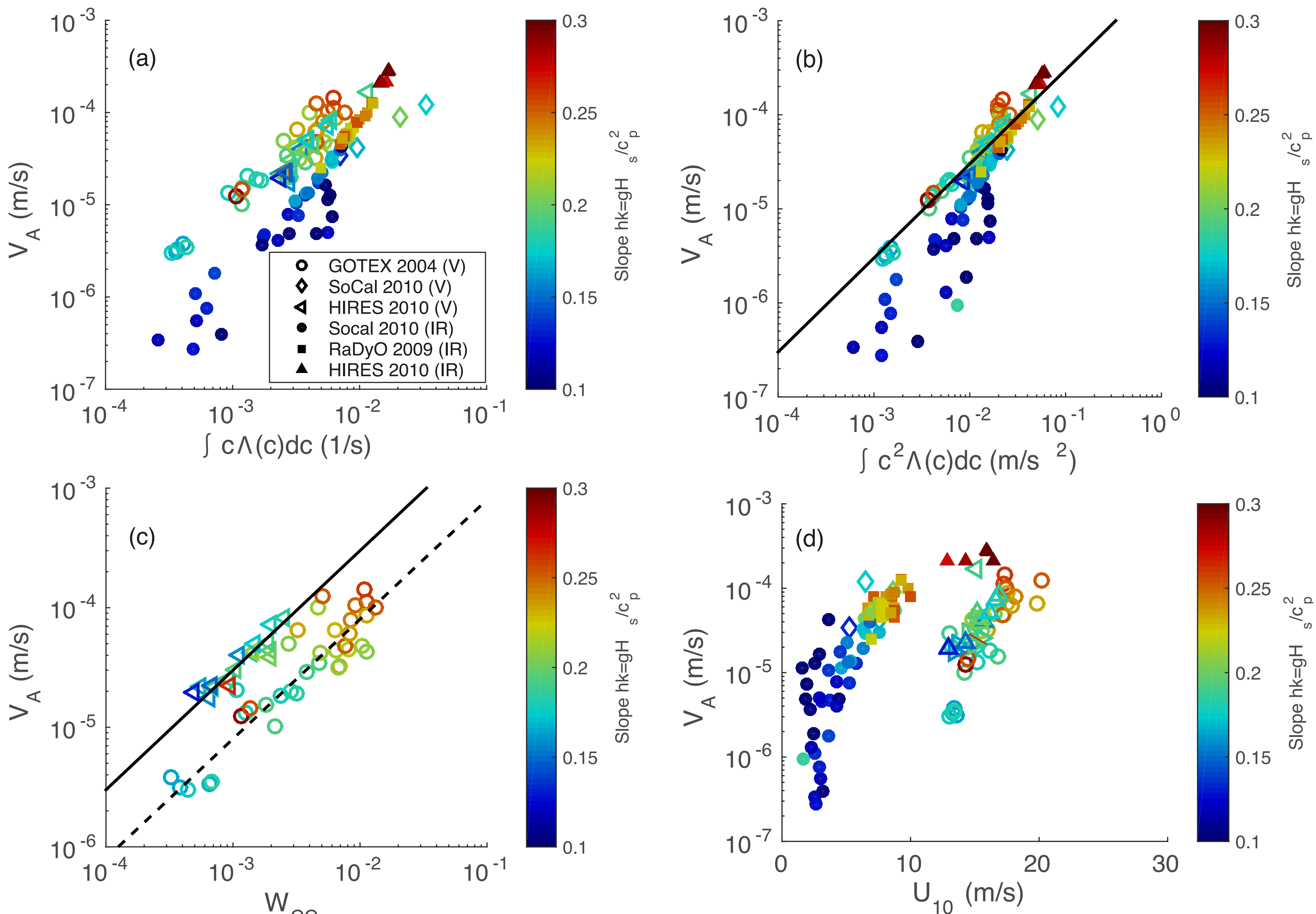
Breaking and air entrainment statistics (visible video)



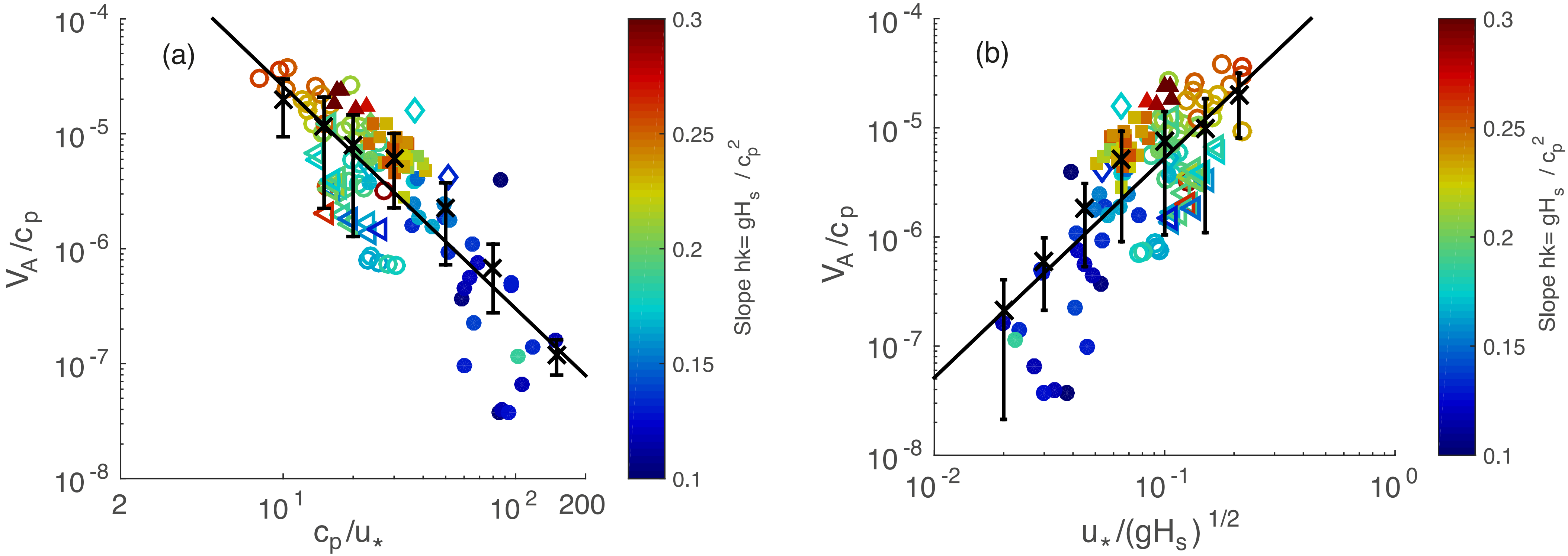
Wave slope: $B(k) = \phi k^3 = (hk)^{1/2}$

Dispersion relation to go from k to c: $c = \sqrt{gk}$

Volume flux of air



Volume flux of air scales with wave age



$$\frac{V_A}{c_p} \propto \left(\frac{c_p}{u_*}\right)^{-2} \propto \left(\frac{u_*}{\sqrt{gH_s}}\right)^{2}$$

Conclusions

General understanding of the two-phase flow associated with breaking

Model for 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.

Upscaling 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 prep.

This approach, combining lab experiments, numerical simulations & field data
can be applied to other ocean atmosphere problems:
spray generation, Lagrangian drift and mass transport, gas transfer…