SSGF Program Review 2021

A Big Slice o' Pizza: Supernova Mixing in a Lab

Benjamin Musci

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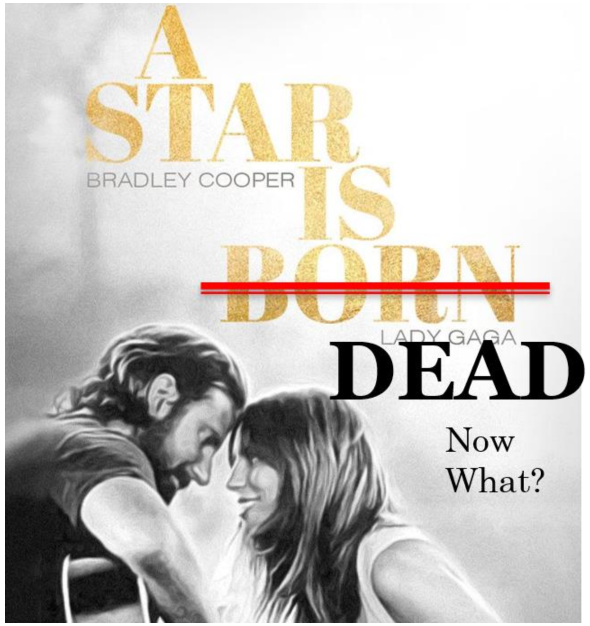
STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP

Georgia Tech

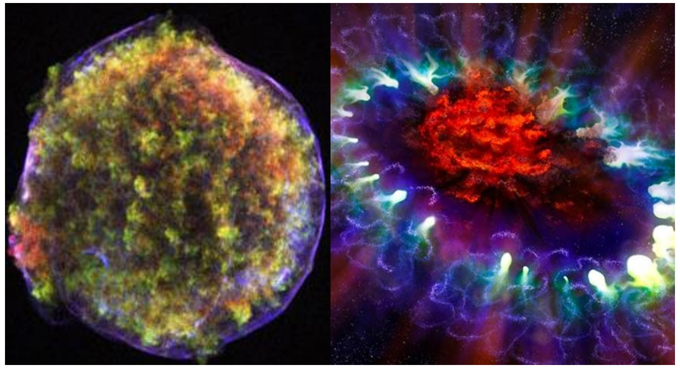
STAM Lab

Shock Tube and Advanced Mixing Laboratory

What happens when a Star dies?



Observation



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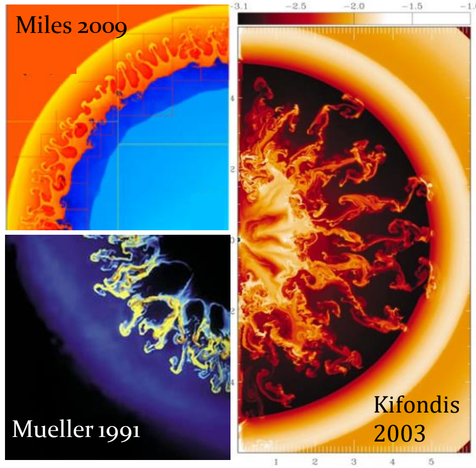
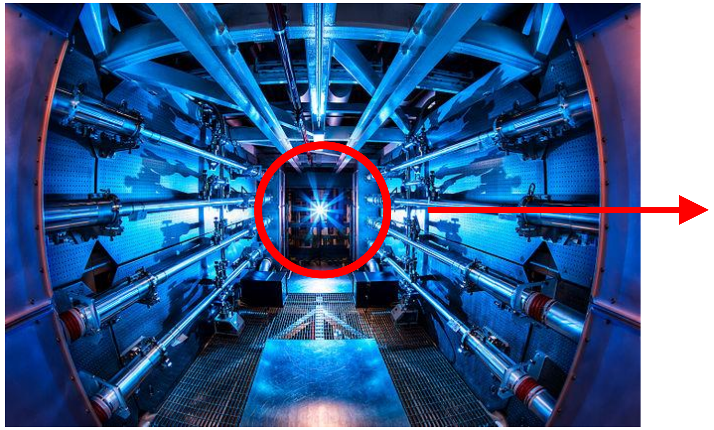
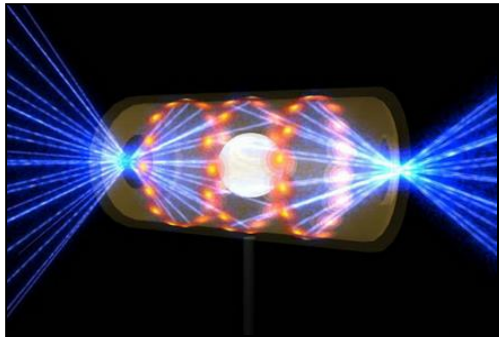
Simulation



