The impact of physical, chemical and biological processes on the fate of oil spills – Bridging small scale processes with meso-scale modeling

Dispersion Research on Oil: Physics and Plankton Studies (DROPPS) Consortium

THE UNIVERSITY OF TEXAS AT AUSTIN

GULF OF MEXICO RESEARCH INITIATIVE

MARINE SCIENCE INSTITUTE
THE UNIVERSITY OF TEXAS AT AUSTIN

DROPPS Consortium: Overarching Research Goals

- Distribution, dispersion and dilution of petroleum under the action of physical processes
- Chemical evolution and biological degradation of petroleum caused by interaction with marine bacteria and plankton
- Focus on small scale processes; link these to mesoscale with mesocosms and modeling efforts

Consortium Members
PI & co-PIs (5 Engineers and 2 biologists)

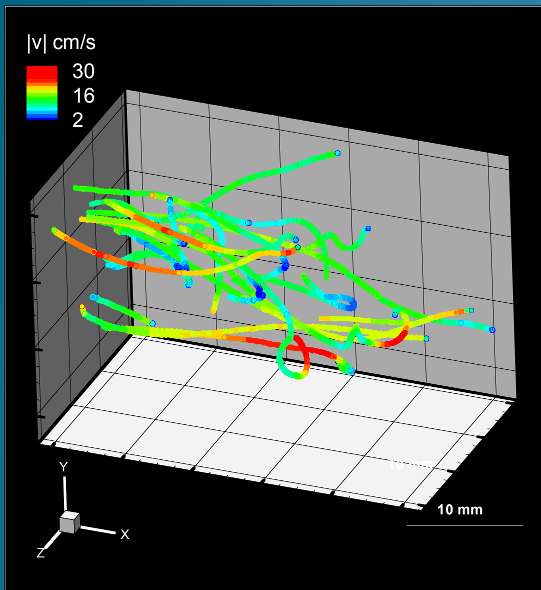
- The University of Texas at Austin, Marine Science Institute, Port Aransas, TX
  - Edward Buskey, PI, Consortium Director
- The Johns Hopkins University, Department of Mechanical Engineering
  - Joseph Katz
- University of Pennsylvania, Dept. of Chemical & Biomolecular Engineering
  - Kathleen Stebe
- University of Minnesota, Dept. of Aerospace Engineering and Mechanics
  - Jian Sheng
- SINTEF, Norway (**SINTEF** (Norwegian: *Stiftelsen for industriell og teknisk forskning*), means "The Foundation for Scientific and Industrial Research".
  - Mark Reed
- University of Wisconsin, Milwaukee, Department of Biological Science
  - J. Rudi Strickler
- Clarkson University / COSS (Coastal Oil-spill Simulation System), Department of Civil and Environmental Engineering
  - Jim Bonner

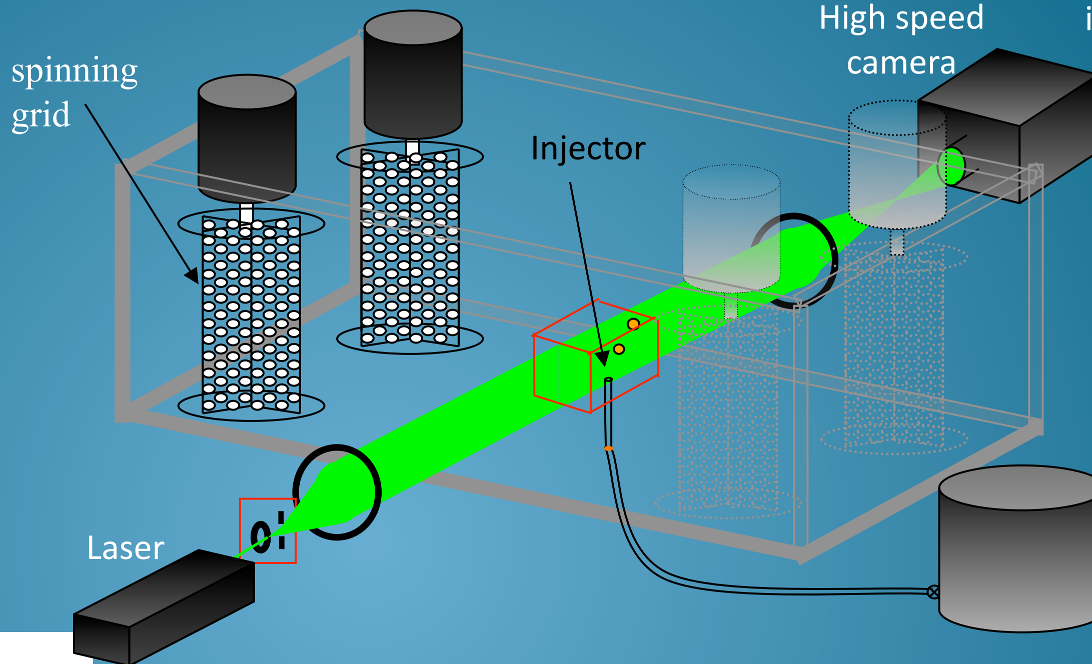
Small scale processes

- Breakup and dispersion of oil by chemical and physical processes
- Effects of dispersants and bacteria on surface properties of oil droplets
- Factors affecting colonization and growth of bacteria on oil droplets
- Interactions between small oil droplets and planktonic organisms

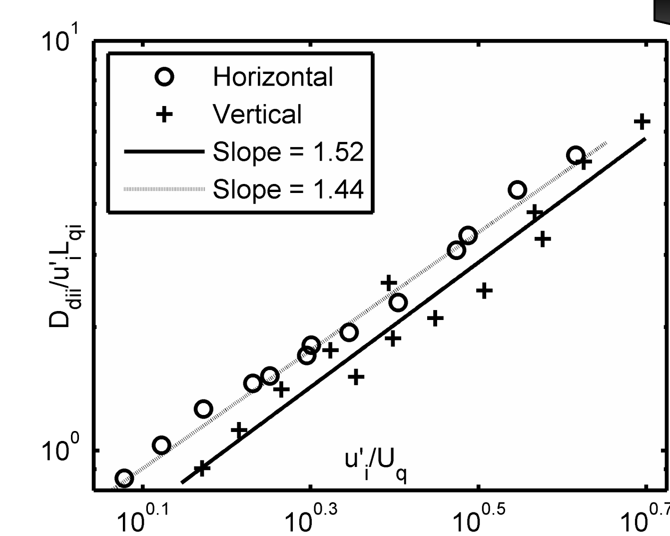
Rise and Dispersion Rate of Oil Droplets in Turbulent Flows – Katz JHU

Sample 3D droplet trajectories

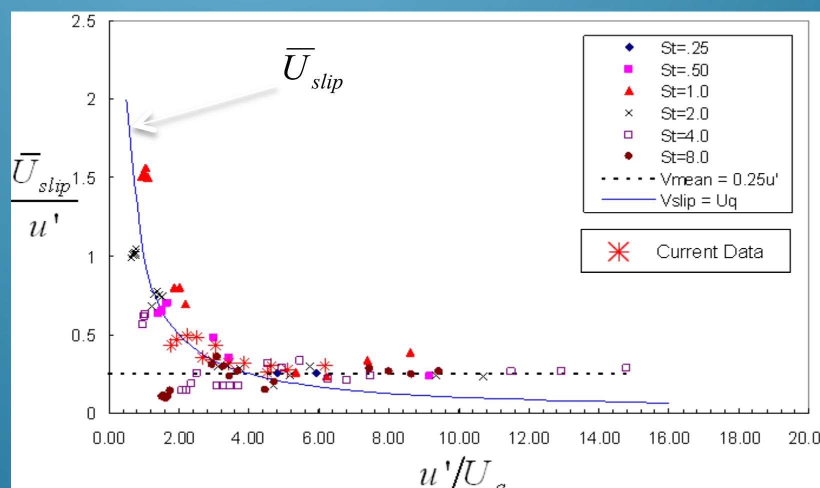




Reconstructed image



Turbulent Diffusion Coefficients



$\overline{U}_{slip}$ mean rise velocity in turbulent flow

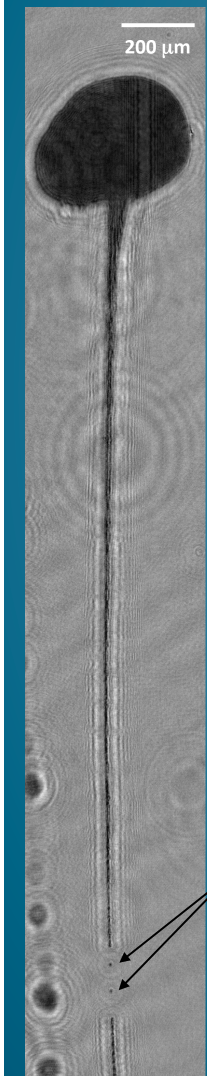
u' Rms of fluid fluctuating velocity

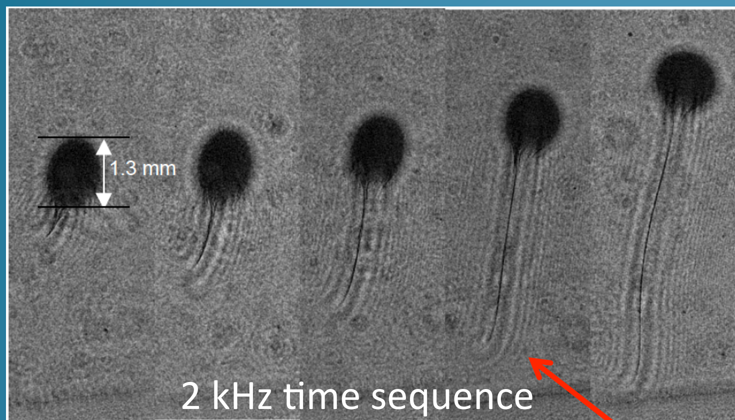
U_q rise velocity in quiescent flow

Mean rise rate of droplets in a turbulent flow

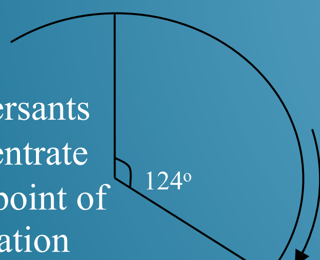
Breakup of Droplets Mixed with Dispersants by Turbulence

