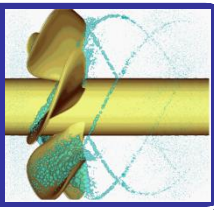

Numerical Modeling of Cavitation and Two-phase Flow using a Multiscale Approach

Drs. Jingsen Ma, Chao-Tsung Hsiao & Georges L. Chahine
jingsen@dynaflow-inc.com
DYNAFLOW, INC.
Jessup, MD, 20794

Acknowledgements
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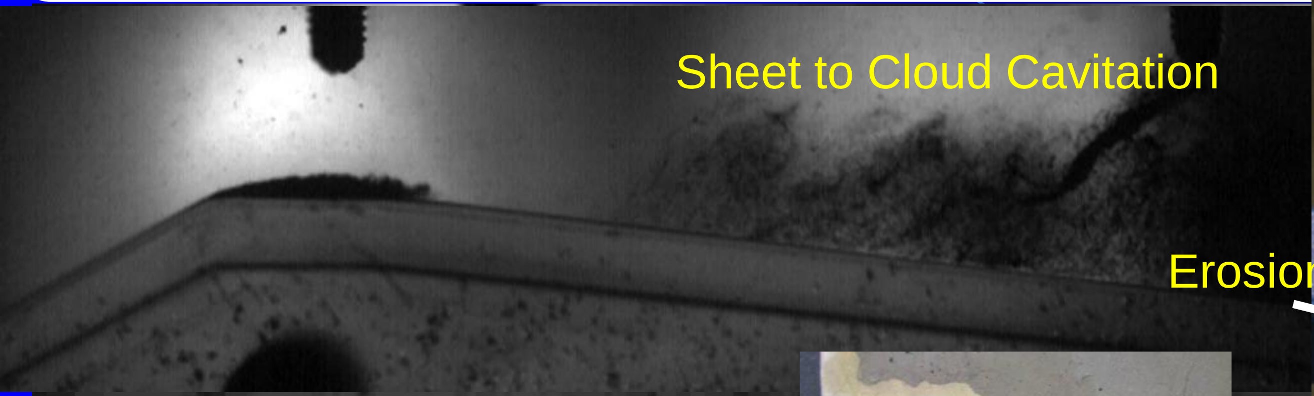
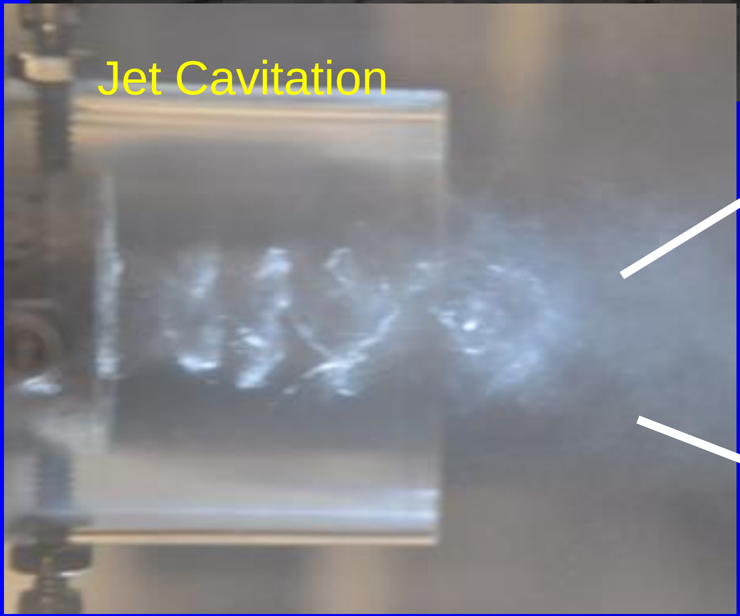
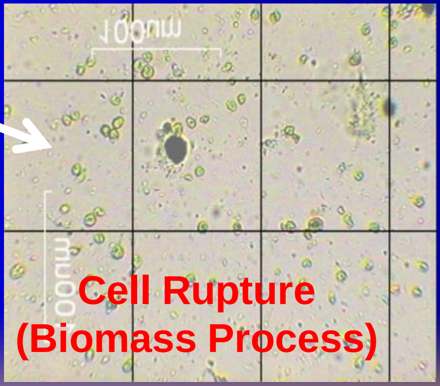
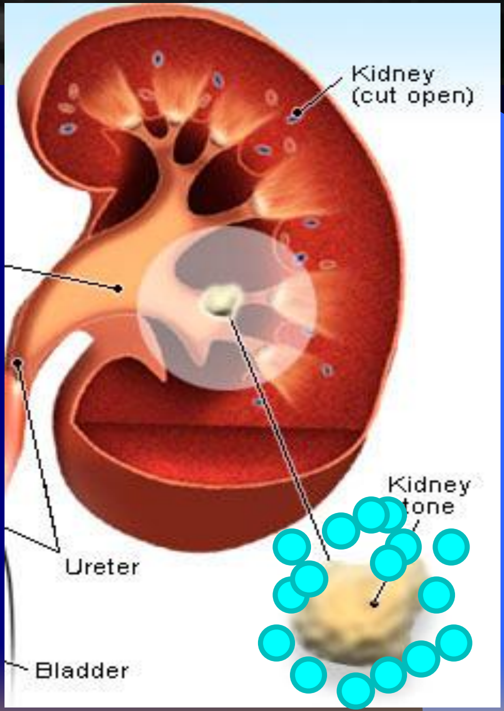
Background & Motivation

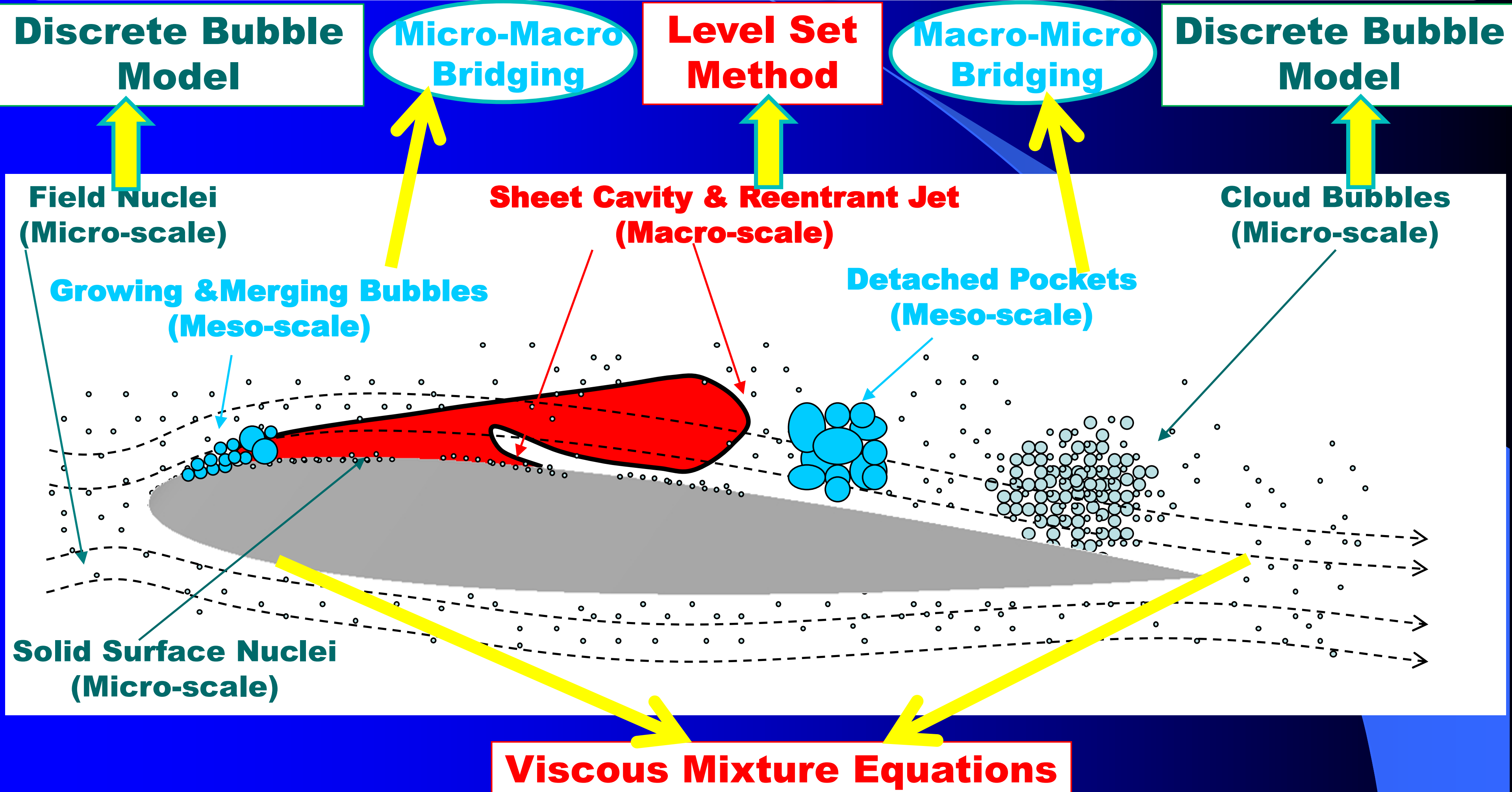








Overview of Problem & Modeling Strategy



Ref: Ma et al, A physics based multiscale modeling of cavitating flows. Computers & Fluids. 2017