- Simulations don't' replicate Supernova observations
  - The occurrence of heavy elements ejecta occur much earlier than predicted

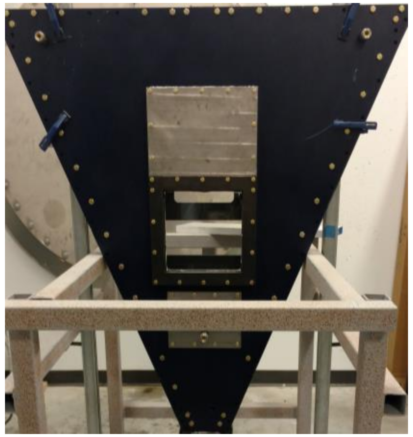
- Also…. huge Clean Energy potential
  - Inertial Confinement Fusion
  - Mixing caused by compression degrades nuclear yield



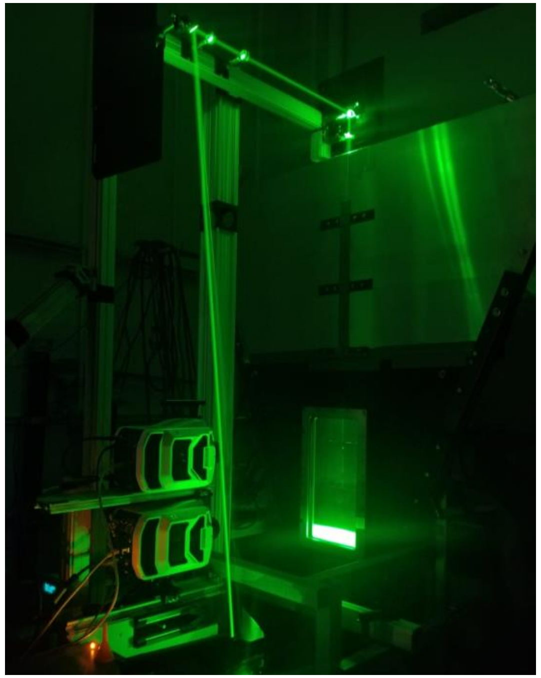


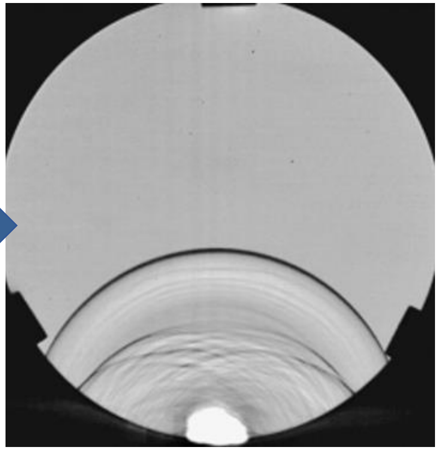
Supernova, but make it Lab

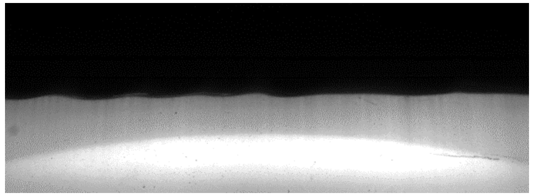
- How? --Similar physics, different scales-- E.g

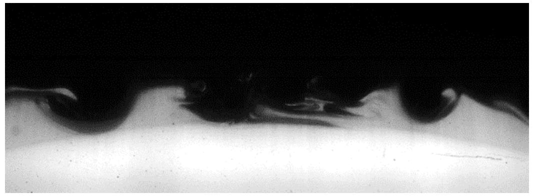


- Experimental facility (pizza) that uses explosives, lasers and gases to generate Supernova physics