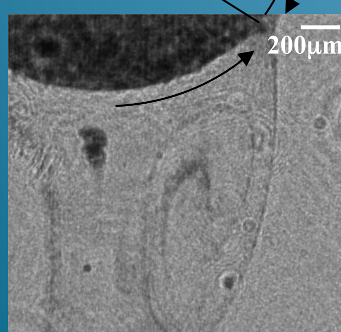
Breakup of “strings” trailing behind droplets
Size of droplets is smaller than turbulence scales, typically in the order of 1-3 μm

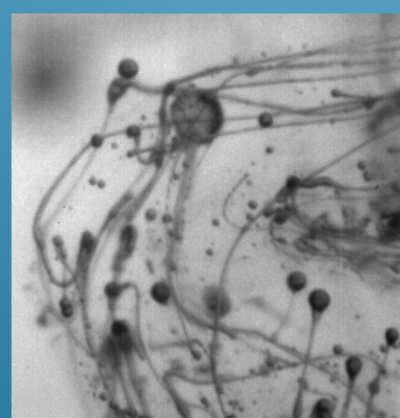




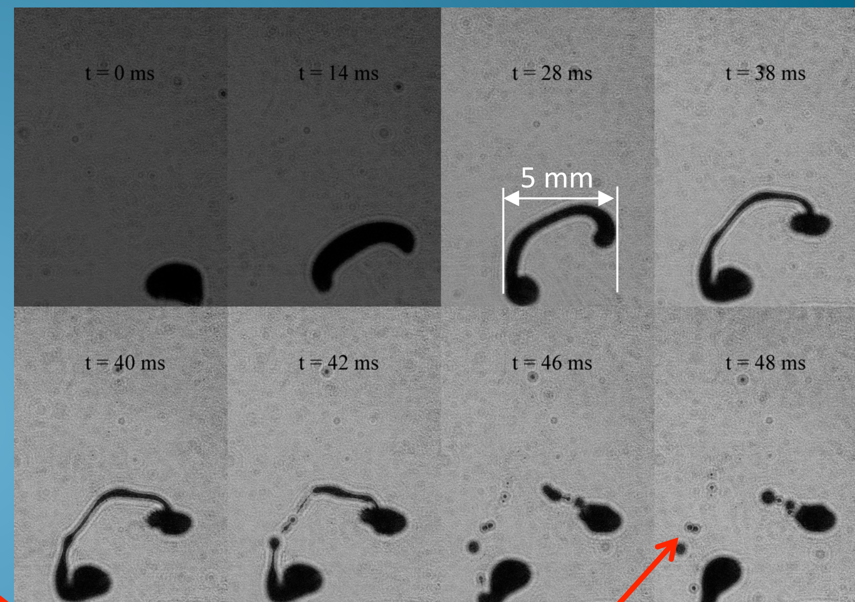
Dispersants concentrate near point of separation

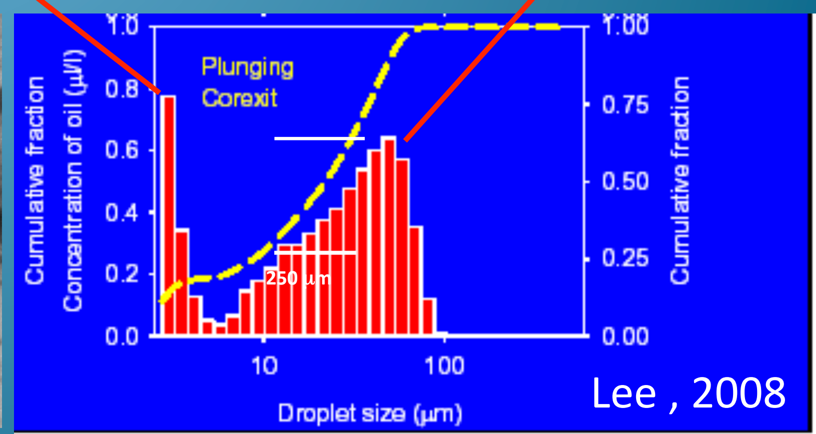






Breakup by Capillary Instabilities
Size is determined by turbulence scales

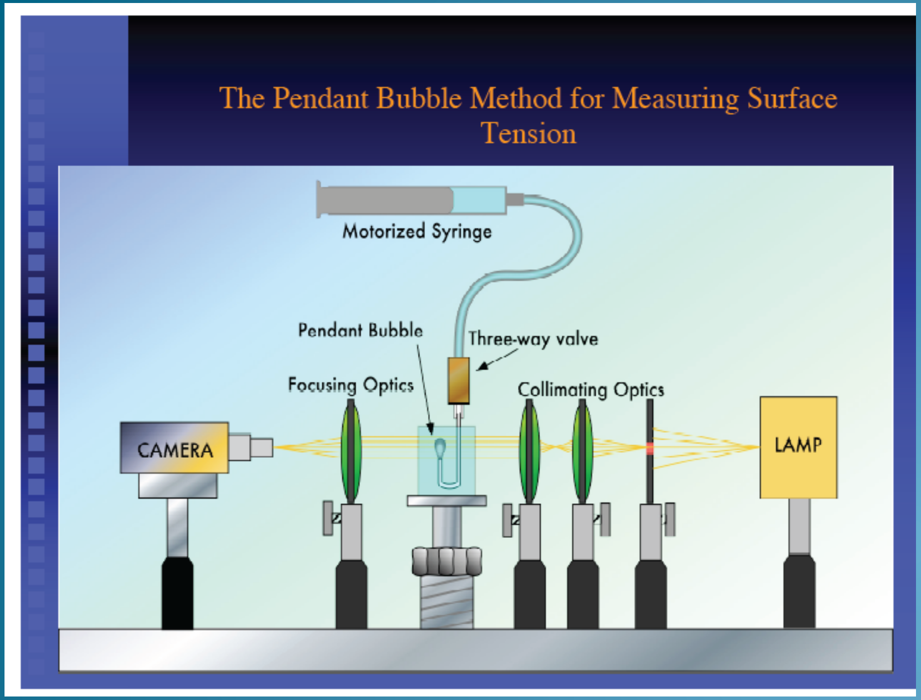




Lee , 2008

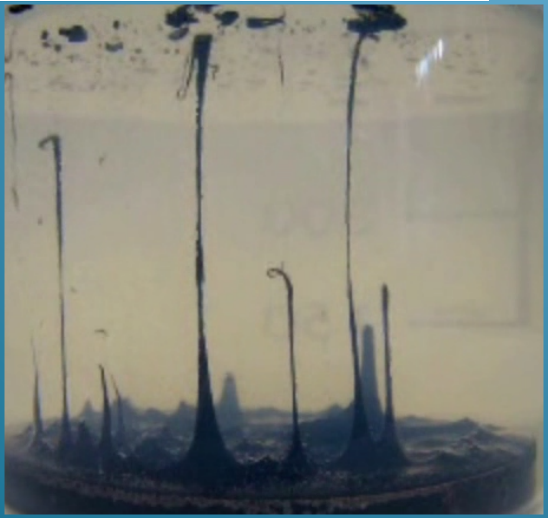
Mechanical consequences of complex oil-water interfaces

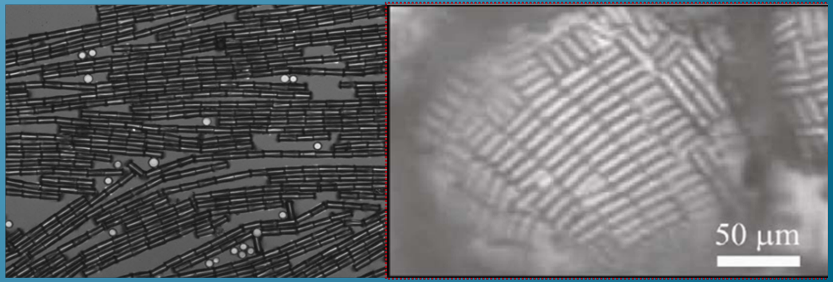
KJ Stebe University of Pennsylvania



1. **Characterize interfacial mechanics: Oil/saline interfaces with dispersant**

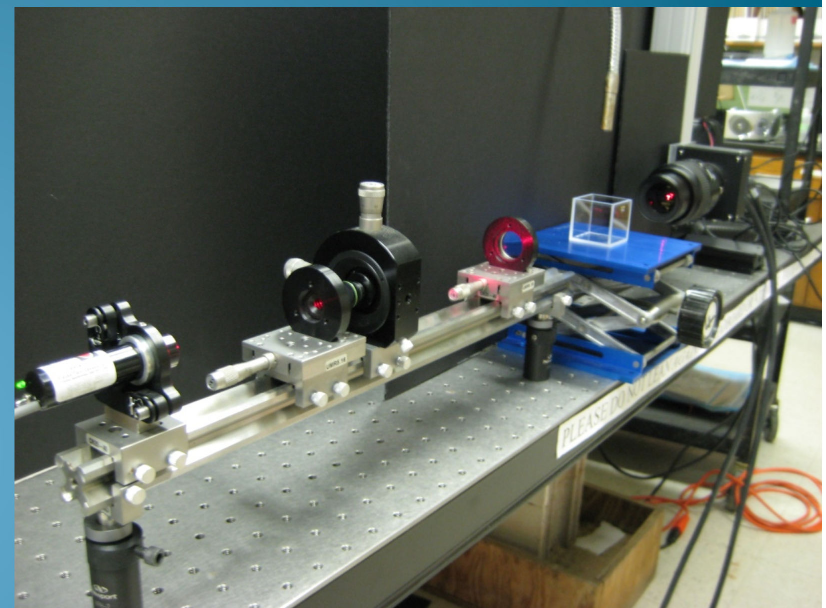
2. **Characterize interfacial mechanics: Oil/saline interfaces with dispersant, particles, bacteria and plankton**

