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► **To cite this version:**

Nicole Anderton, Craig Stuart Carlson, Michiel Postema. Pulsating bubbles with nanoparticle shells. Workshop on Bionanomaterial and Nanomaterial Engineering, Jun 2023, Łódź, Poland. hal-04130586

HAL Id: hal-04130586

<https://hal.science/hal-04130586>

Submitted on 16 Jun 2023

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Pulsating bubbles with nanoparticle shells

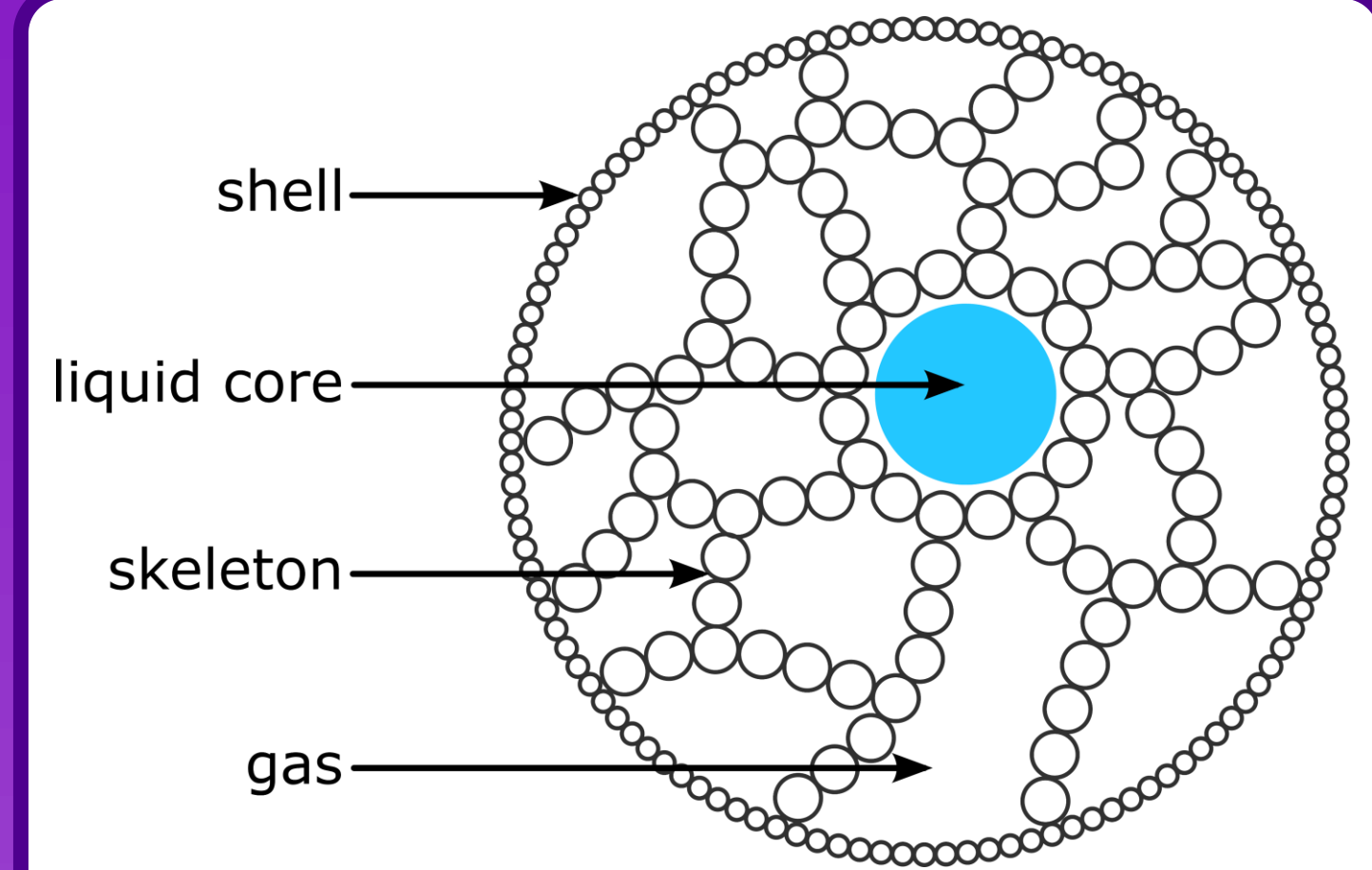


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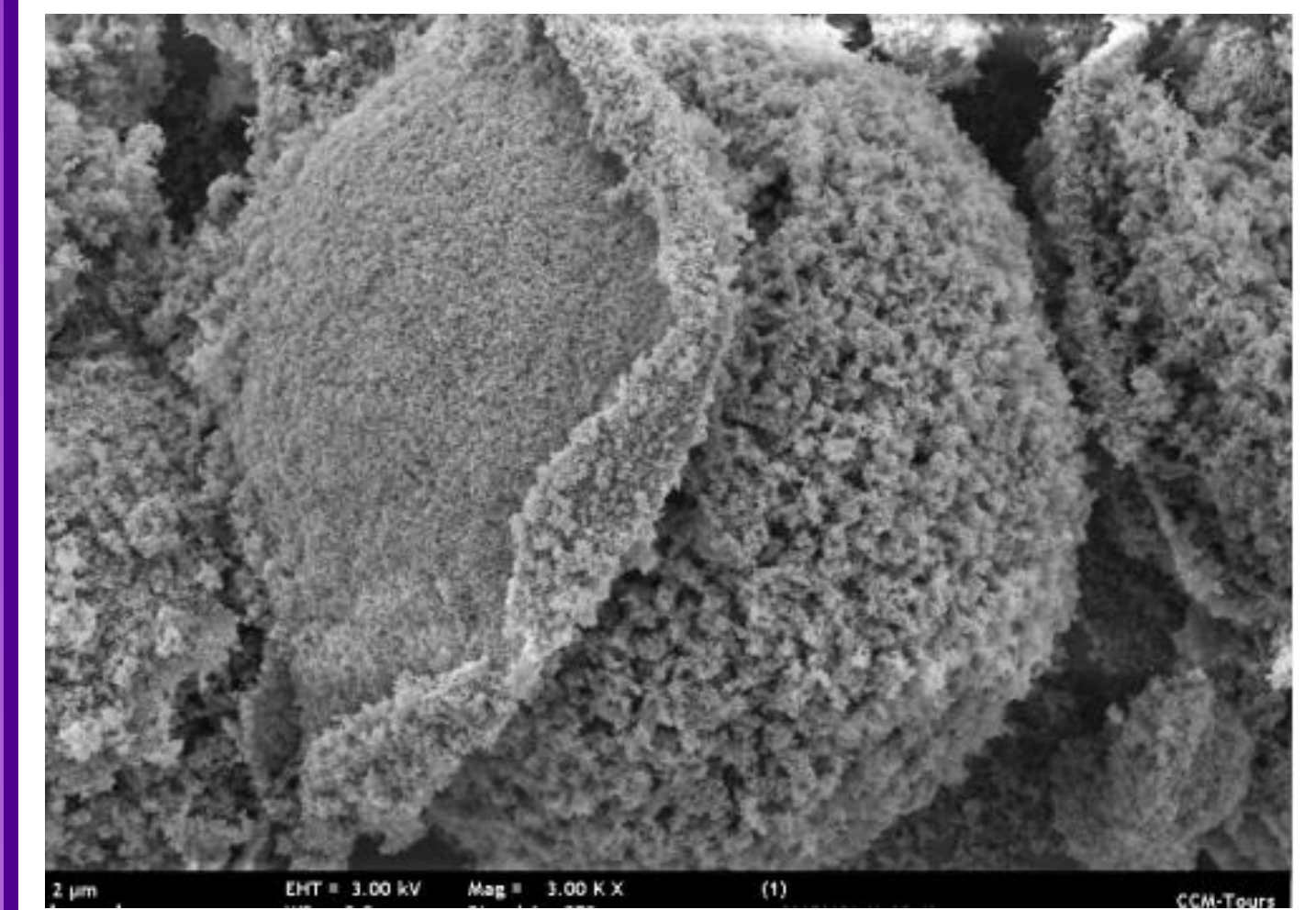
Antibubbles are microscopic gas bubbles comprising one or multiple liquid or solid cores, typically surrounded by stabilising shells. Hydrophobised silica nanoparticles are used to create this stabilised shell, a process called Pickering-stabilising. Pickering-stabilised antibubbles possess acoustic properties required to act as both diagnostic and therapeutic agents. This research aimed to determine the dynamic response of Pickering-stabilised antibubbles to pulsed ultrasound and identify and quantify the contribution of the shell and core to that behaviour.