Outline

- Background: Problem & Strategy
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  - Hydrodynamic Cavitation
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Eulerian Solver: 3DYNAFS-VIS© for Viscous Continuum Mixture

- Two-phase mixture is treated as a Continuum:

$$\rho_m = (1-\alpha)\rho_\ell + \alpha\rho_g \qquad \mu_m = (1-\alpha)\mu_\ell + \alpha\mu_g$$

α : void fraction (*determined by the bubble distribution*)

- Mixture Continuity and Momentum equations

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial \rho_m u_i}{\partial x_i} = 0$$

$$\frac{\partial \rho_m u_i}{\partial t} + \frac{\partial \rho_m u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu_m \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right]$$

- Eulerian Solver: 3DYNAFS-VIS©
  - Artificial compressibility method
  - Dual time stepping scheme for time-accurate solutions

Lagrangian Solver: 3DYNAFS-DSM© for Dispersed Bubbles

- Bubble Motion Equation

$$\frac{d\mathbf{u}_b}{dt} = -\frac{3}{\rho_m}\nabla P_{SAP} - 2gz + \frac{3}{4}\frac{C_D}{R}\left(\mathbf{u}_{SAP} - \mathbf{u}_b\right)\left|\mathbf{u}_{SAP} - \mathbf{u}_b\right| + \frac{3}{4}\frac{C_L}{\pi R}\sqrt{\frac{\mu_m}{\rho_m}}\frac{\left(\mathbf{u}_{SAP} - \mathbf{u}_b\right)\times\left(\nabla\times\mathbf{u}_{SAP}\right)}{\sqrt{\left|\nabla\times\mathbf{u}_{SAP}\right|}} + \frac{3}{R}\left(\mathbf{u}_{SAP} - \mathbf{u}_b\right)\dot{R}$$

- Bubble Dynamics Equation: Surface Averaged Pressure (SAP) modified Rayleigh-Plesset-Keller-Herring Equation

$$\left(1-\frac{\dot{R}}{c_m}\right)R\ddot{R} + \frac{3}{2}\left(1-\frac{\dot{R}}{3c_m}\right)\dot{R} = \frac{\left(\mathbf{u}_{SAP} - \mathbf{u}_b\right)^2}{4} + \frac{1}{\rho_m}\left(1+\frac{\dot{R}}{c_m}+\frac{R}{c_m}\frac{d}{dt}\right)\left[p_v + p_g - p_{SAP} - \frac{2\gamma}{R} - 4\mu_m\frac{\dot{R}}{R}\right]$$

Level Set Method for Large Gas/Liquid Interfaces

- Define a smooth level set function $\psi(x,y,z,t)$ whose zero level coincides with the liquid/gas interface at t

$$\psi(x,y,z,t) = d\,(x,y,z)$$

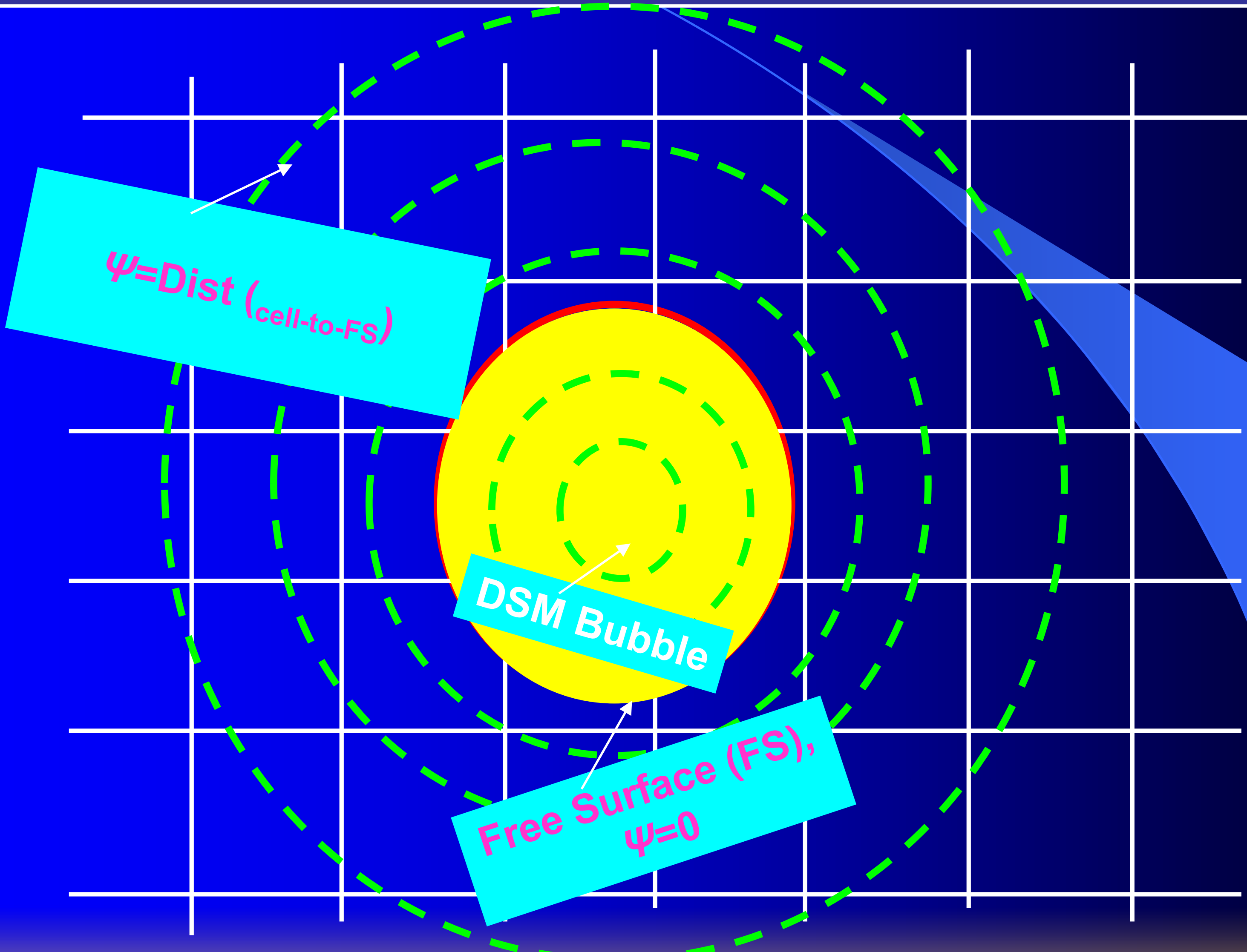
where d is the signed distance from the interface