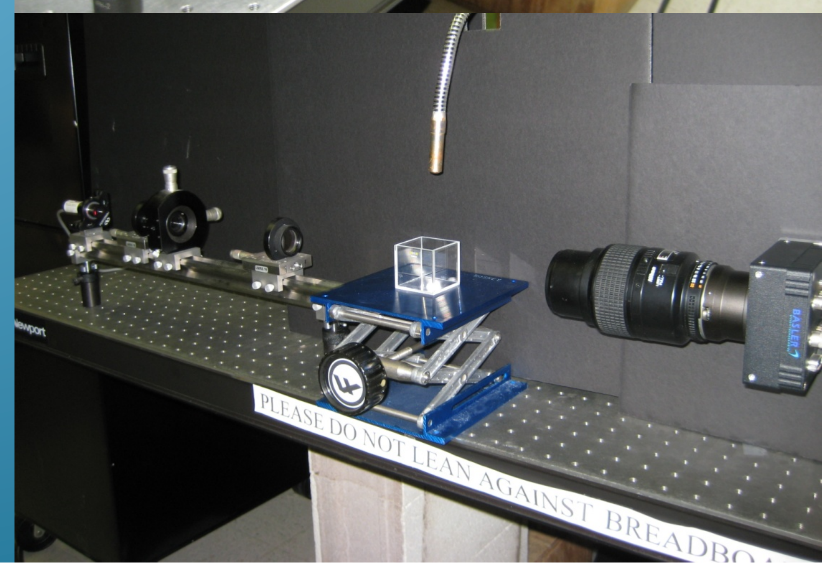




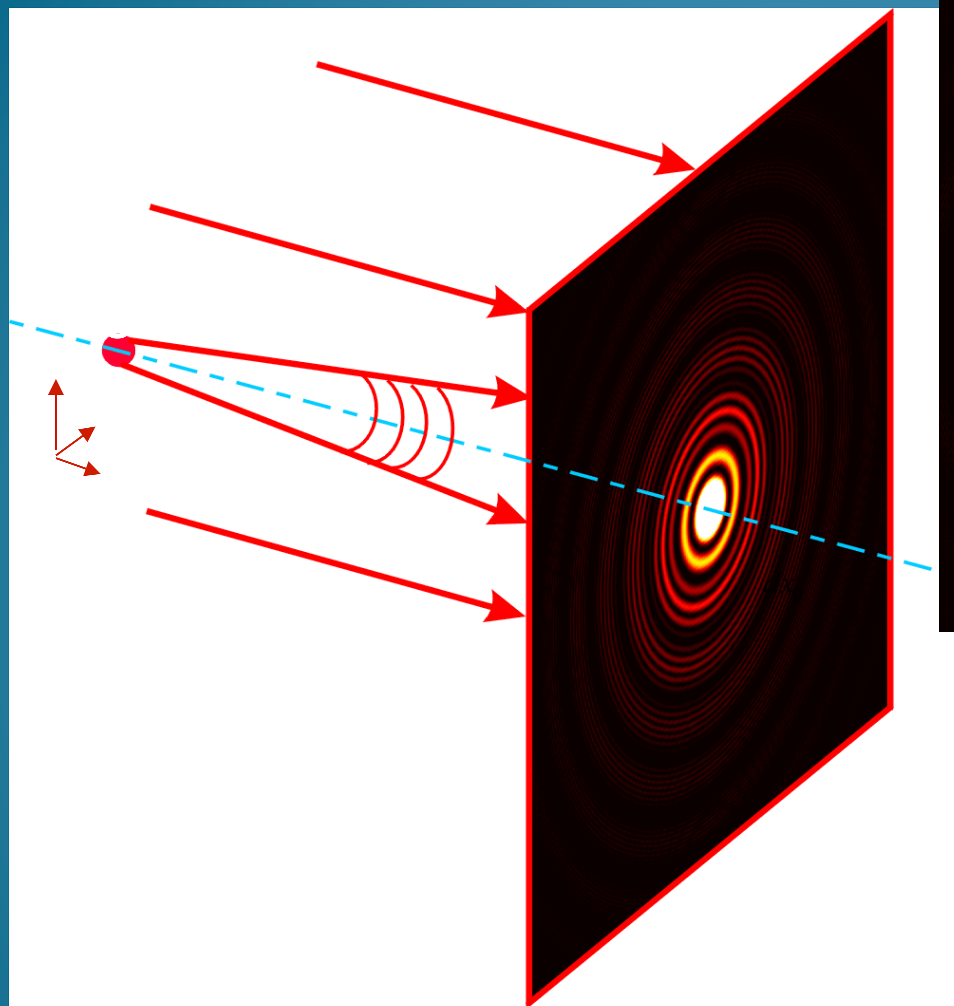
Sidebar: Observing small scale physical and biological phenomena using Holography

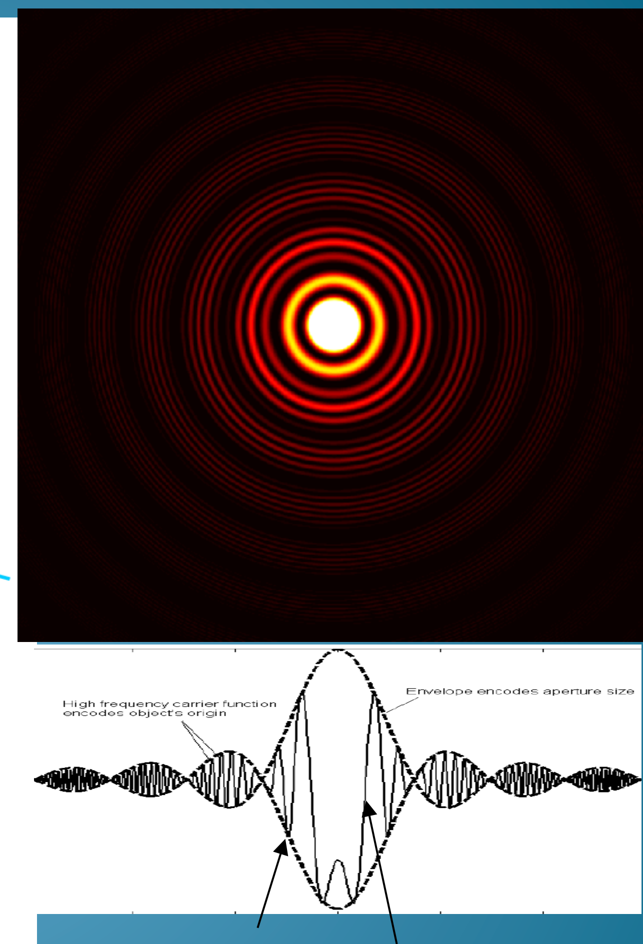
- All consortium members use sophisticated optical methods to study small scale processes in seawater, and try to put these results into context for understanding larger scale processes
- Provide a short introduction to holography





Principle of In-line Holographic Recording

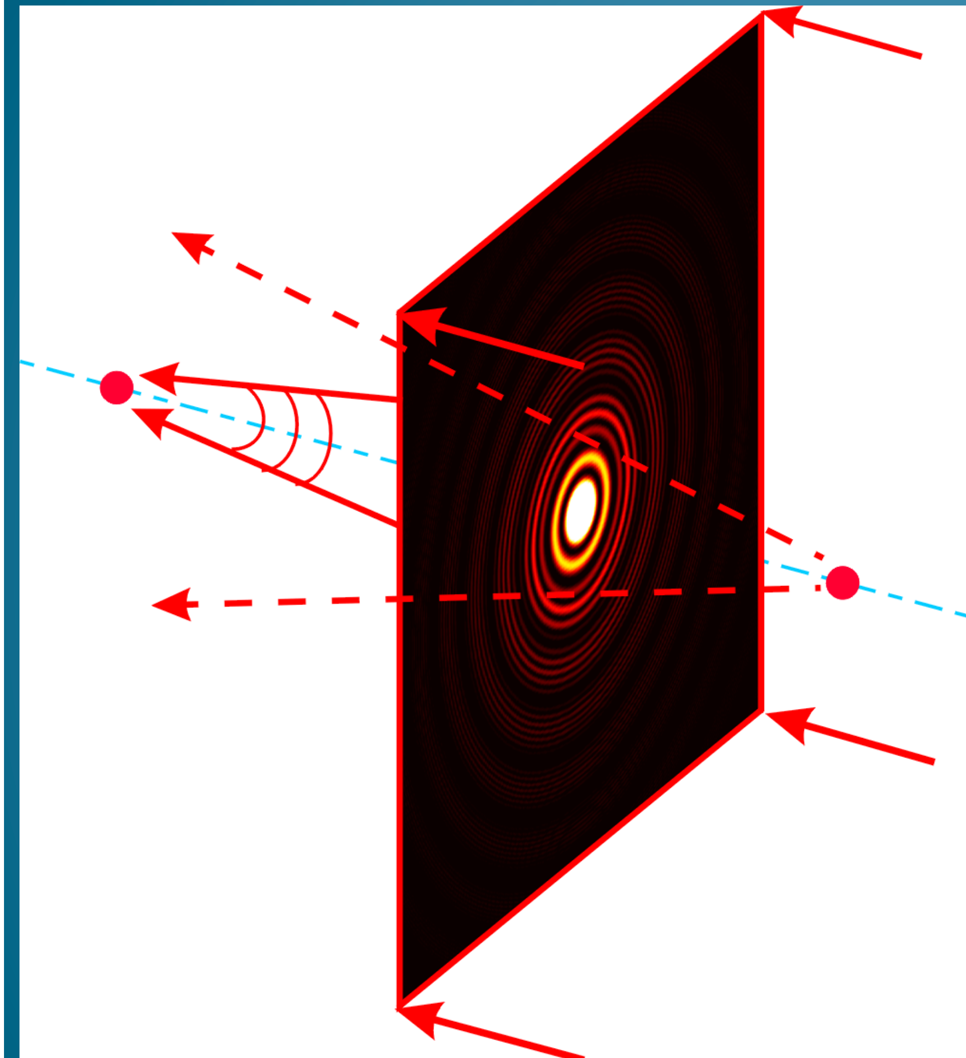




$$I = f\left(\frac{rD}{\lambda z}\right)\cdot g\left(\frac{r^2}{\lambda z}\right)$$

- A hologram is a record of *interference patterns* between scattered light from an object and reference light of known phase distribution.
- *Envelope* of interference records the *shape* of the object, whereas the *spacing* of fringes encodes the origin of the object.