Aims

- 1 Quantify oscillation asymmetry of antibubbles.
- 2 Determine the influence of endoskeletal and shell friction on antibubble pulsation phase.
- 3 Predict the fragmentation threshold of antibubbles



Schematic representation of an endoskeletal antibubble.

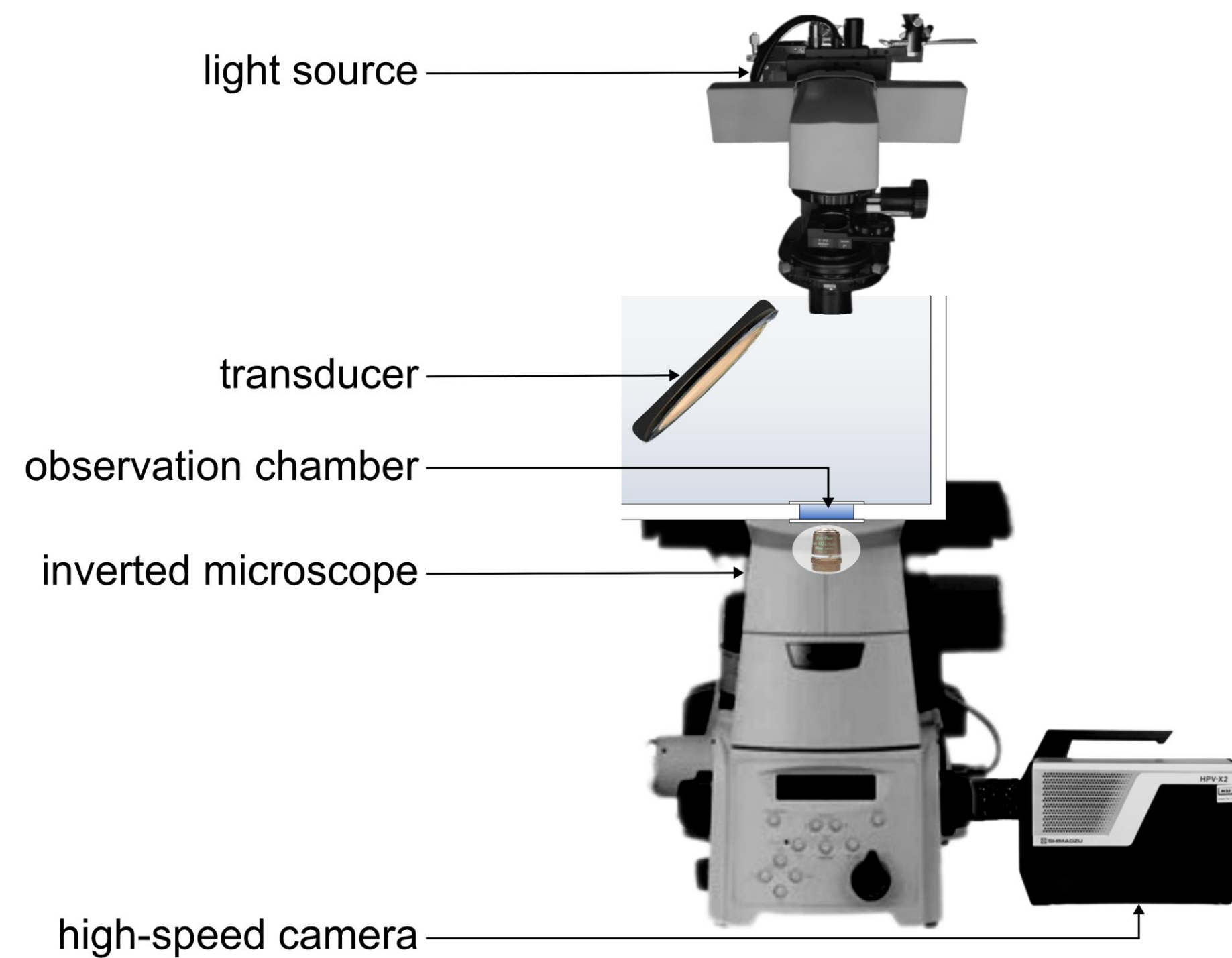


Scanning electron micrograph of an antibubble

Methods

Experiments

Radial excursions of antibubbles during ultrasound exposure were extracted from high-speed footage. Medically safe conditions were maintained throughout the experiments; with an ultrasonic frequency of 1MHz and peak negative pressure of either 200kPa or 1MPa.



Simulations

Fundamental pulsation

$$R\ddot{R} + \frac{3}{2}\dot{R}^2 = \frac{1}{\rho} \left[\left(p_0 - p_v + \frac{2\sigma R_0}{R_0^2 - R_c^2} \right) \left(\frac{R_0^3 - R_c^3}{R^3 - R_c^3} \right)^\gamma + p_v - \frac{2\sigma R}{R^2 - R_c^2} - 2\chi \left(\frac{1}{R_0} - \frac{1}{R} \right) - \frac{4\eta\dot{R}}{R} - p_0 - P(t) \right]$$