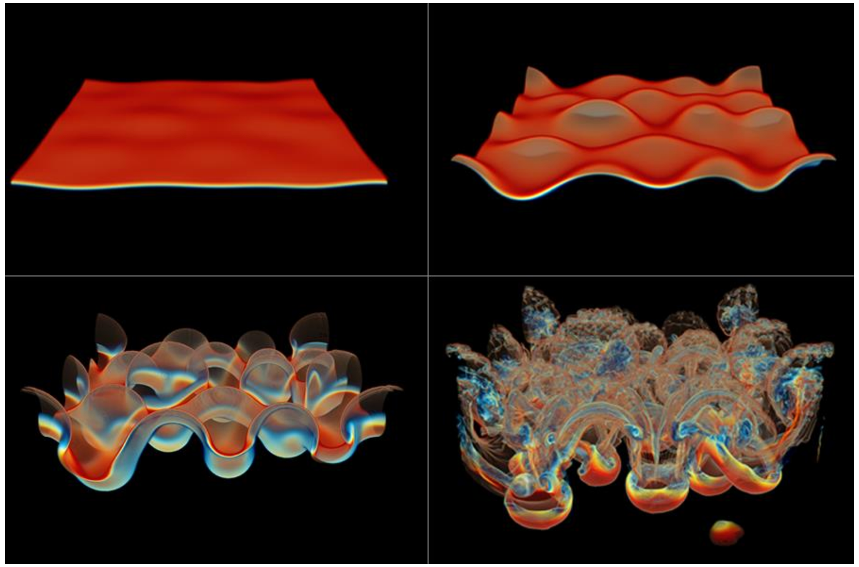


The Physics : Mixing due to The Blast-Driven Instability

A Blast Wave Source

+

Two fluids separated by an interface



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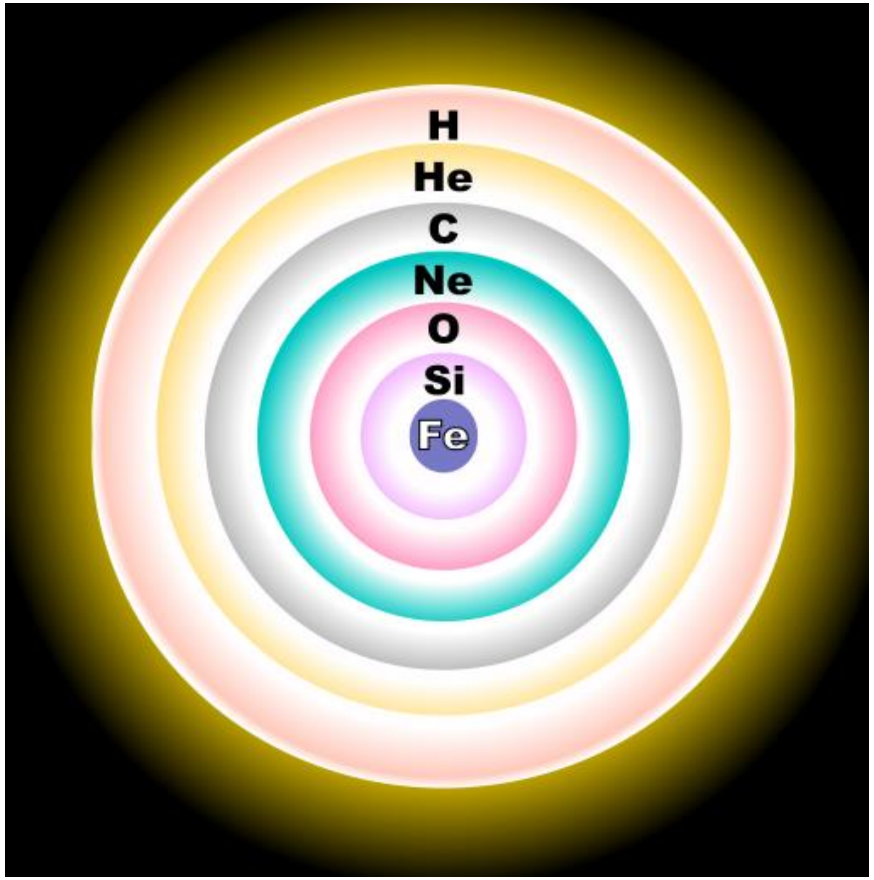