Principle of Holographic Reconstruction



$$RI_H = |R|^2 R^* + |R|^2 O + R^2 O^* + R|O|^2$$

Optical Reconstruction

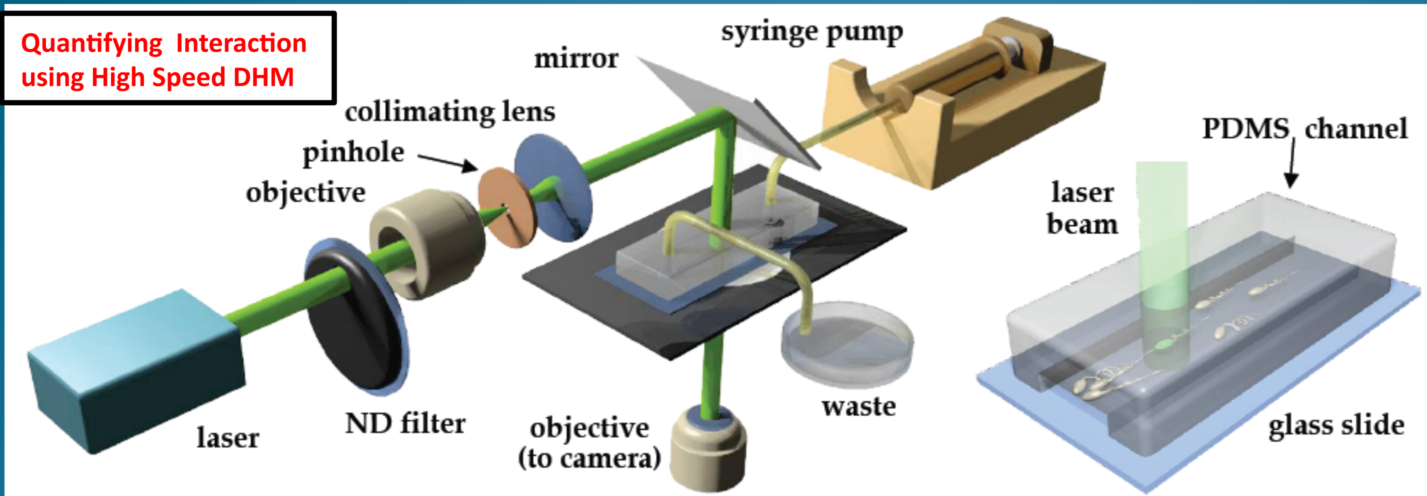
Hologram is illuminated with a conjugate beam, i.e. backward propagating reference beam. R^2O is real image and R^2O^* is virtual image

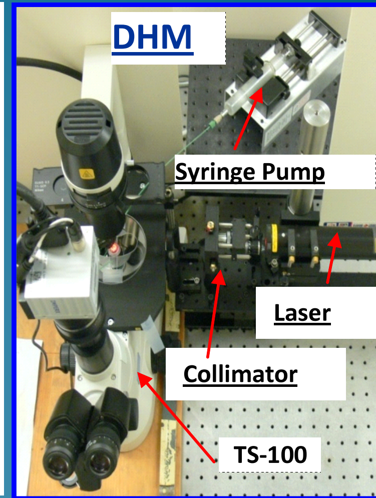
Numerical Reconstruction

Same reconstruction process is performed numerically

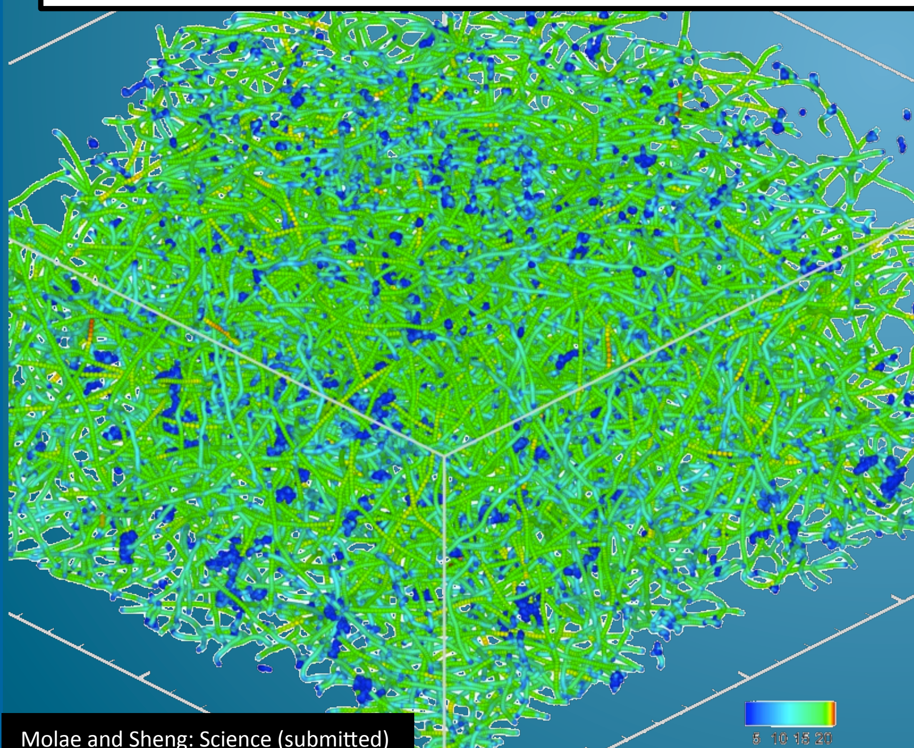
Approach : 3D Digital Holographic Microscopy – Quantify Dynamic Interactions

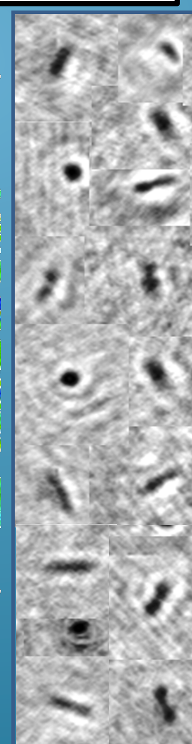
Quantifying Interaction using High Speed DHM



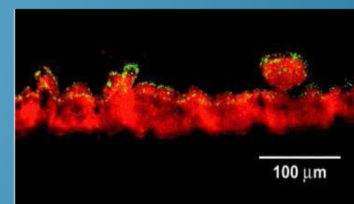


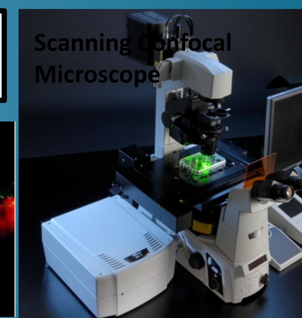
3D Trajectories of *E. coli* Bacteria in a Dense Suspension & In-focus Cell Morphology





Quantifying Consortia Structure using SCM





- High spatiotemporal resolution: 0.2 um & 33 us
- Perform experiments in dense suspension and large volume: 10^6 cells / ml
- Simultaneous measurement of organism motion and flow conditions.

Measurement capability of 3D bacterial motion

Fate of Oil : Micro-scale biophysical processes involving microbes-oil ***Interactions*** by advanced 3-D measurement and microFluidics + milliFluidics

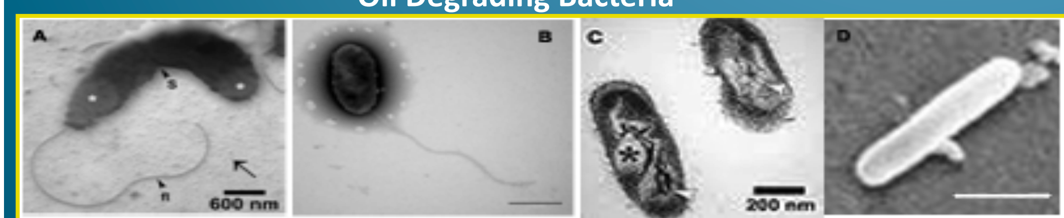
<u>Aim 1</u>: *Encounter rate of microbes with the oil phase*

<u>Aim 2</u>: *Interplay between cell motility and encounter rate of oil, its consequential role in the rate of oil degradation/consumption*

<u>Aim 3</u>: *Implications of bacterial motility for consortia formation, oil consumption*

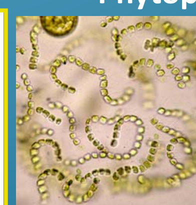
<u>Aim 4</u>: *Interactions between oil droplets and planktonic particles oil degradation, consumption, droplet breakup, and sedimentation.*