Pulsation phase

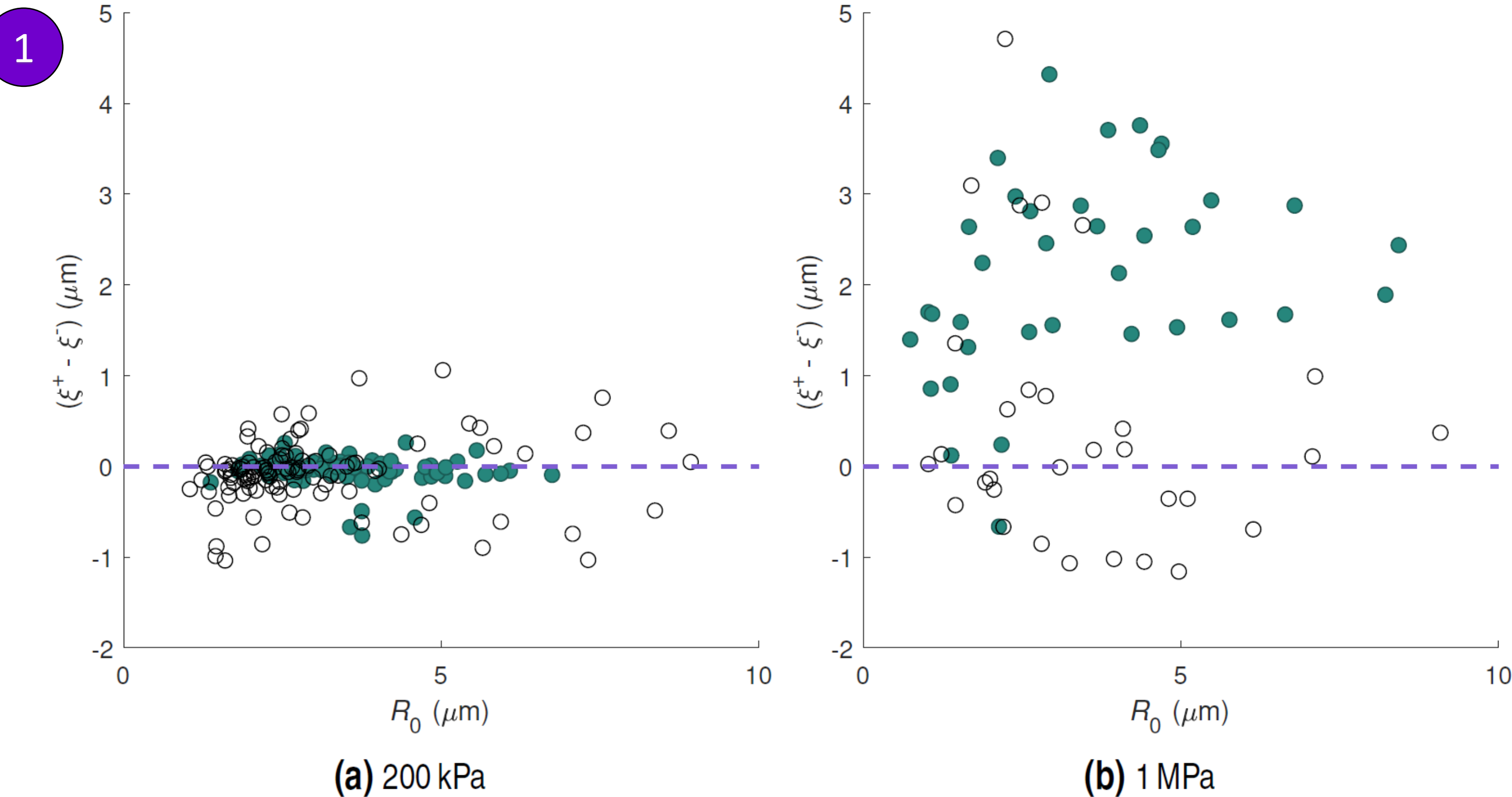
$$\delta = \delta_v + \delta_r + \delta_{\text{sh}} + \delta_{\text{sk}} + \delta_{\text{g}}$$