- Evolve the interface by solving a transport equation

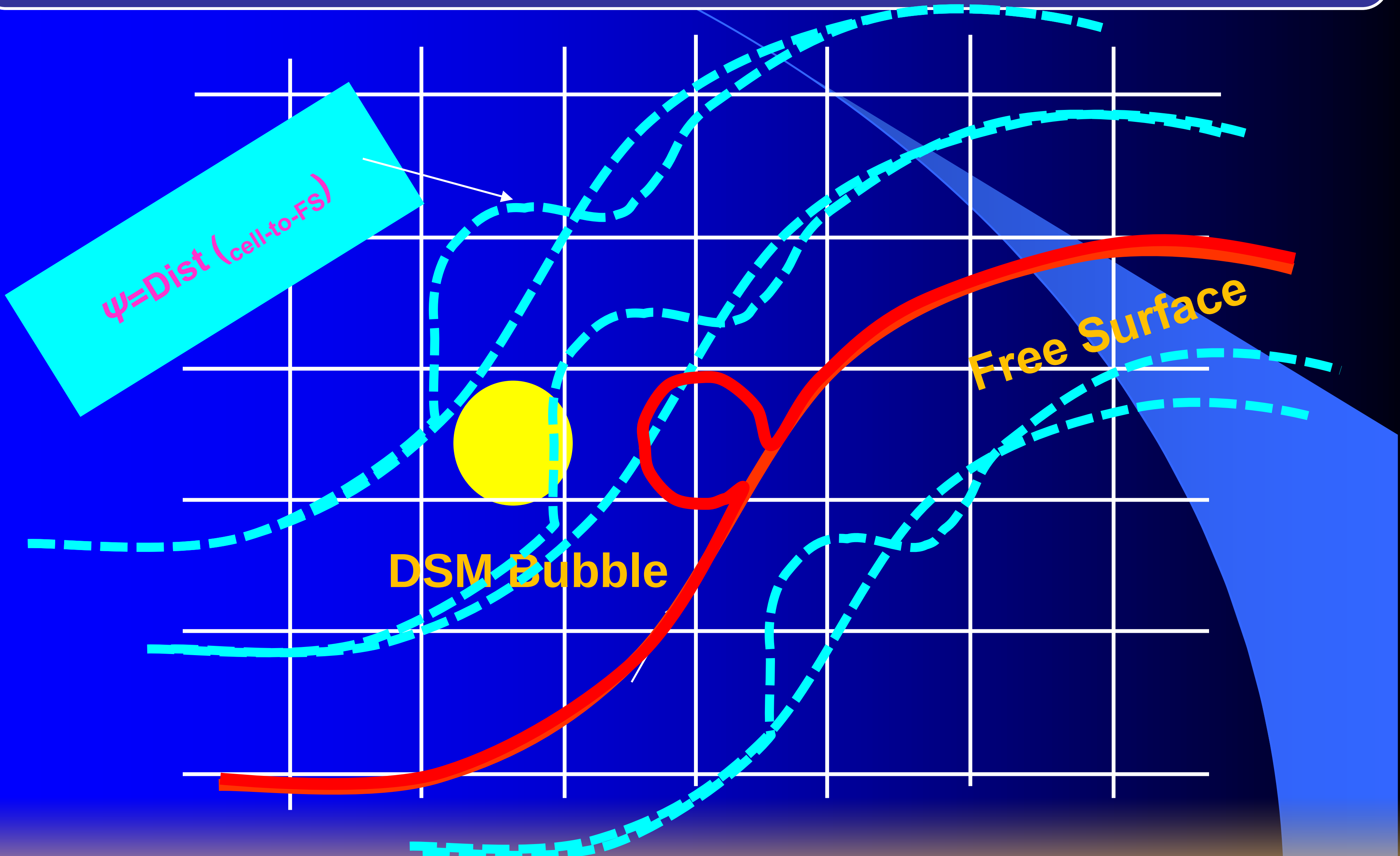
$$\frac{\partial \psi}{\partial t} + u_j \frac{\partial \psi}{\partial x_j} = 0$$

- Apply free surface boundary conditions at $\psi(x,y,z,t) = 0$
  - Normal stress balance
  - Zero shear stress

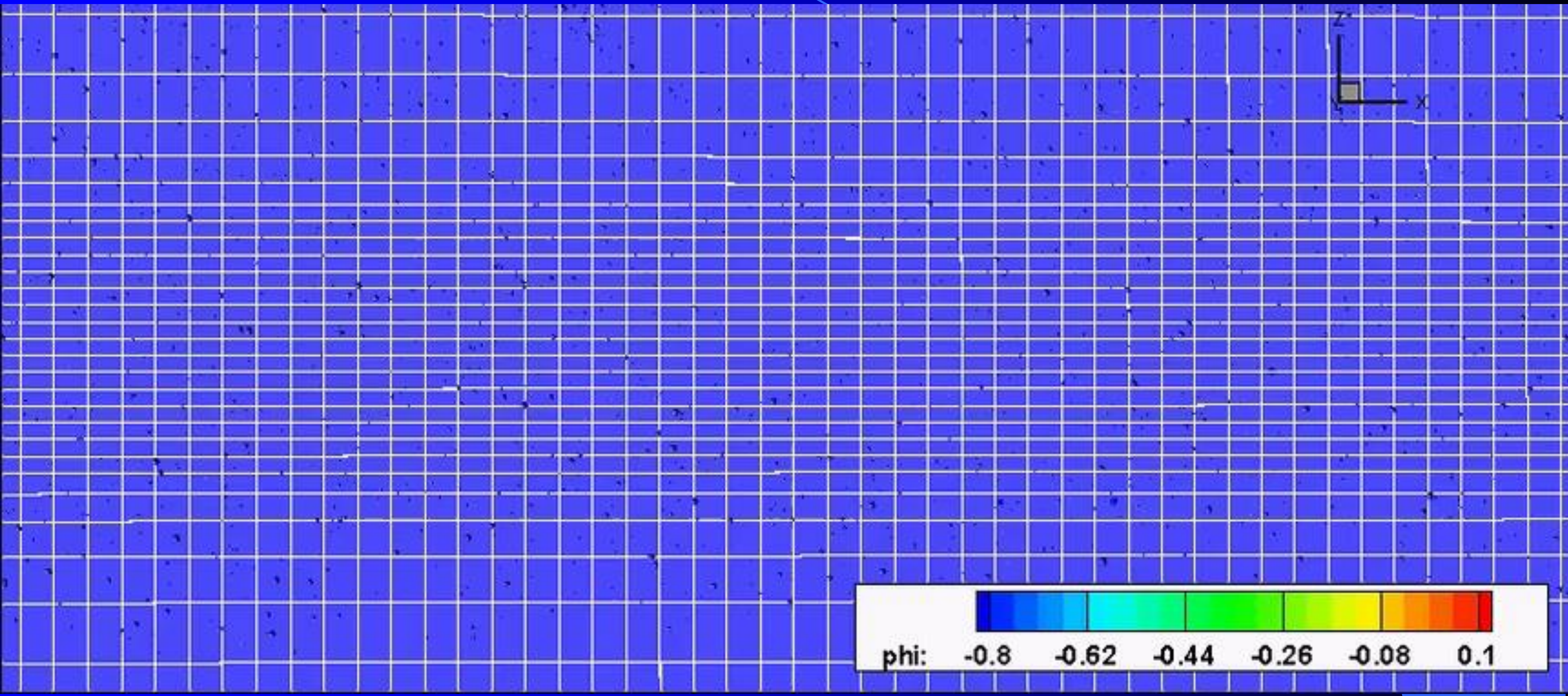
Micro → Macro Bridging: Single Bubble Scenario