Oil Degrading Bacteria



T. oleivorans *N. japonica* *A. borkumensis* *P. aeruginosa*

Phytoplankton



C. socialis

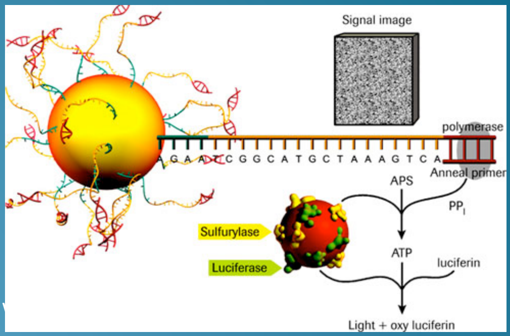
Karenia

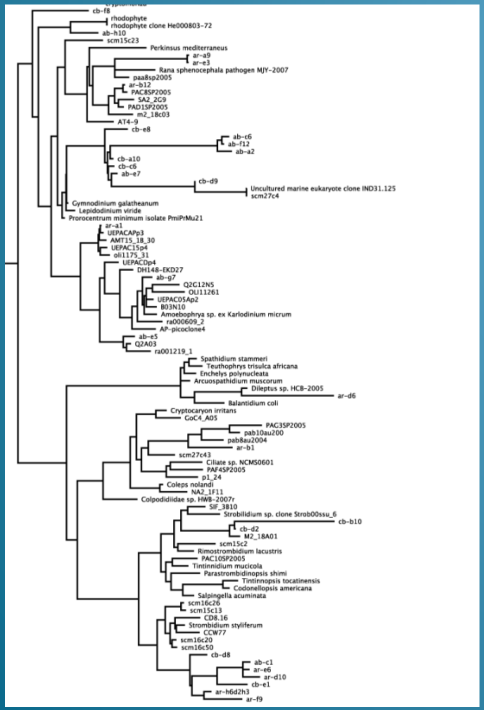
Zooplankton

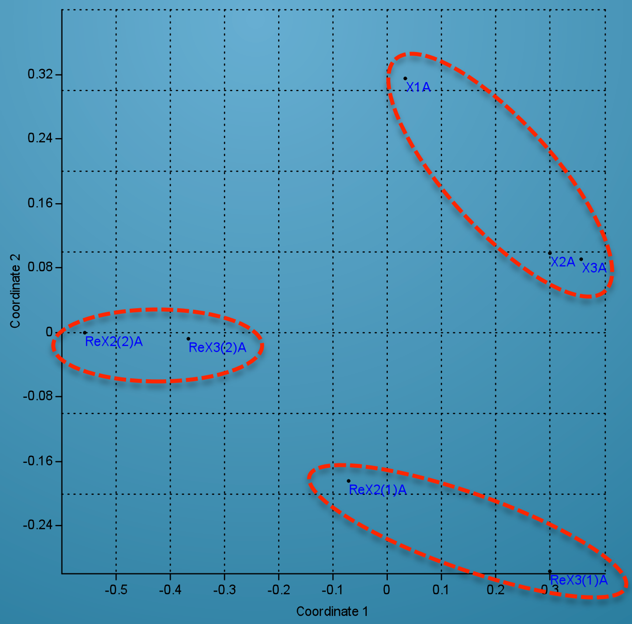
A. tonsa

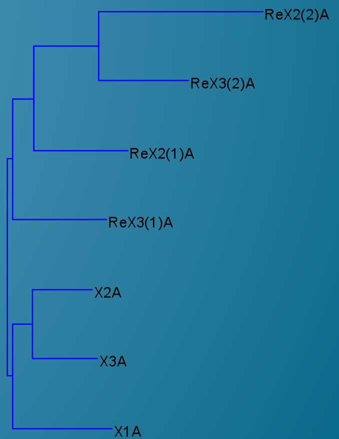
Microbial Community Response to Hydrocarbons - Erdner

1. DNA extraction & high-throughput sequencing of SSU rRNA gene marker
2. Identification of taxa (BLAST) and comparison of community composition



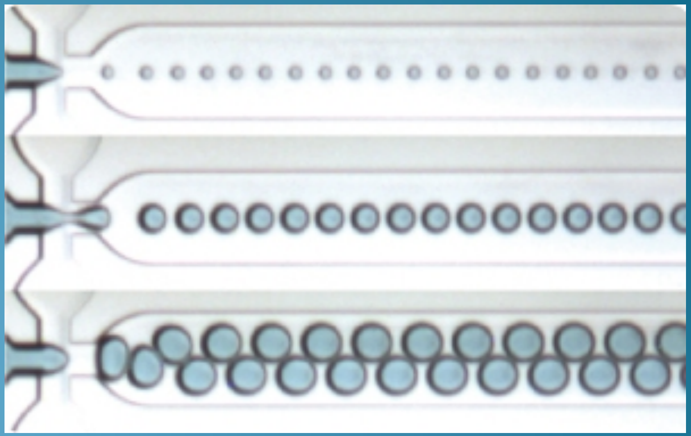


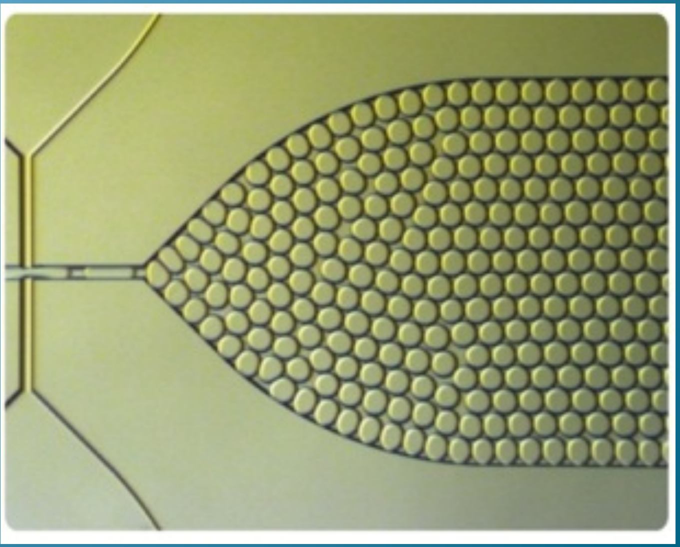




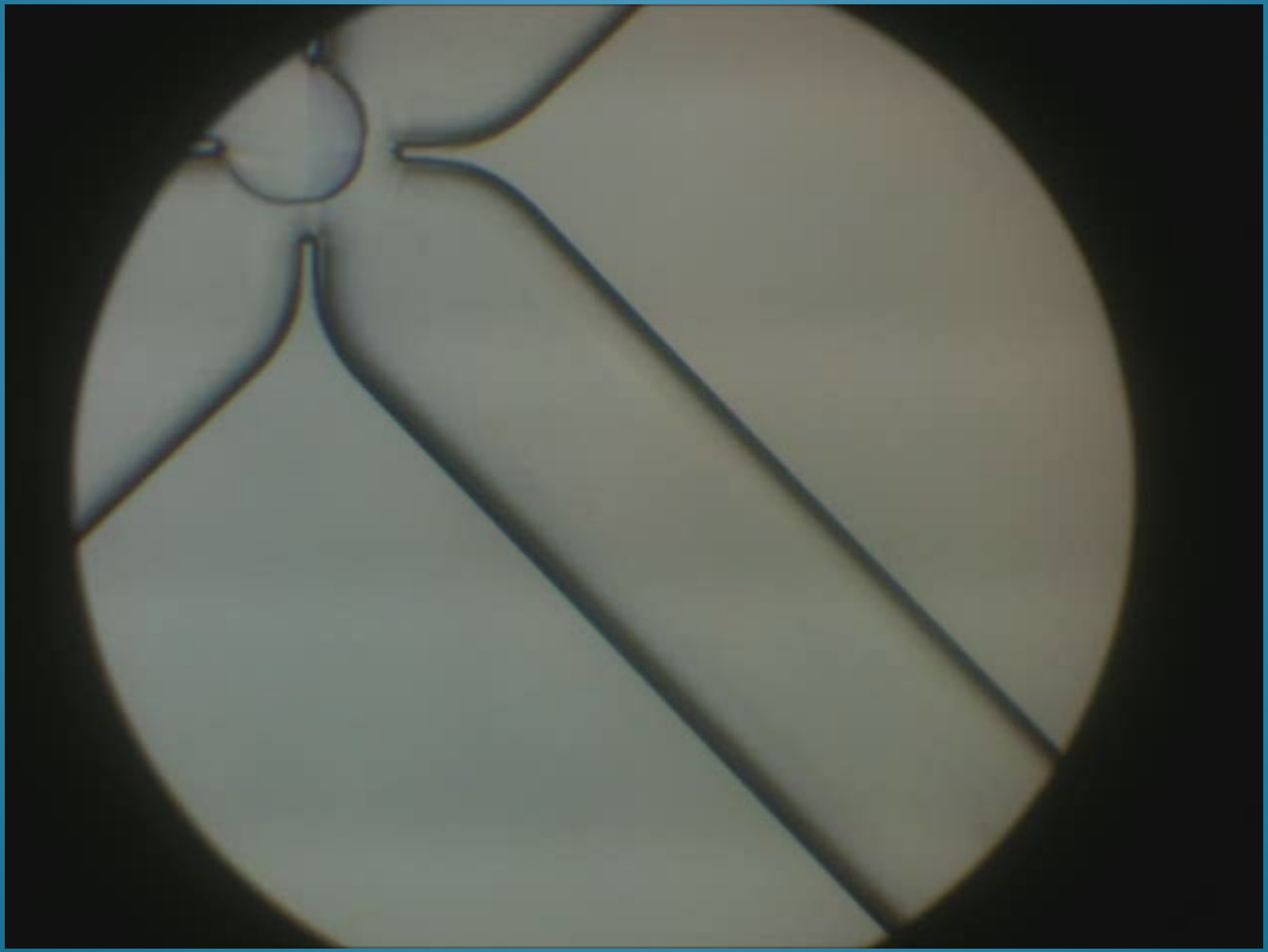
Use microfluidic devices to generate oil droplets of known size distribution

- Engineering studies will reveal size distribution of oil droplets under various physical and chemical conditions
- Oil droplets of appropriate size distribution will be generated to study small scale interactions with plankton