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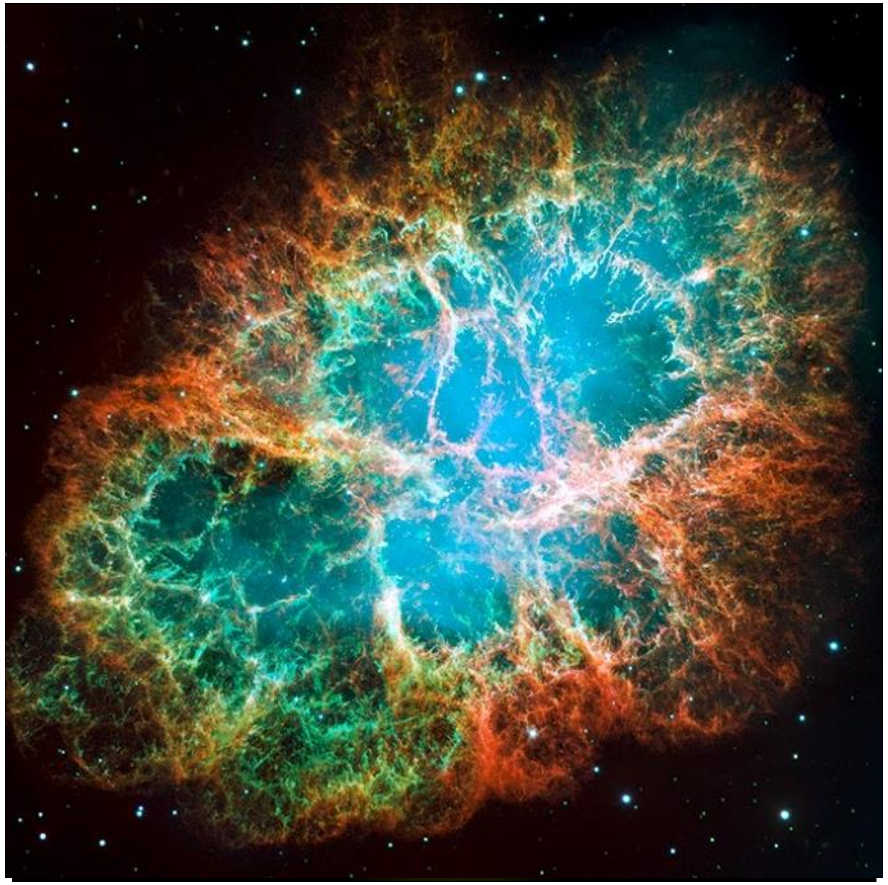

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Blast-Driven Instability

The BDI combines two classic instabilities

- Both the RTI and RMI Instabilities develop at interface
- Initial perturbations on the interface grow due to vorticity deposition

Vorticity Transport Equation

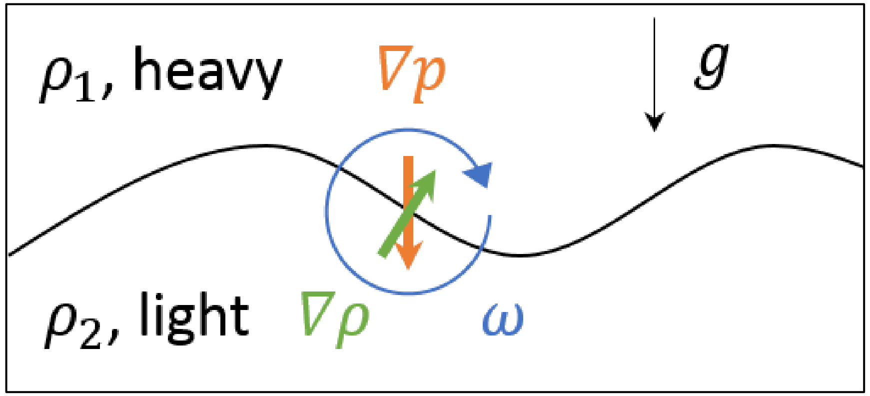
$$\frac{D\omega}{Dt} = (\omega \cdot \nabla)v - \omega(\nabla \cdot v) + \nu\nabla^2\omega + \frac{1}{\rho^2}(\nabla\rho \times \nabla p)$$