Micro → Macro Bridging: Bubble Merge Scenario

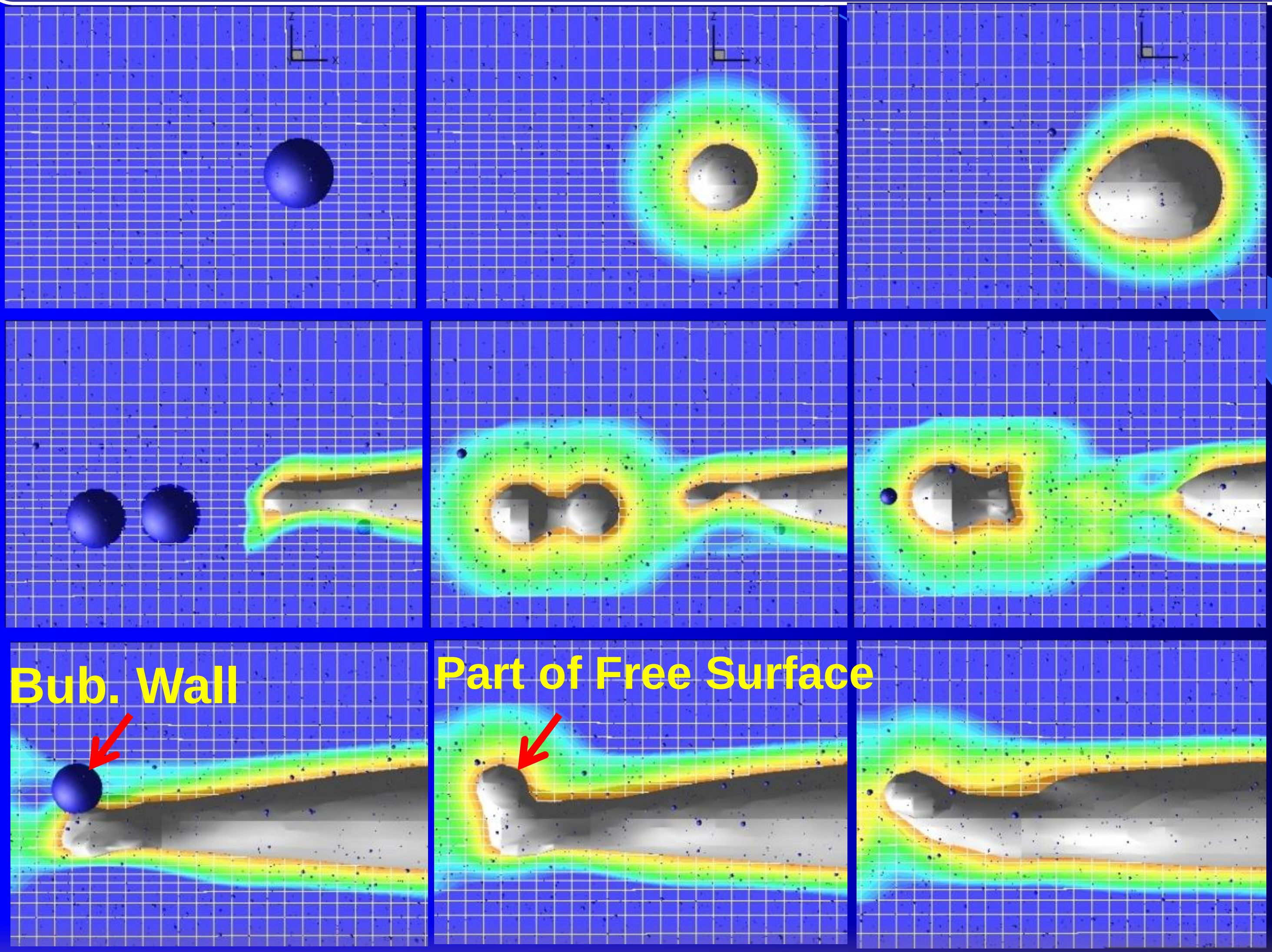


Demo: Cavitation in a Line Vortex (Tangential Injection of Bubbles)



Contoured by distance function

Meso-Scale Transition Allows Capture of…

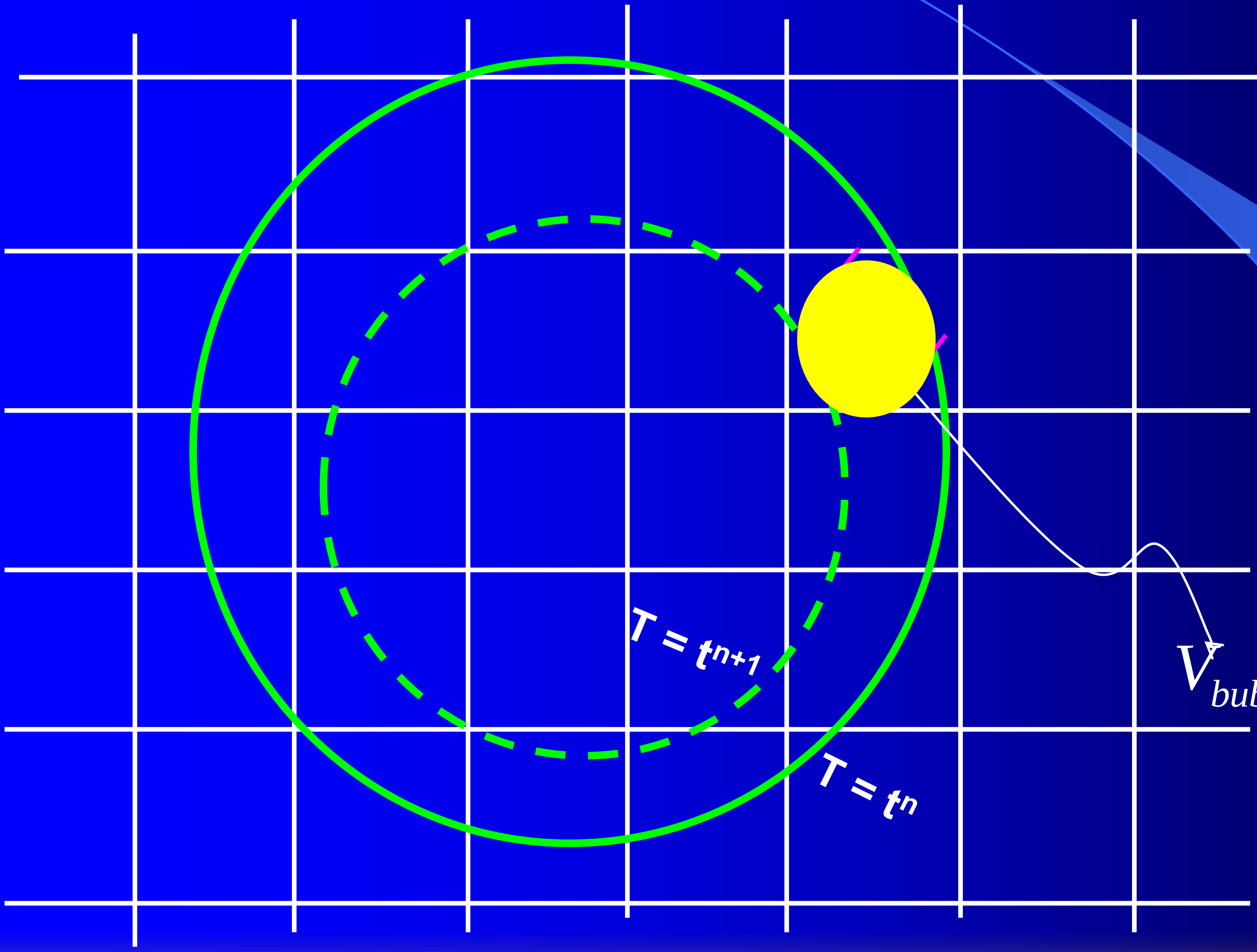


Inception & Deformation

Coalescence

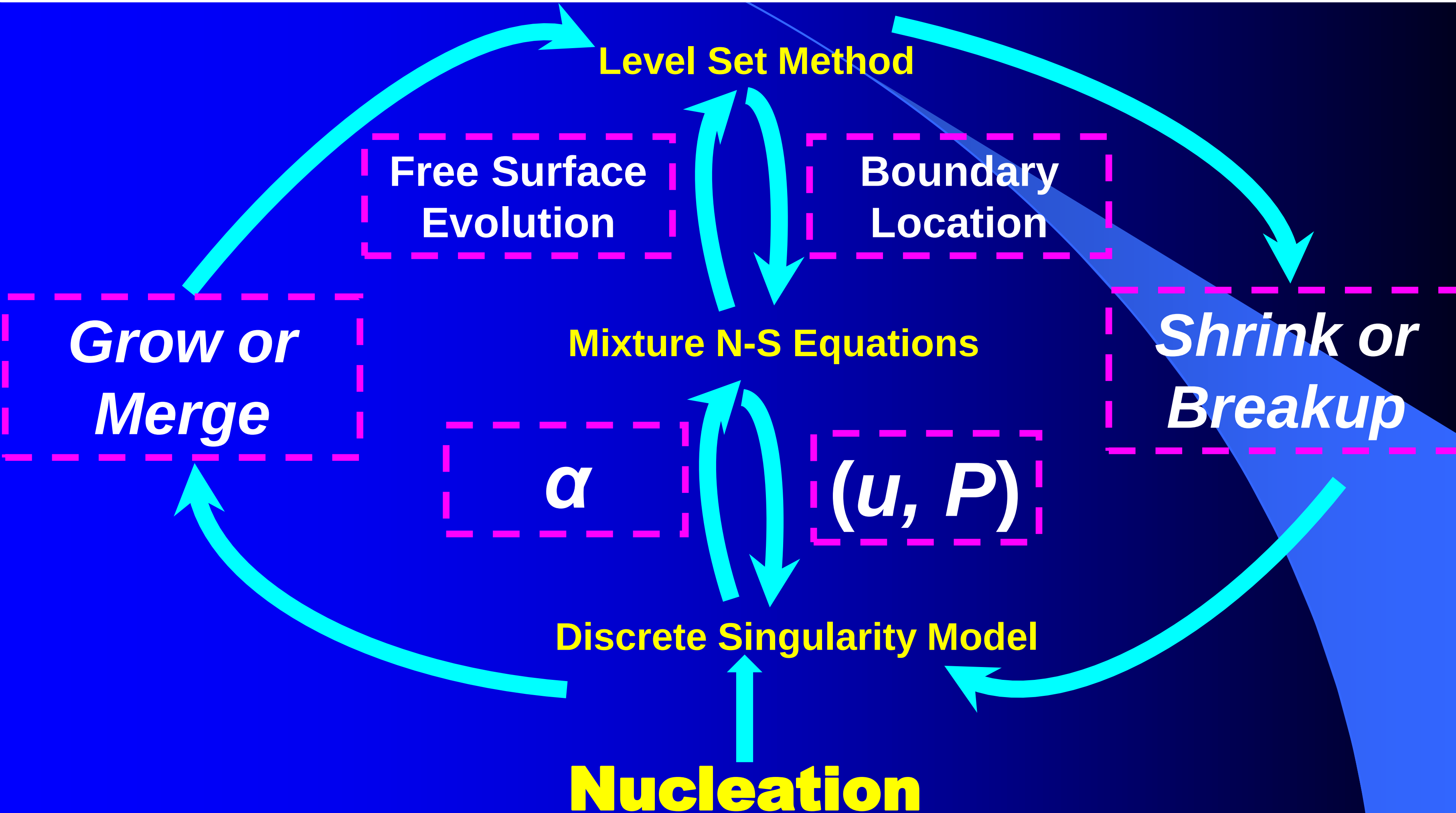
Merger

Macro → Micro Bridging: Bubble Generation



$$V_{bub} = (-\frac{\partial \alpha}{\partial t} V_{cell})\Delta t$$

Fully Coupled, Fully Predictive
3DYNAFS-VIS-DSM©



Ma, Hsiao & Chahine, A physics based multiscale modeling of cavitating flows. Computers & Fluids. 2017

Parallelization for HPC Applications

❖ OpenMP Parallelization

Ma, J., Hsiao, C-T., & Chahine, G.L. "Shared-Memory Parallelization for Two-Way Coupled Euler–Lagrange Modeling of Cavitating Bubbly Flows". ASME J. of Fluids Eng., 2015.