$$\alpha = f(\delta, R_0, \omega)$$

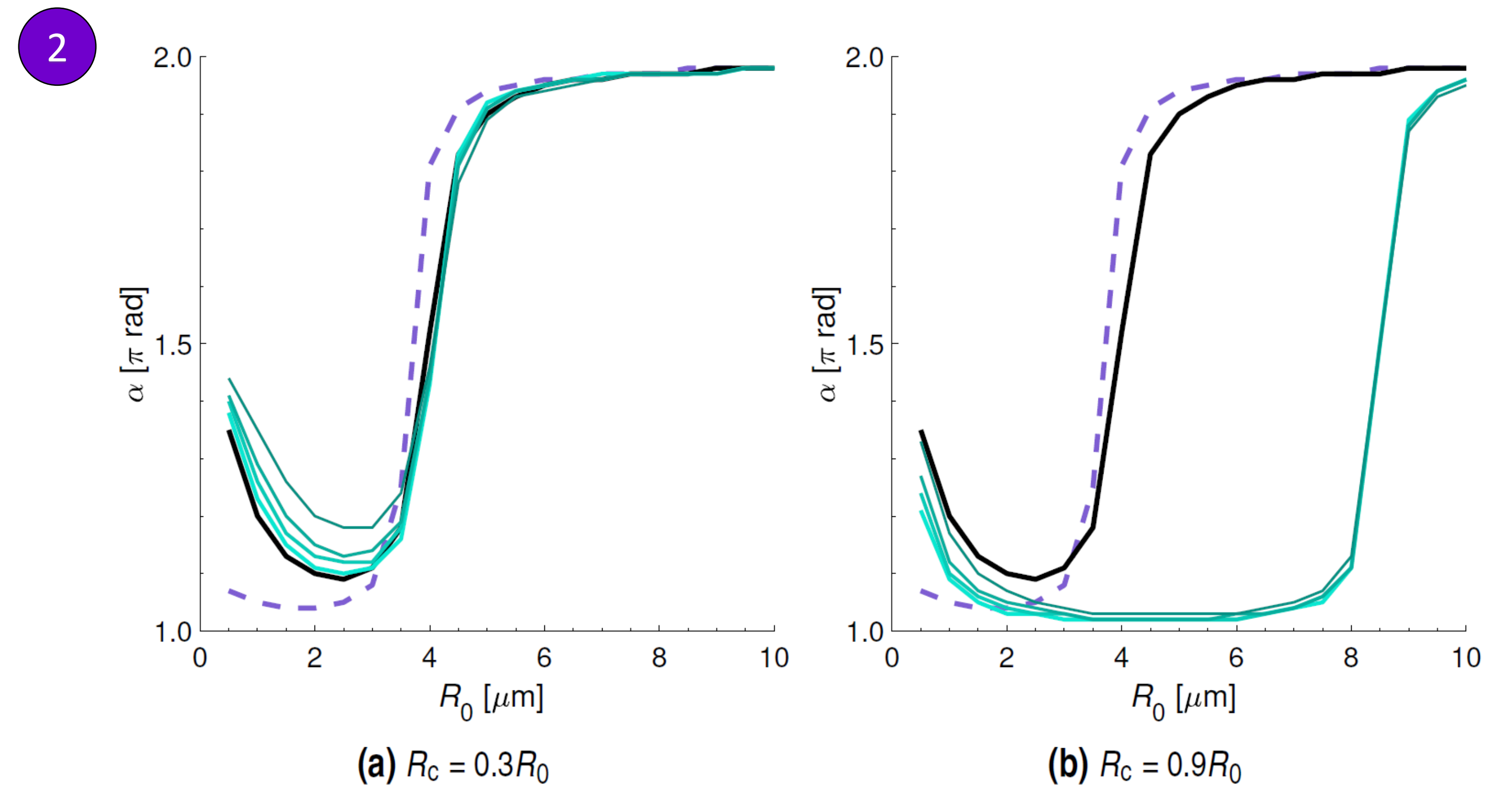
Point of fragmentation

$$E_k \approx 2\pi\rho\dot{R}^2R^3 > \Delta E_s \approx (N^{\frac{1}{3}} - 1) \cdot 4\pi R^2\sigma$$