Atwood Number

$$\mathcal{A} = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$$

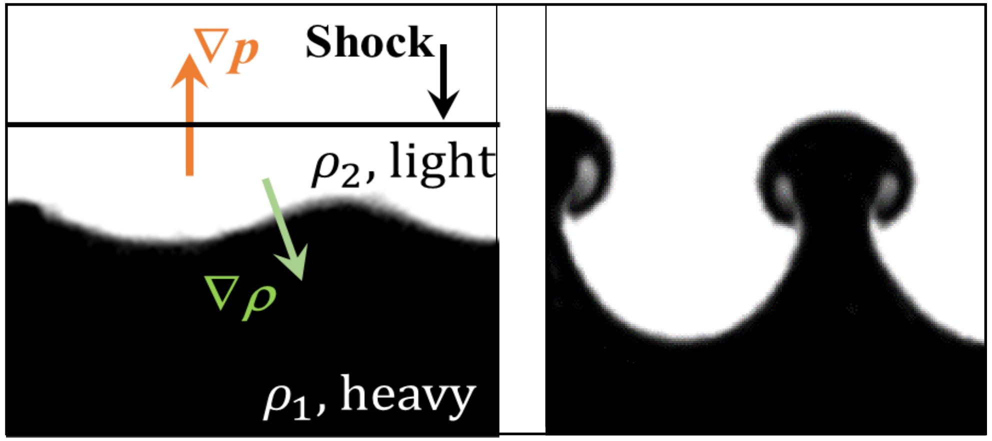
Rayleigh-Taylor Instability (RTI)

Criteria: $\nabla\rho \cdot \nabla p < 0$



Richtmyer-Meshkov Instability (RMI)

Criteria: $\nabla\rho \cdot \nabla p \neq 0$



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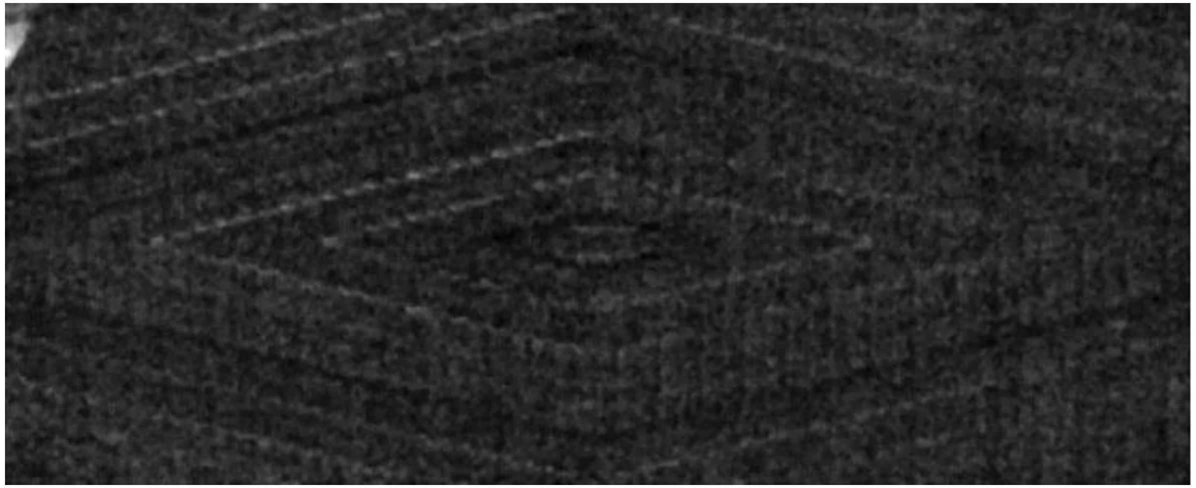