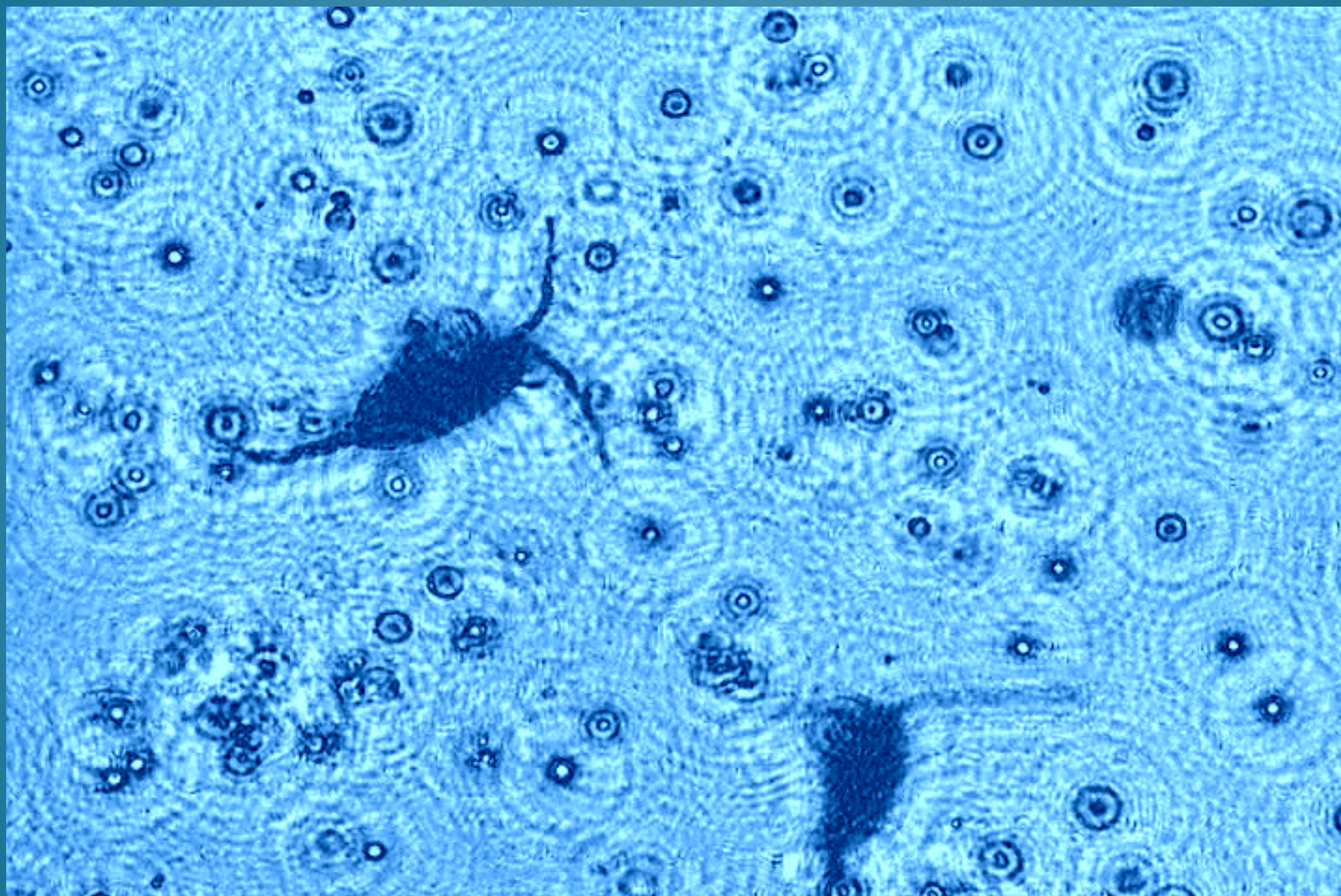
Creating oil droplets using microfluidics



Zooplankton interactions with oil and algae - Buskey and Strickler

- The ingestion of oil droplets by copepods has been reported repeatedly, and is recognized as one of sinks of oil dispersed in the water column.
- Do the animals actively capture oil droplets, handle them, and ingest them with behavior similar to feeding on algae?
- Do the oil droplets adhere to the feeding appendages and interfere with the normal feeding process?
- How long will the oil stay within the animal until it is released by the animal in fecal pellets?

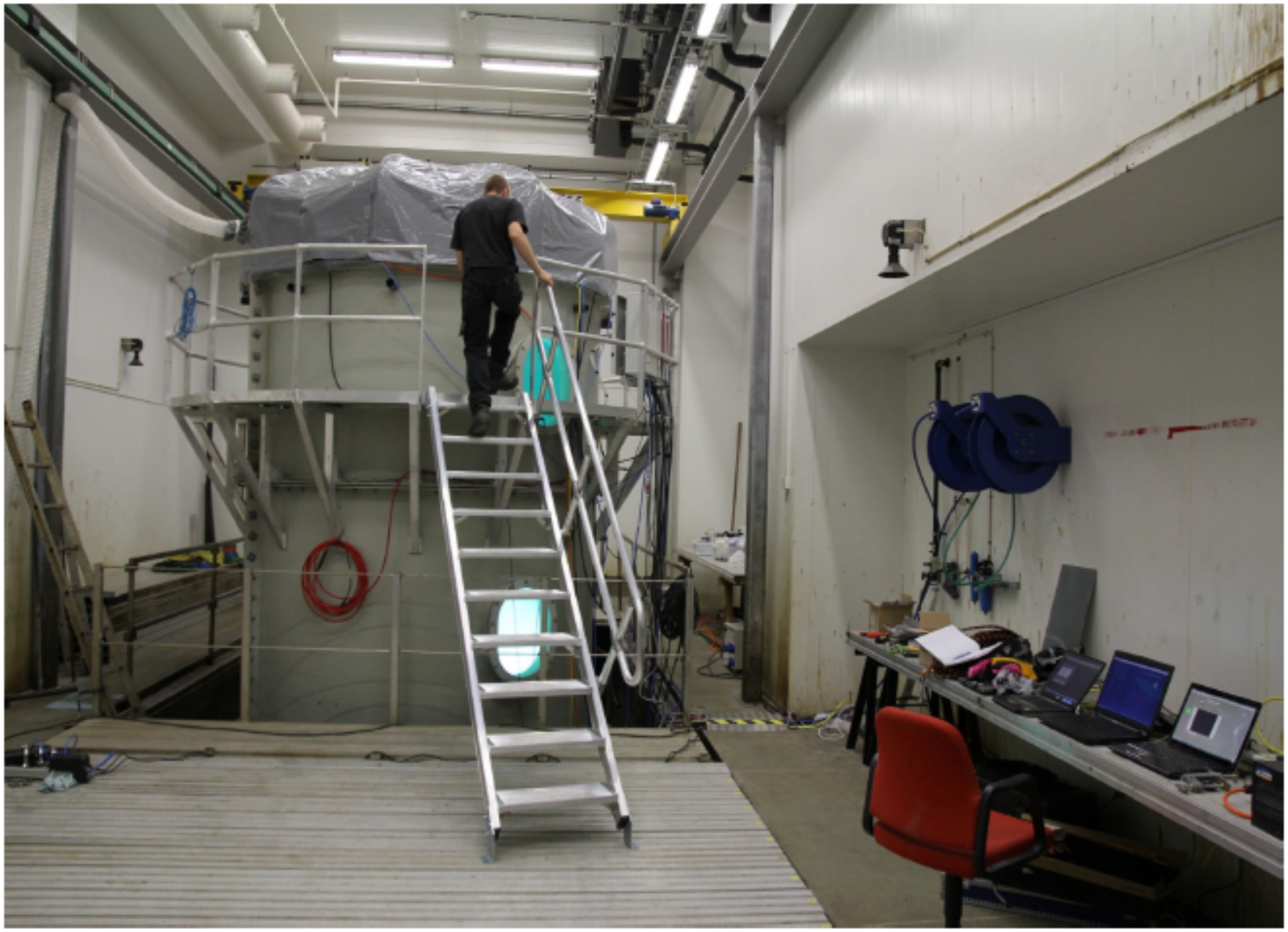
Techniques include high-speed digital holography and generation of oil droplets of same size by microfluidic devices.



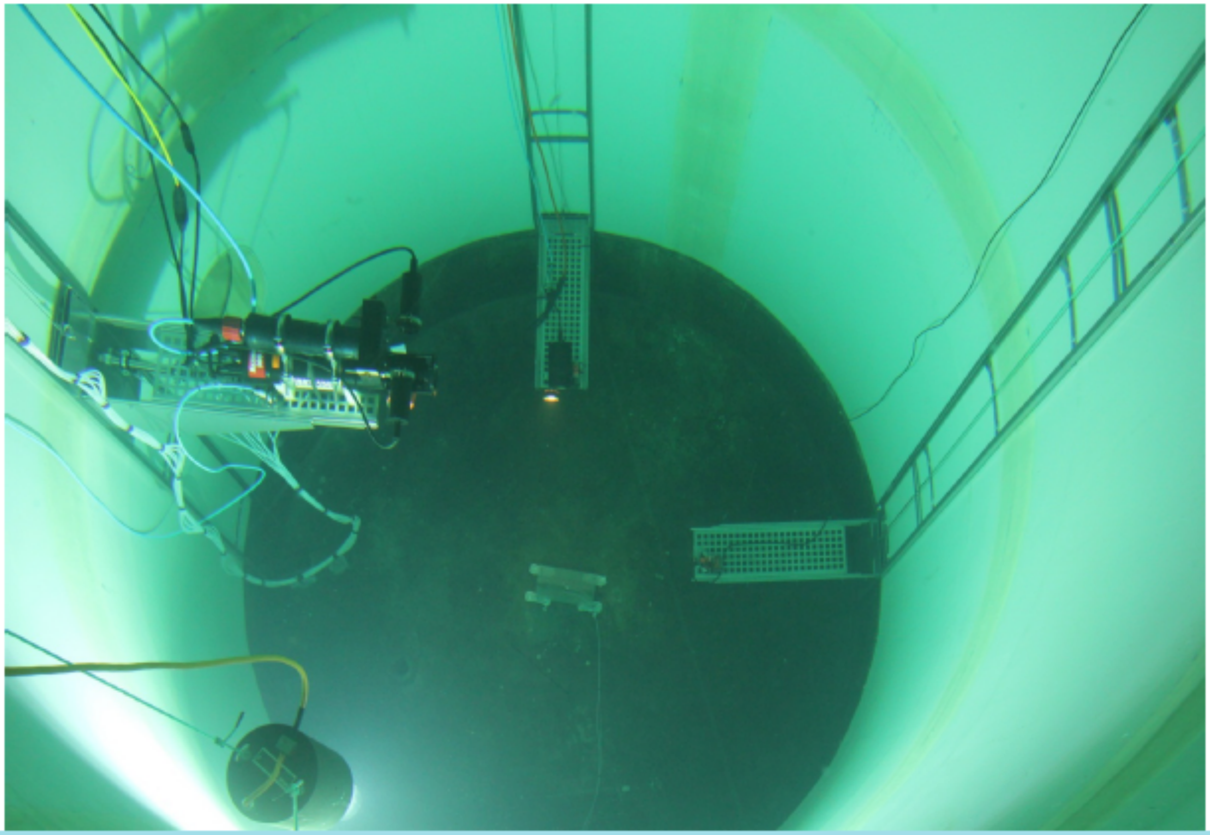
Experminental methods and goals for meso-scale underwater blowout studies - SINTEF

- Meso-Scale plume experiments will be performed using the 3 m diameter, 6 m high blowout tank
- Specific objectives include:
  - (a) Understanding the behavior of oil when released underwater and through jets with various gas to oil ratios, flow rates, oil types, and with and without dispersants,
  - (b) Measuring the droplet size distributions, and developing appropriate empirical relations for oil droplet formation and breakup based on the properties the oil and the jet.