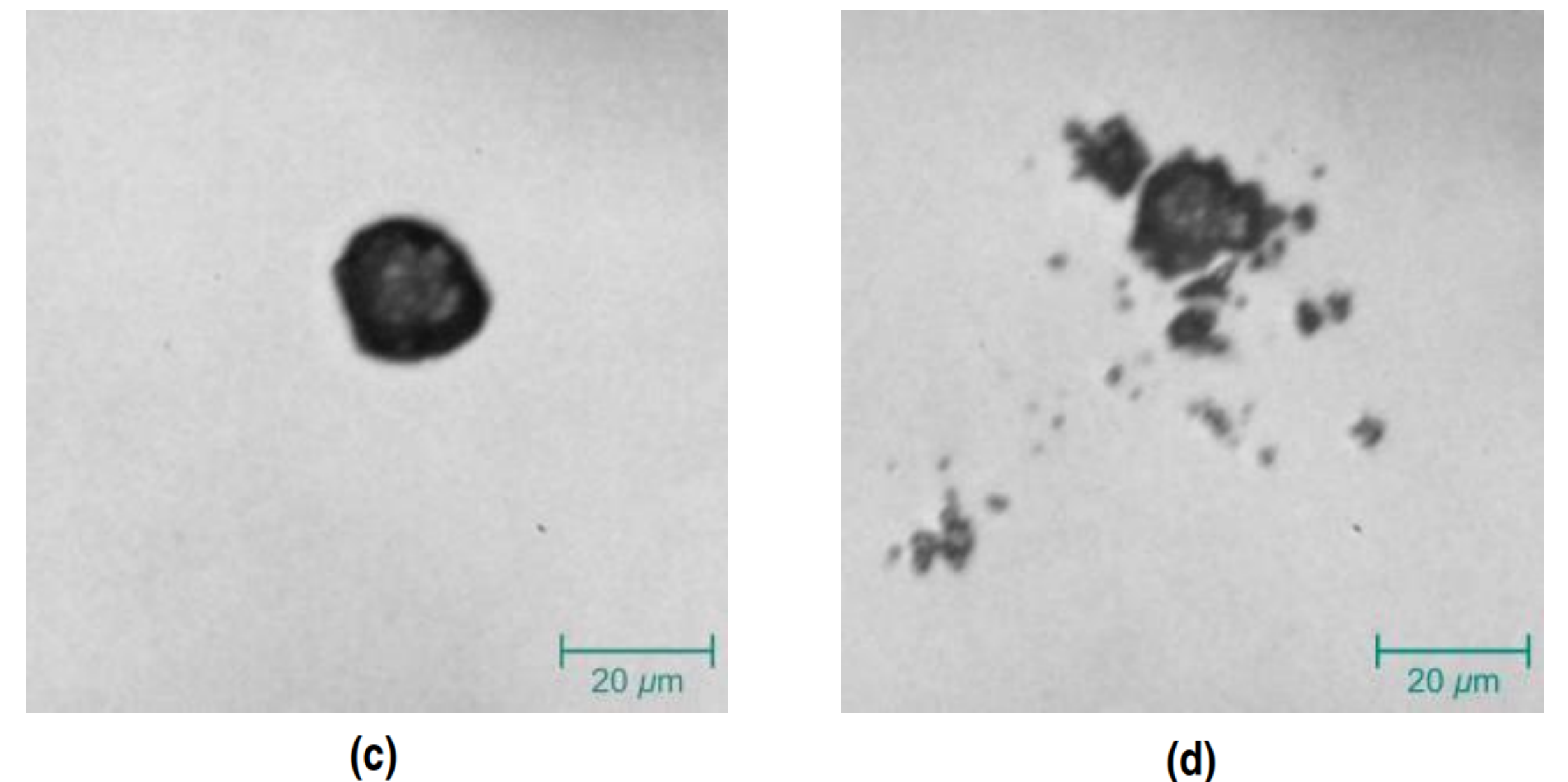