❖ MPI Parallelization

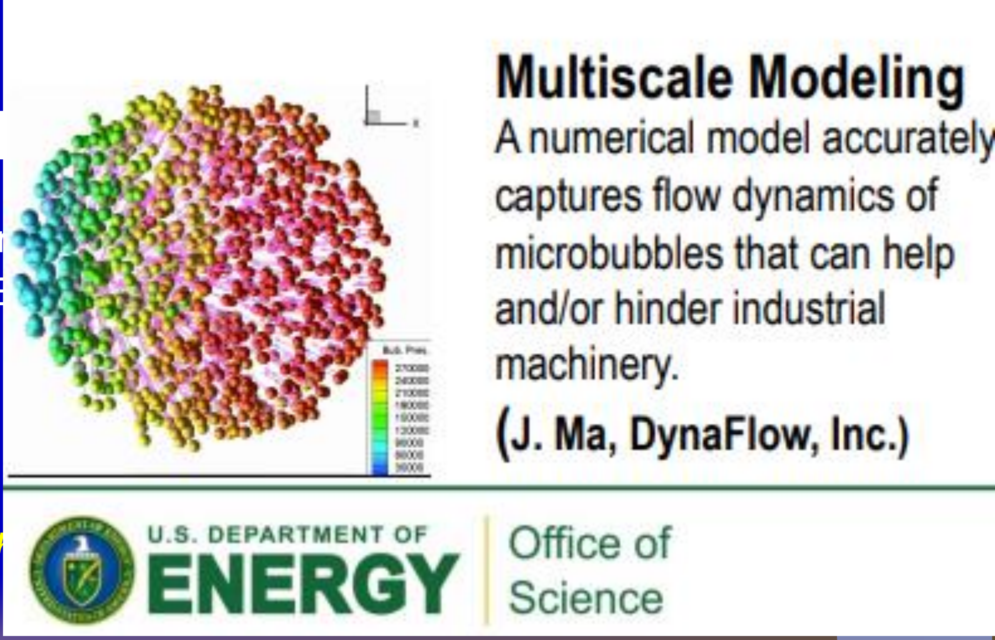
Ma, J., Gnanaskandan, A., Hsiao, C., & Chahine, G. L. "Message Passing Interface Parallelization for Two-Way Coupled Euler–Lagrange Simulation of Microbubble Enhanced HIFU." ASME. J. Fluids Eng., 2021 (*ASME CFDTC Best Paper of 2020*)

❖ Hybrid MPI-OpenMP Paral

Ma, J., Deng, X., Hsiao, C., & Chahine, G. L. “Hybr
Simulation of Microbubble Enhanced HIFU." ASME

❖ OpenMP+OpenACC(GPU)

Hsiao, C-T., Ma, J., Kapahi, A., & Chahine, G.L. M
SBIR Report, 2015 (*NERSC User Science Highligh*



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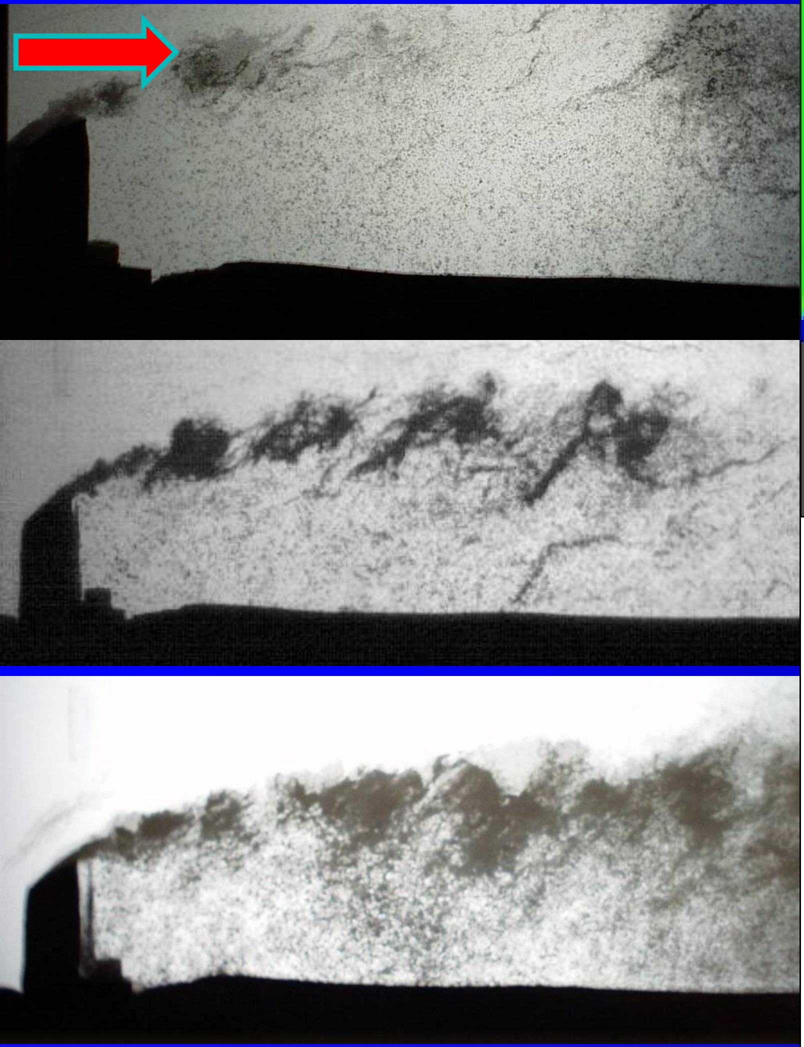
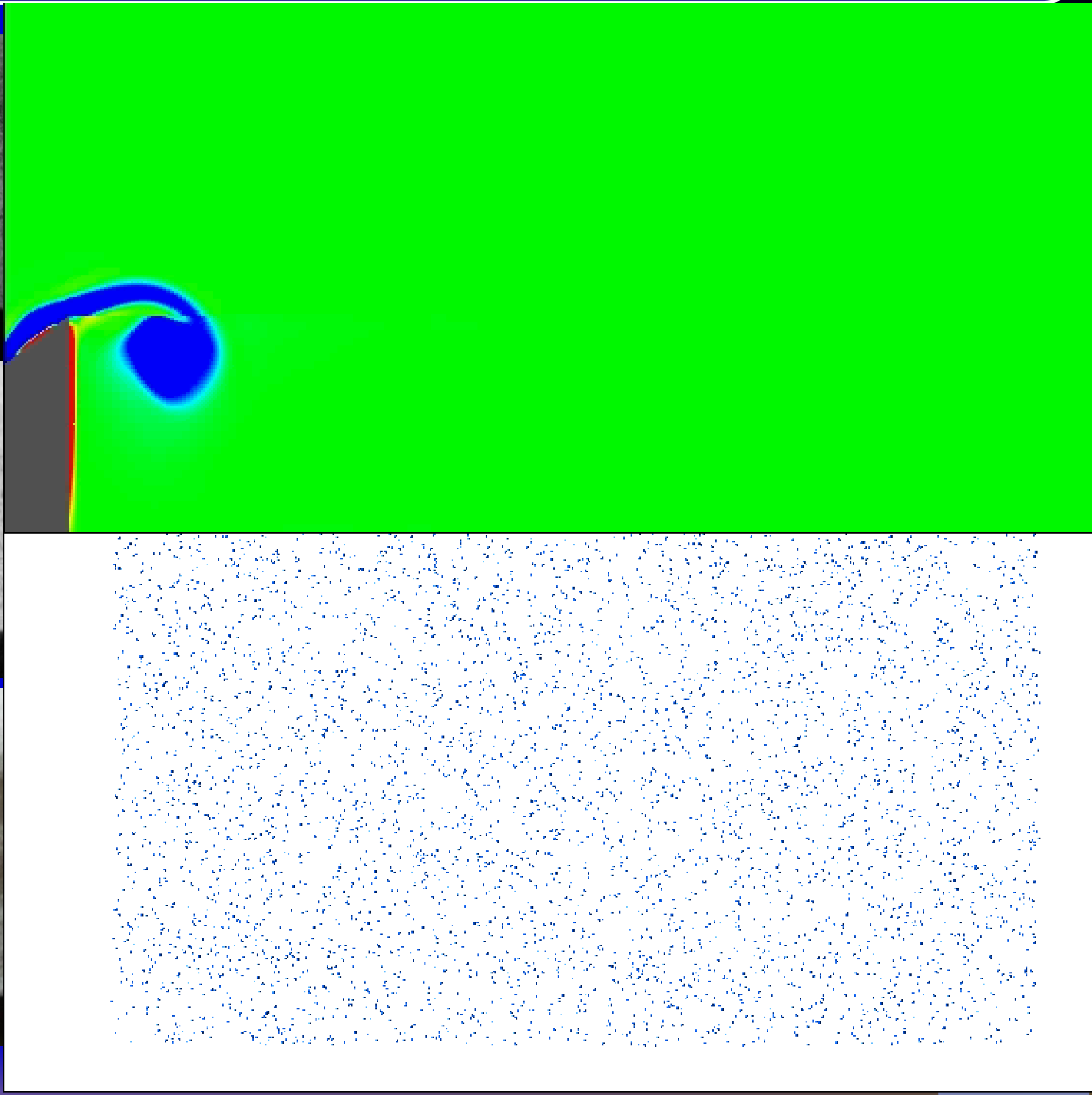
Cavitation behind Obstacle: Separation, Vortex & Bub. Entrainment