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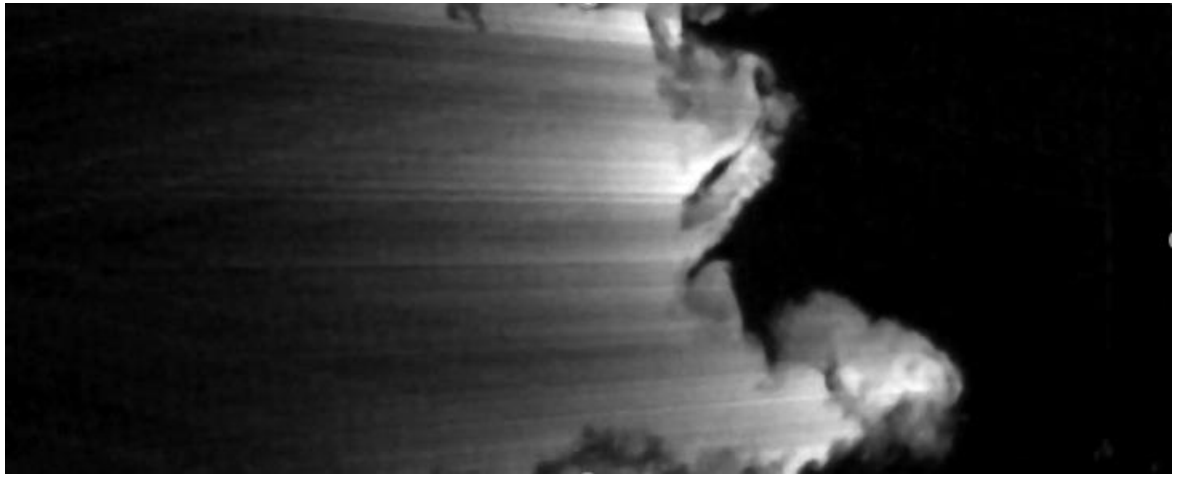
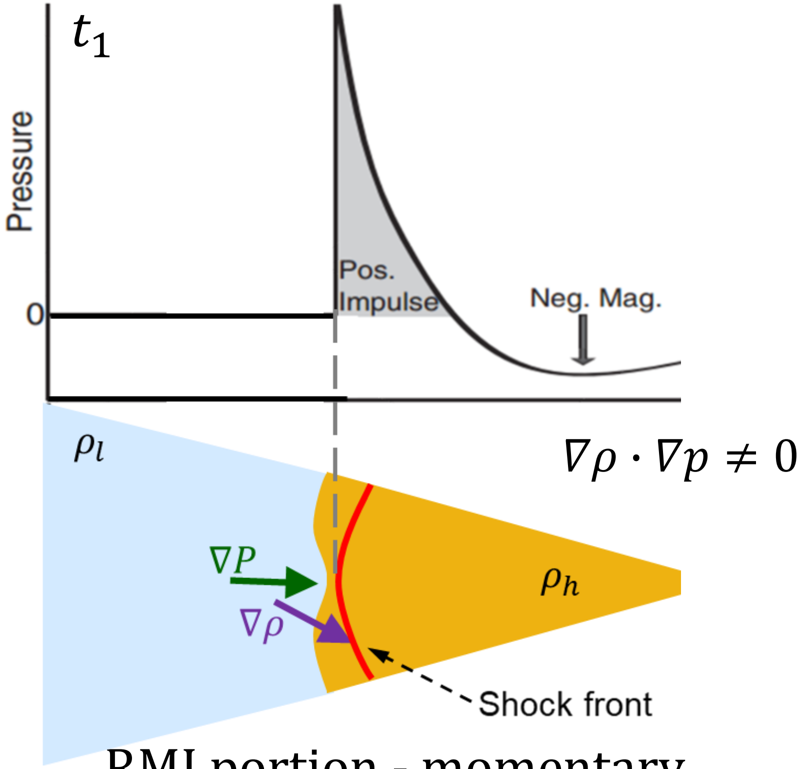


What is a "Blast Wave"