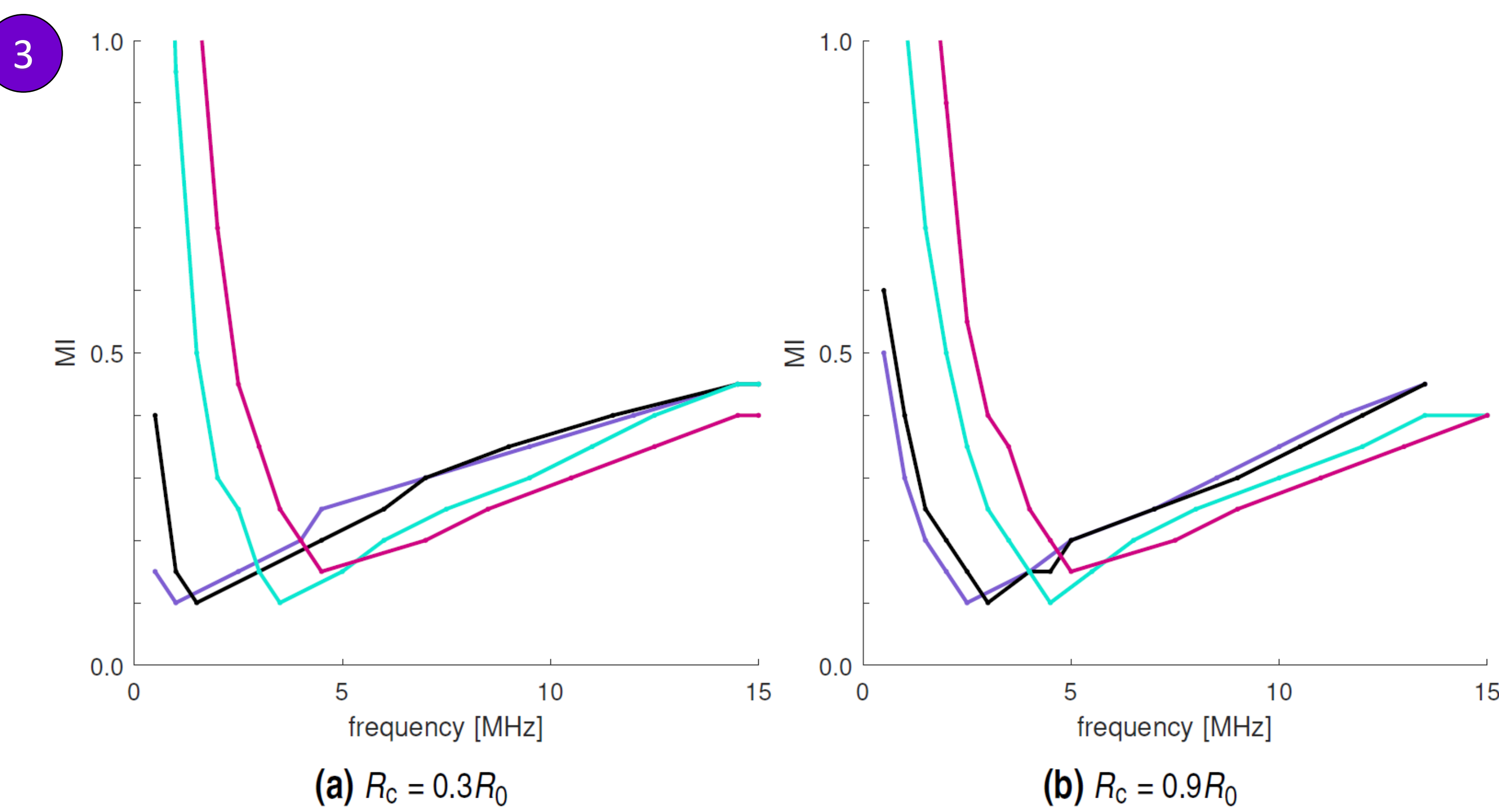
Results