Cavitation behind Obstacle: Inception → Cavitation → Supcavitation

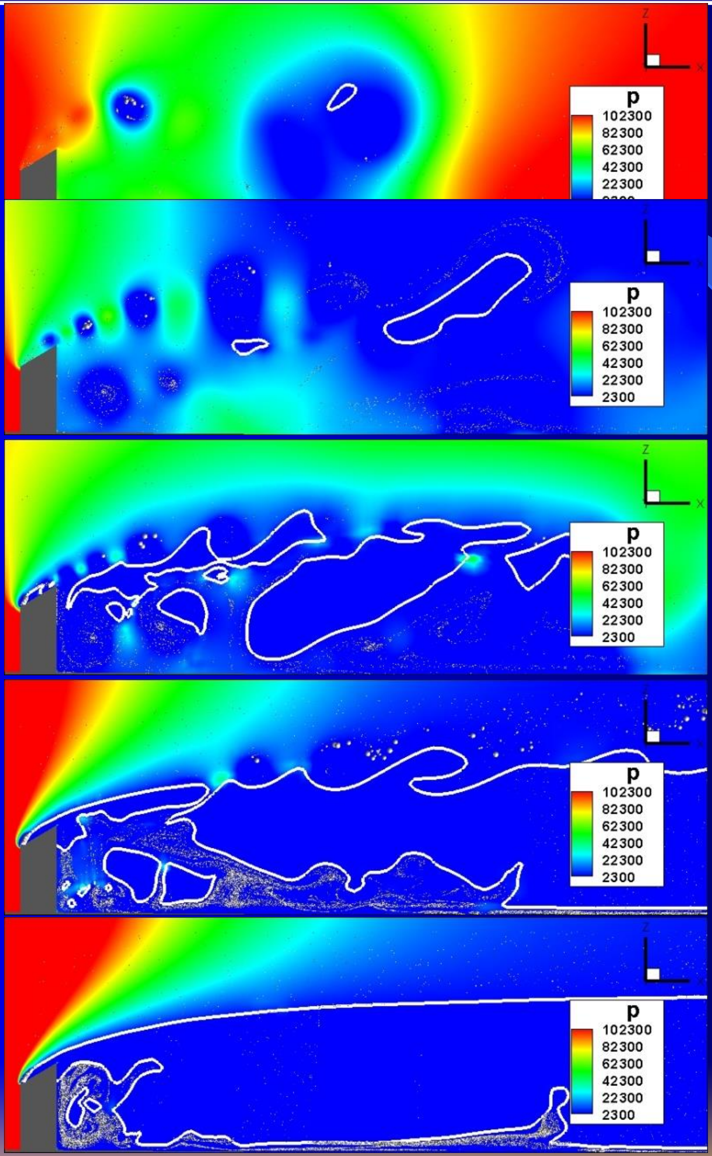
U = 8 m/s

U = 10 m/s

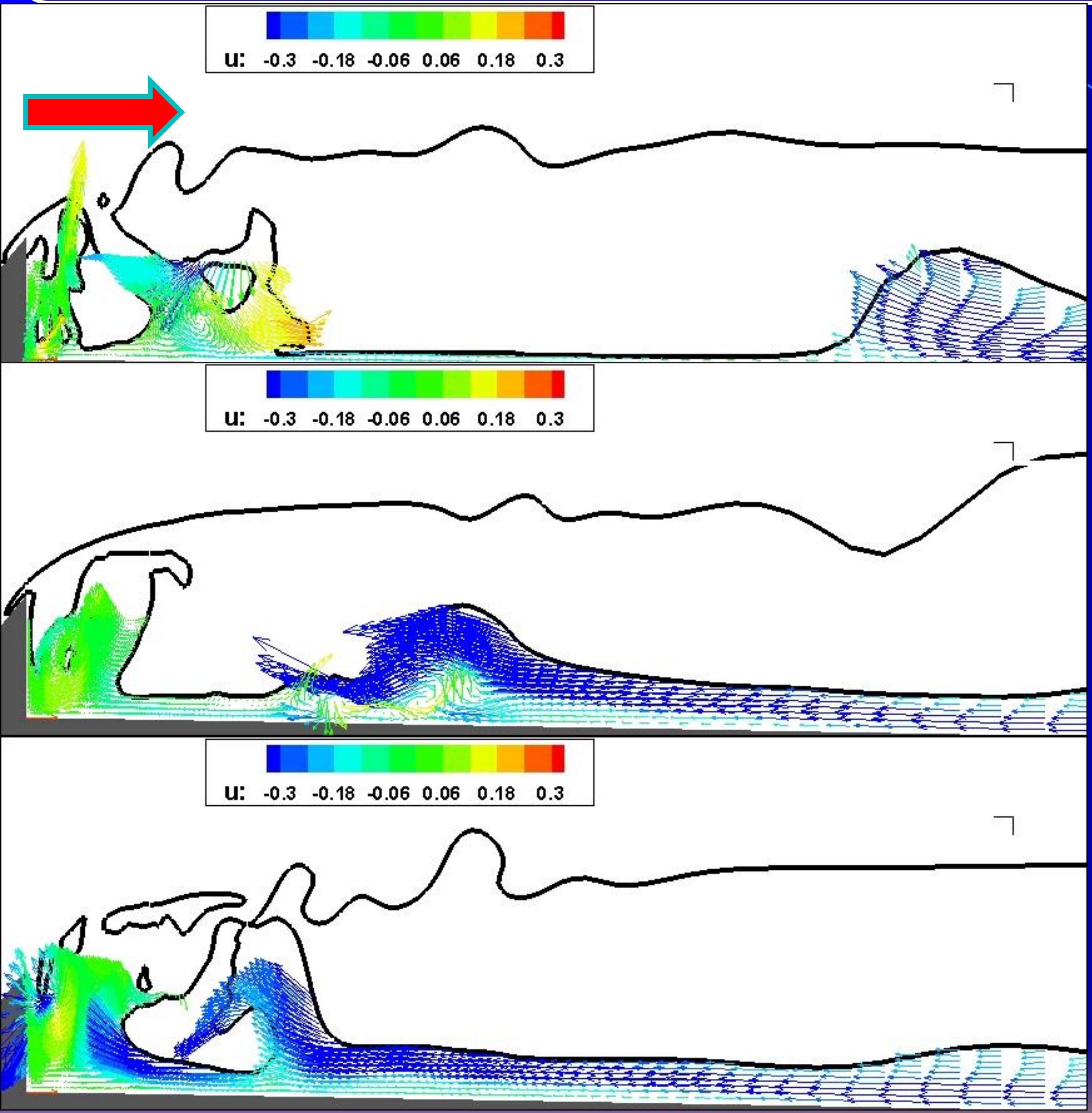
U = 12 m/s

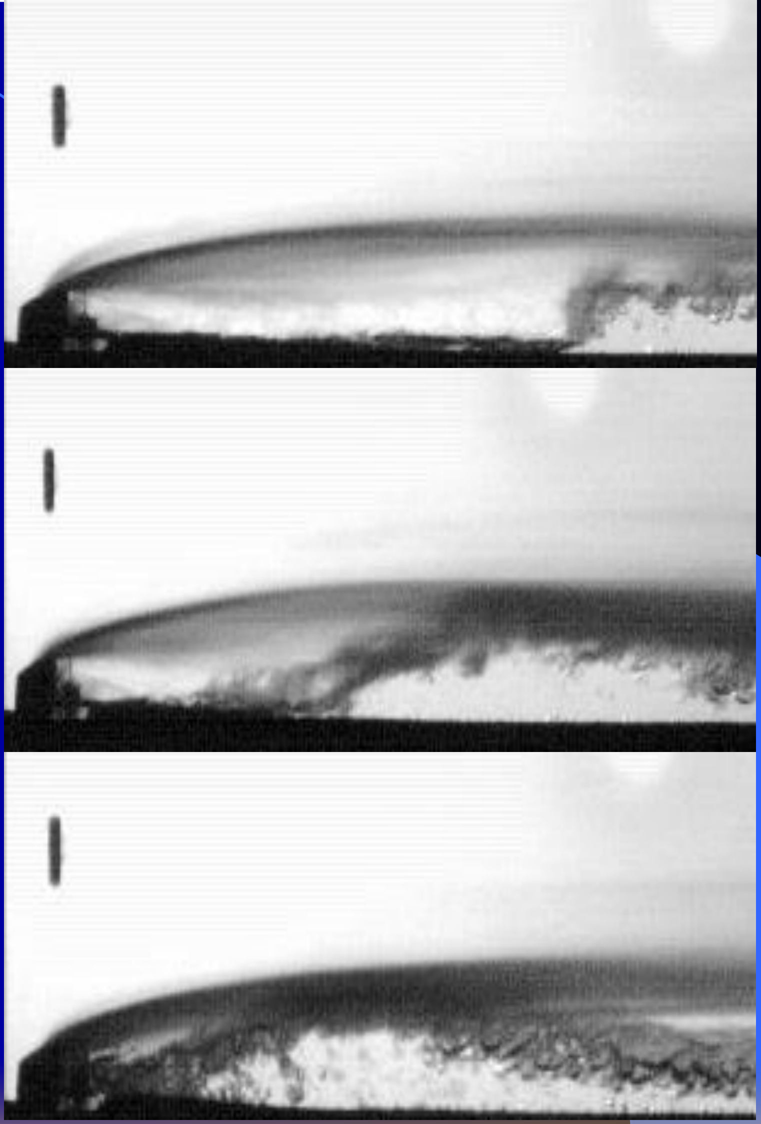
U = 15 m/s

U = 18 m/s

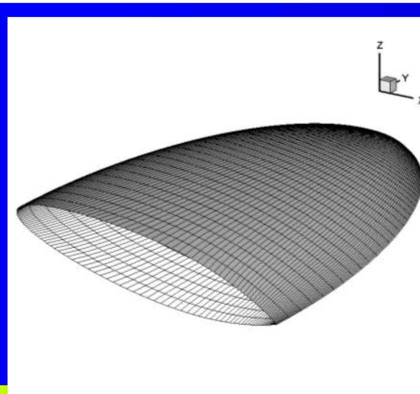


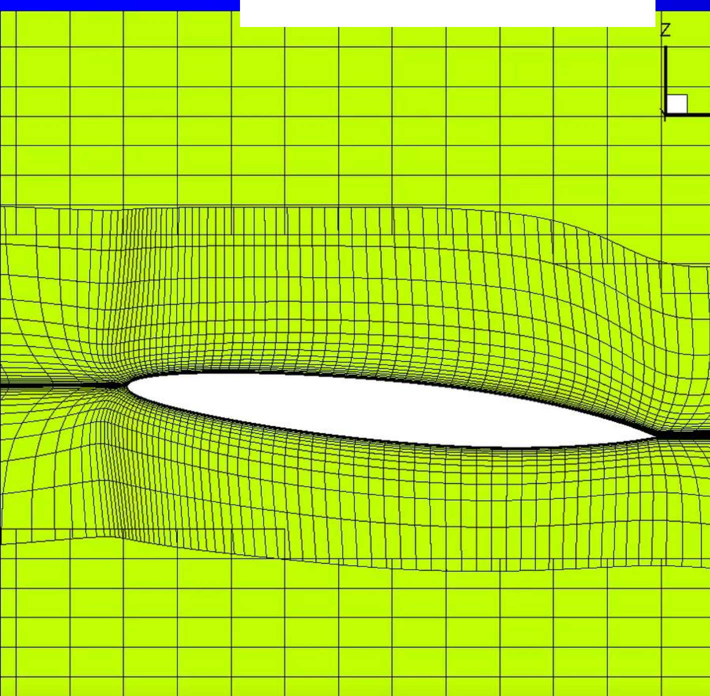
Reentrant Jet under Supercavity & Comparison with Lab Observations