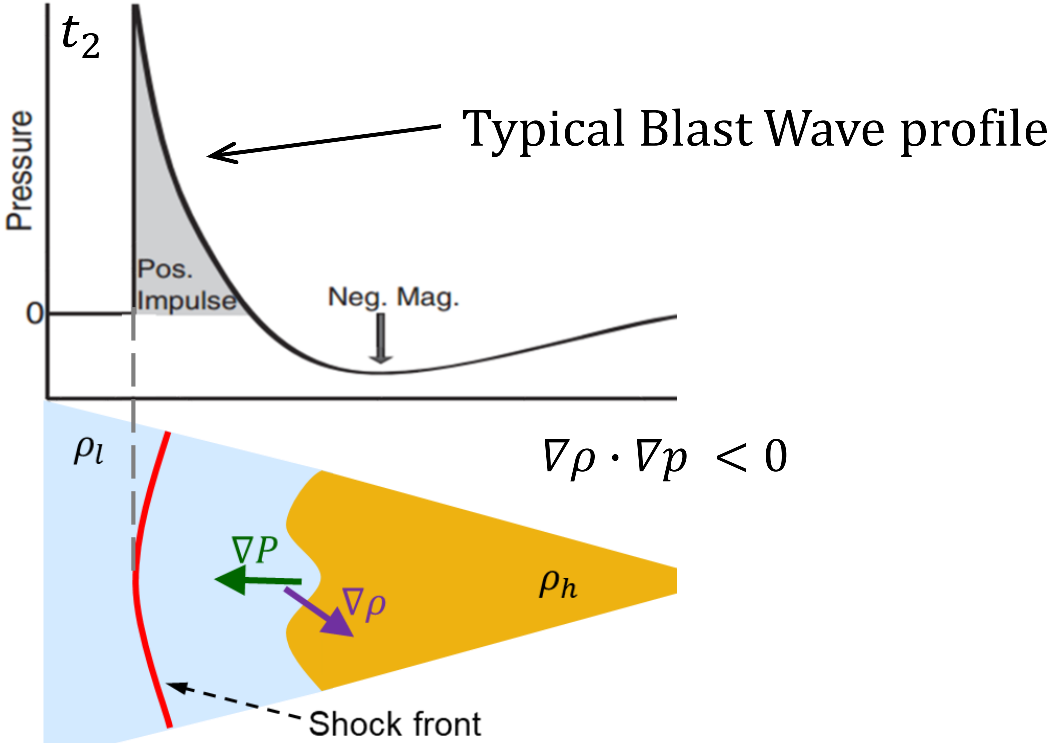
- Sudden deposition of energy in negligible time and space compared to scales of interest
- Shock front followed immediately by a rarefaction – causes RMI and RTI combo

$t_2 > t_1$

$\rho_h > \rho_l$



RMI portion - momentary



RTI portion – sustained

How we study BDI

Experiments

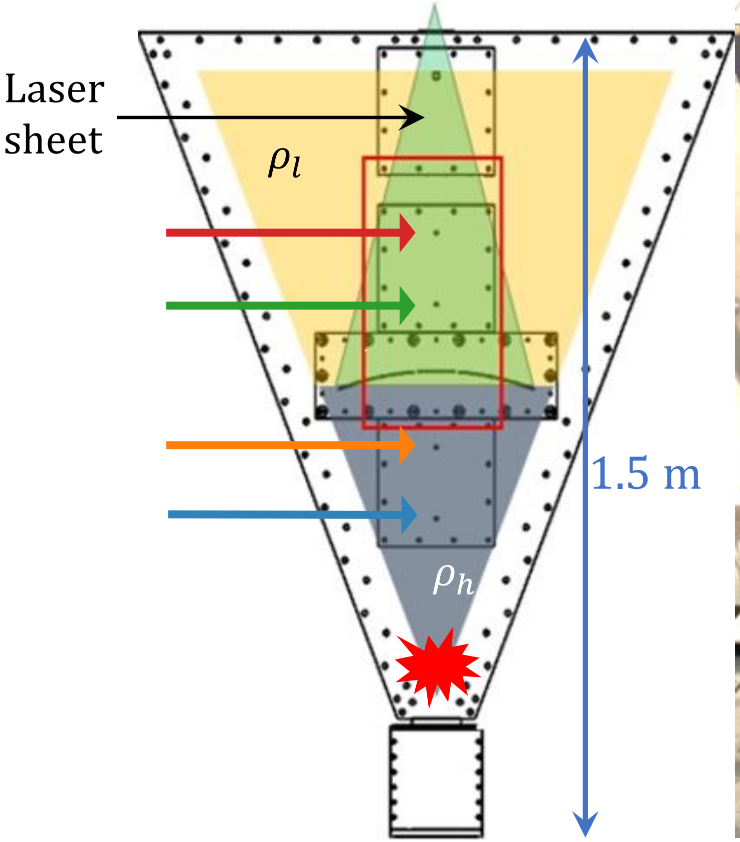
- Design and build facility
- High Speed diagnostics
- Extract mix data from images