Scatter plot of initial resting radius (R_0) versus oscillation asymmetry ($\xi^+ - \xi^-$) as a result of a single cycle of ultrasound at pulse pressure amplitudes of (a) 200 kPa and (b) 1 MPa for antibubbles with cores (●) and without (○). The dotted purple line (--) represents perfectly symmetrical excursion, where $(\xi^+ - \xi^-) = 0$.



Pulsation phase with respect to incident sound field as a function of R_0 for a free gas bubble (—), an antibubble with no core (—), and antibubbles with core content having endoskeletal damping coefficients equal to 0.3 (—), 0.6 (—), 0.9 (—) and 2 (—).



Fragmentation threshold as a function of driving frequency for two different core volume ratios (a,b). Shell stiffnesses are represented by different line colours: $\chi = 0 \text{ N m}^{-1}$ (—), $\chi = 1.1 \text{ N m}^{-1}$ (—), $\chi = 7.6 \text{ N m}^{-1}$ (—), and $\chi = 15 \text{ N m}^{-1}$ (—). High-speed video frames are shown before (c) and after (d) fragmentation.

Conclusions

1. Antibubbles oscillate stably and symmetrically at low amplitudes, and with unique asymmetry at higher amplitudes.
2. The damping properties of the shell and skeletal materials of minute antibubbles may alter the degree to which a particle oscillates in phase with the sound field.
3. As the rigidity of the antibubble is increased, either through the addition of core content or a stiffer shell, the wall velocity during excursion decreases, reducing the kinetic energy of the shell, ultimately increasing the fragmentation threshold.