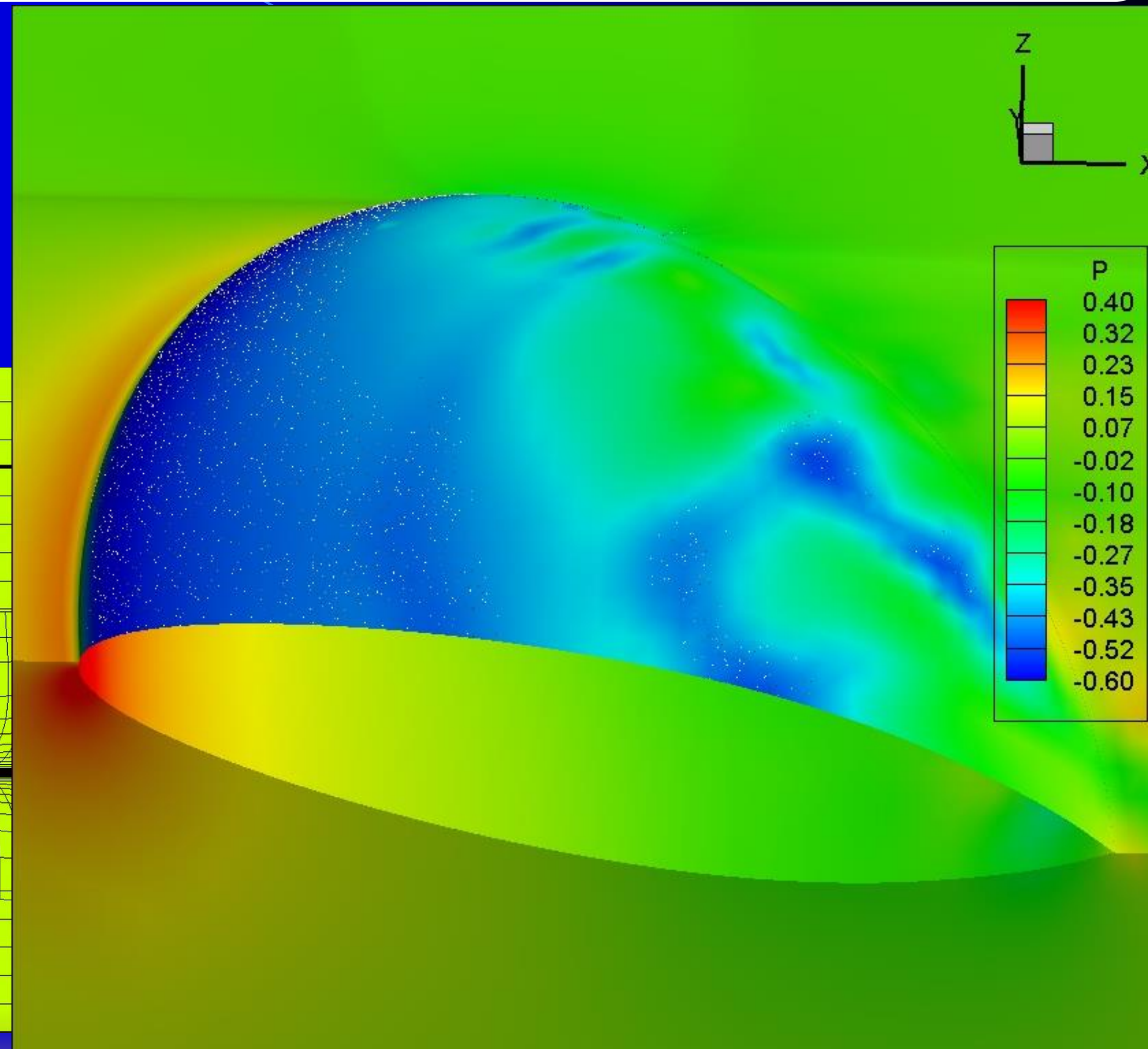




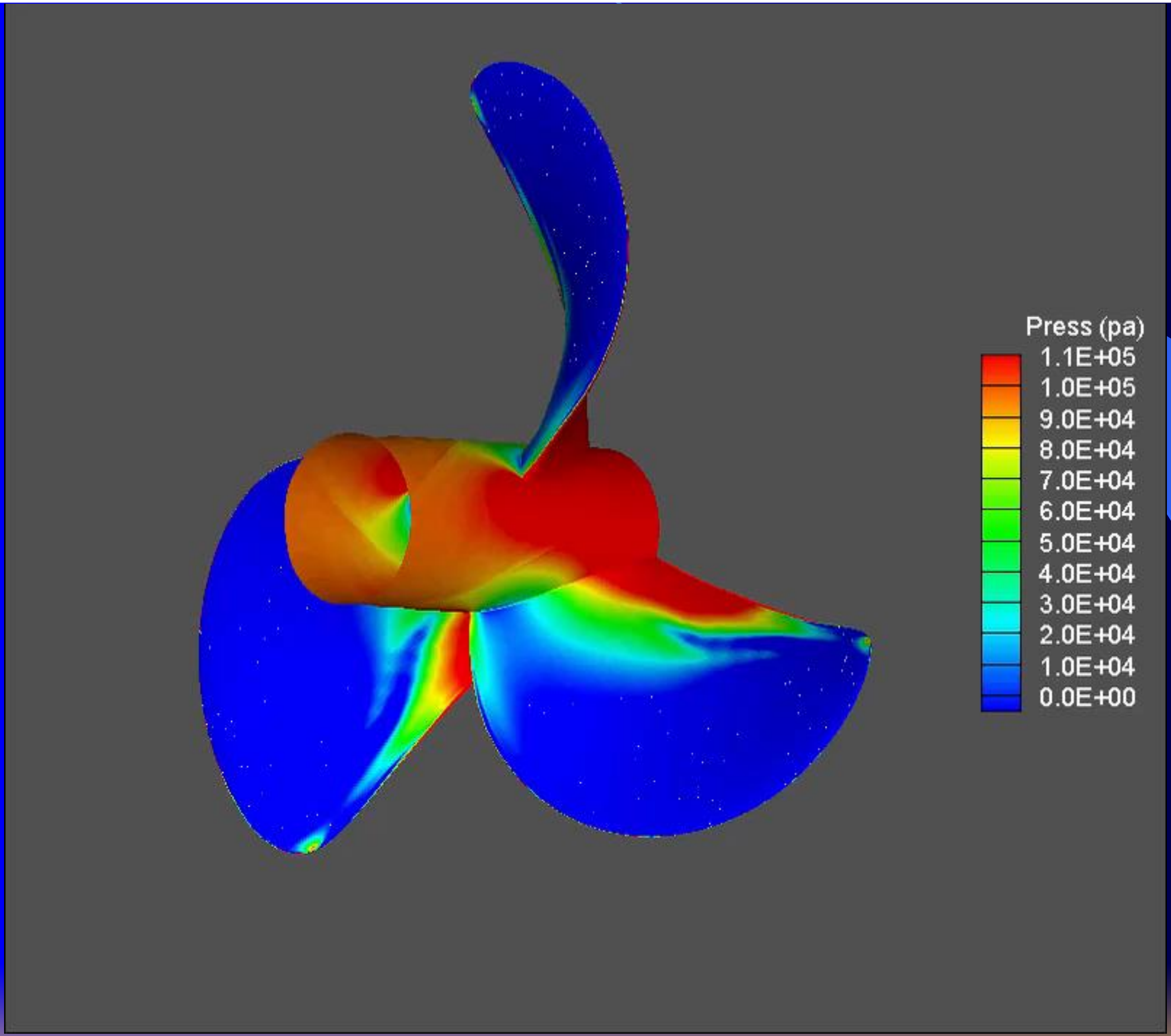
Oscillating Finite-Span Hydrofoil NACA16020







Open Propeller Prop5530



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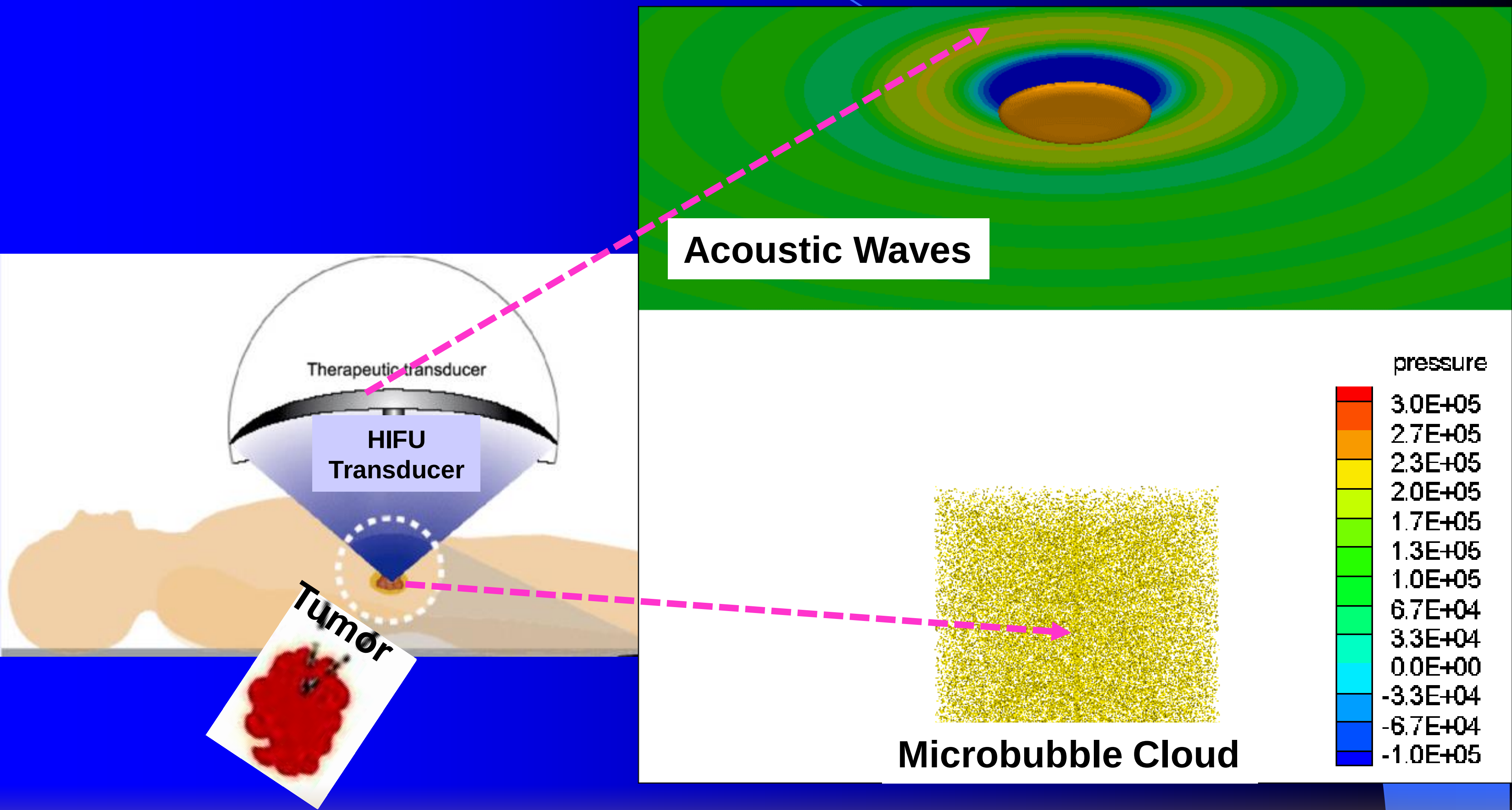
Microbubble Enhanced HIFU for Tumor Treatments



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Summary

- Modelling of cavitating flows is important but challenging as it involves a wide range of scales and gas-liquid interface structures
- DYNAFLOW addresses this using a multiscale modeling platform 3DYNAFS©, which integrates several specialized modules with proper coupling/transitions in between
- The developed methods have been tested and are able to predict the full range of cavitation stages over an obstacle: from Inception to Supcavitation
- Novel applications also include modeling cloud bubble for HIFU bio-medical treatments

Thanks !

Questions, Collaboration?

jingsen@dynaflow-inc.com
www.dynaflow-inc.com