SINTEF Tower Basin



Tower Basin - prior to initial oil release



Droplet size monitoring equipment at 3 meters depth, cameras at bottom

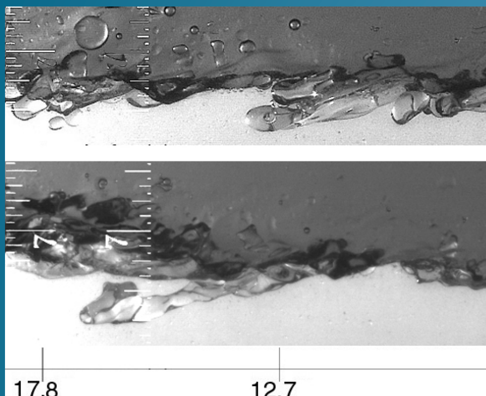
Meso-scale studies - Coastal Oil-spill Simulation System (COSS)

- Oil droplet aggregation and transport
  - Sub-surface oil-droplets
  - Surface generated oil droplets
  - Interaction with ambient particles
  - Function of velocity gradients (breaking waves)
  - In-situ droplet particle analysis

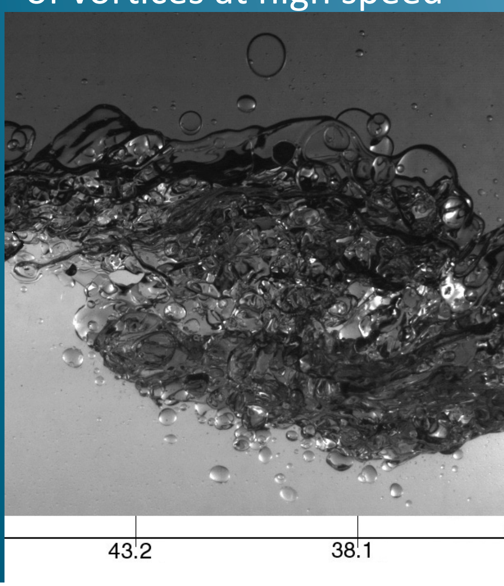
Water-Oil mixing in Stratified Shear Layers (plumes, surface layers)

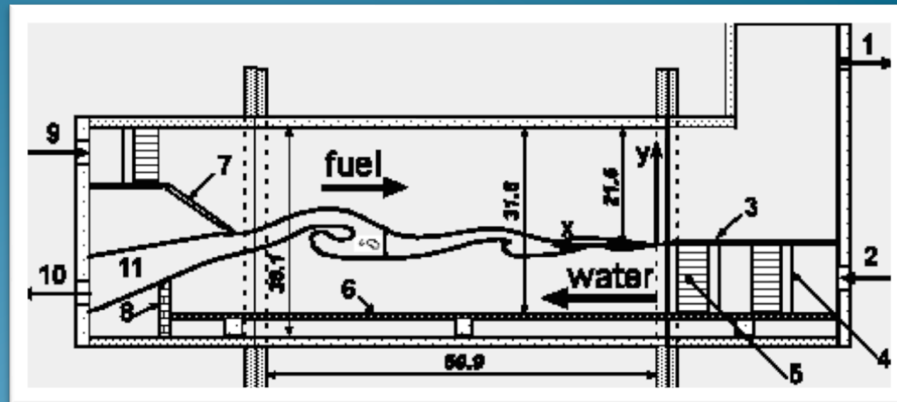
Katz – John Hopkins

Droplet formed by fingering at low speed

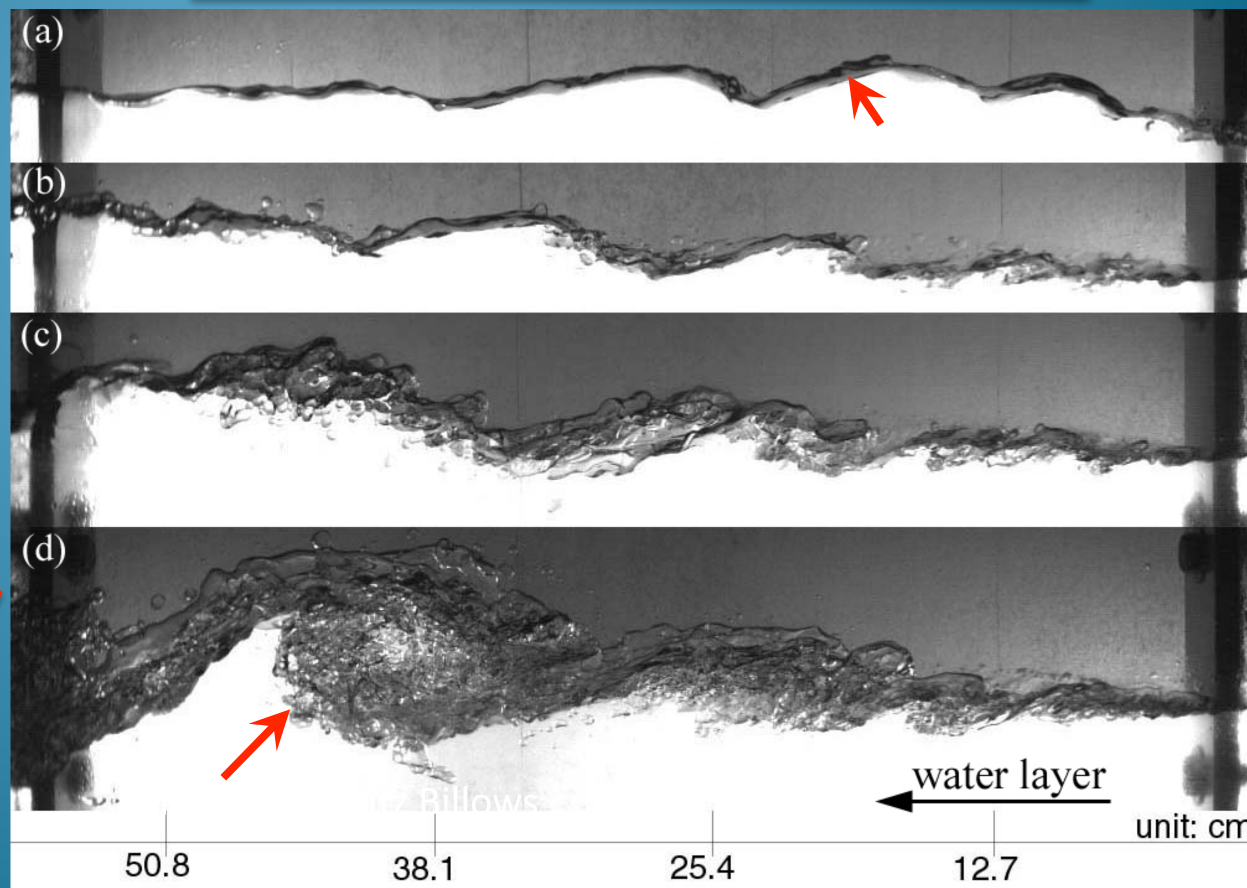


Droplet formation by rollup of vortices at high speed



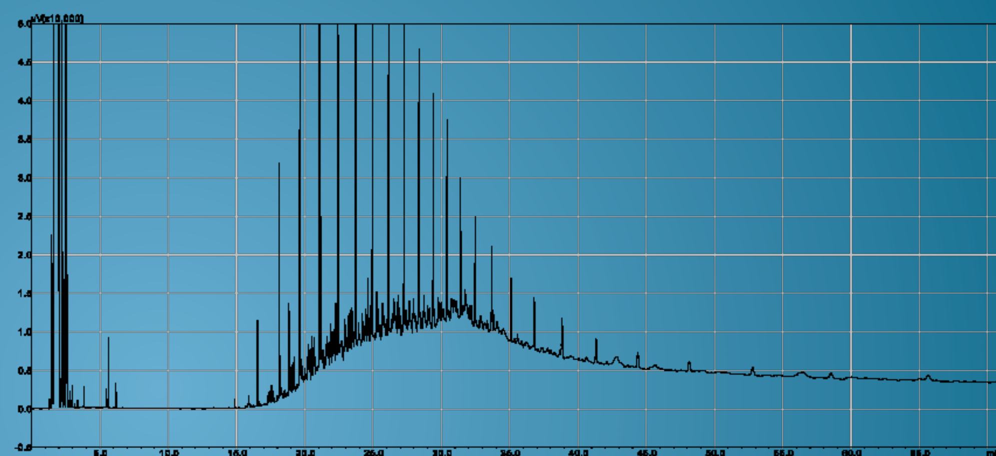


Increasing velocity



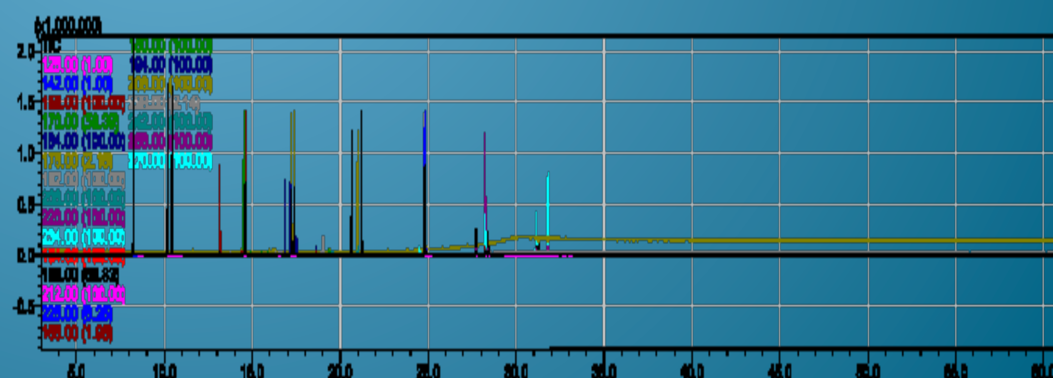
Deciphering chemical composition of oil droplets during the physical, chemical, and biological processes – Liu

- Analyzing oil components is essential to deciphering the processes that control the fates of oil in marine environments.
- We will focus on *n*-alkanes (from C_8-C_{40}), pristane, phytane, 16 EPA priority PAHs, and 18 alkylated PAHs, over 50 compounds altogether.
- The instruments will include GC-FID, GC-MS, and HPLC-fluorescence detection.



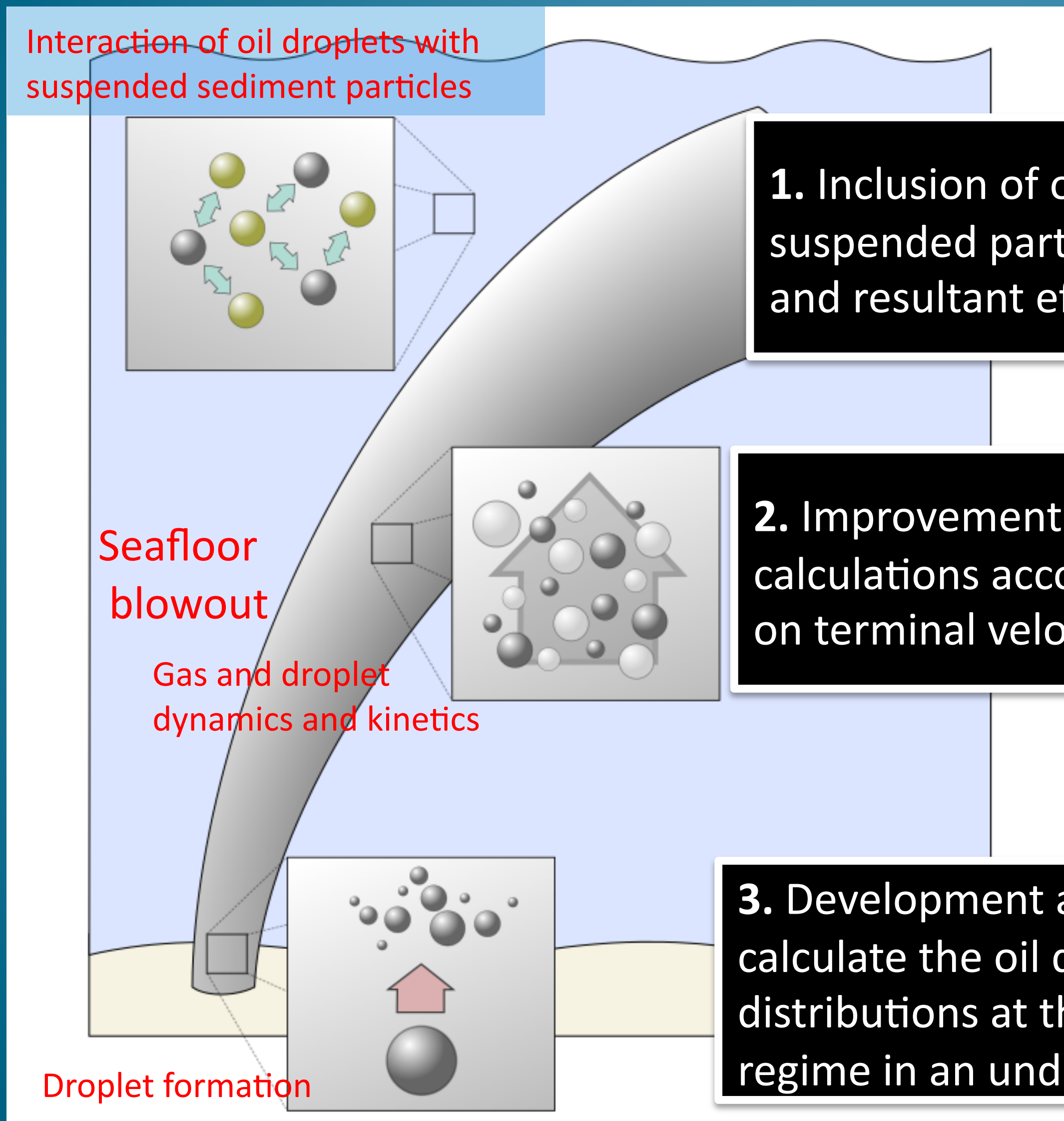
GC-FID spectrum of oil mousse collected from northern GOM, May 2010

Shimadzu GC-MS (QP2010 plus) in Liu Lab



GC-MS spectrum of a PAH standard mix using SIM mode

SINTEF: Incorporation of Experimental and Numerical Results into the Meso-Scale Simulation Software

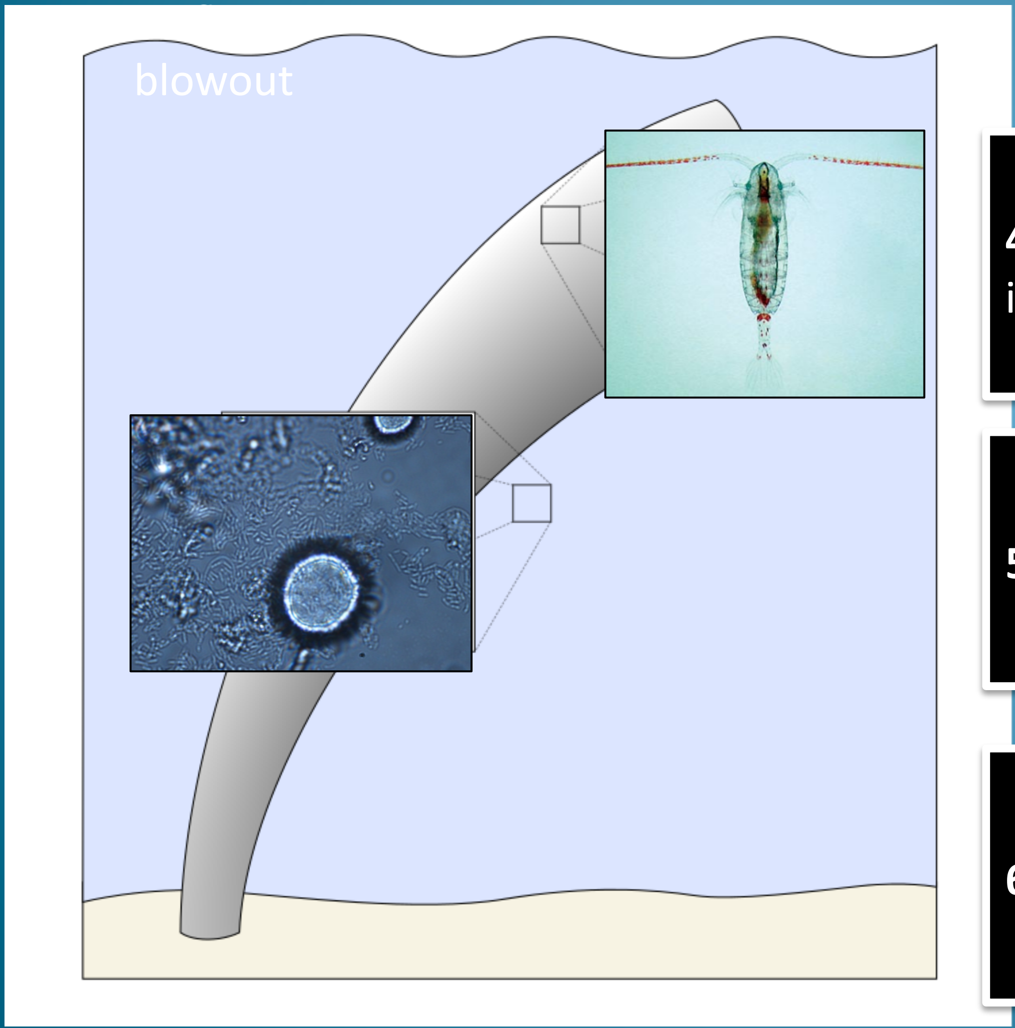


1. Inclusion of oil droplet interactions with suspended particulate matter in the water column, and resultant effects on rising/settling velocities

2. Improvement of droplet and bubble rise rate calculations accounting for the effect of turbulence on terminal velocities

3. Development and testing of algorithm to calculate the oil droplet and gas bubble size distributions at the end of the turbulent breakup regime in an underwater blowout plume

SINTEF: Incorporation of Experimental and Numerical Results into the Meso-Scale Simulation Software



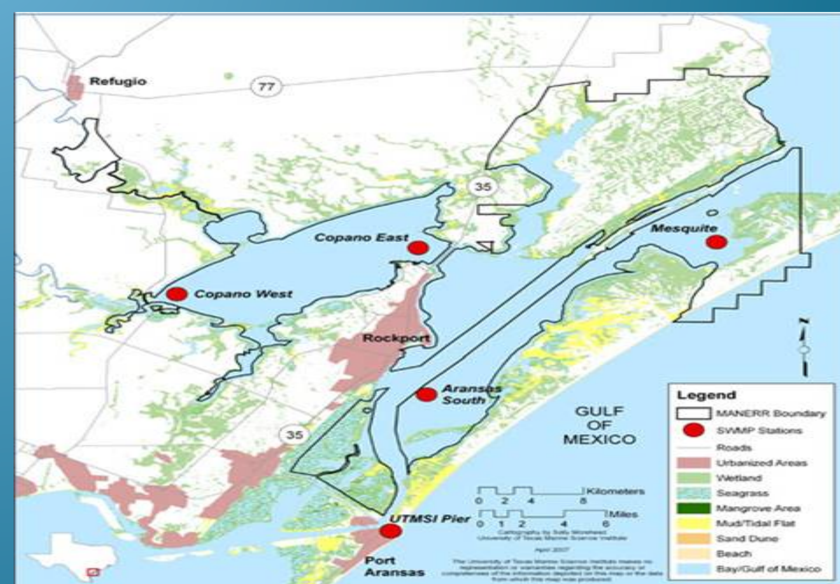
4. Effects of zooplankton-oil droplet interactions on oil fates

5. Bacterial biodegradation rates

6. Model validation and testing

Estuarine Research Center

- Consortium activities housed at new headquarters building for Mission-Aransas NERR opened in July 2011
- Laboratory, meeting facilities, student housing
- One of 28 reserves in US – 3rd largest
- Funded by NOAA and UT
- Research, Education, Stewardship, Coastal Training Program – existing infrastructure for outreach and meetings



Questions?