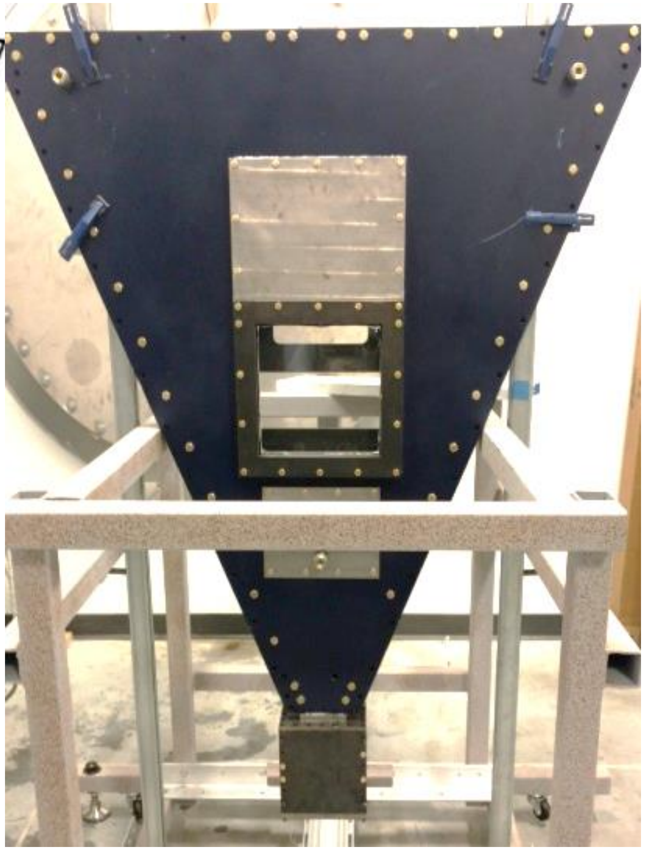
Simulation

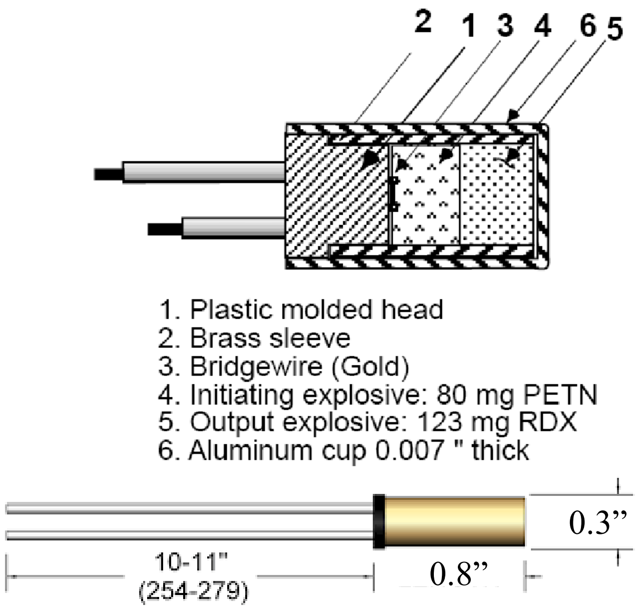
- Create digital twin of experiment
- Implement different models
- Validate simulations
  - Multi-stage validation

Experimental Facility/Pizza

- Uses commercial detonators (RP80 & RP81) to generate Blast Wave







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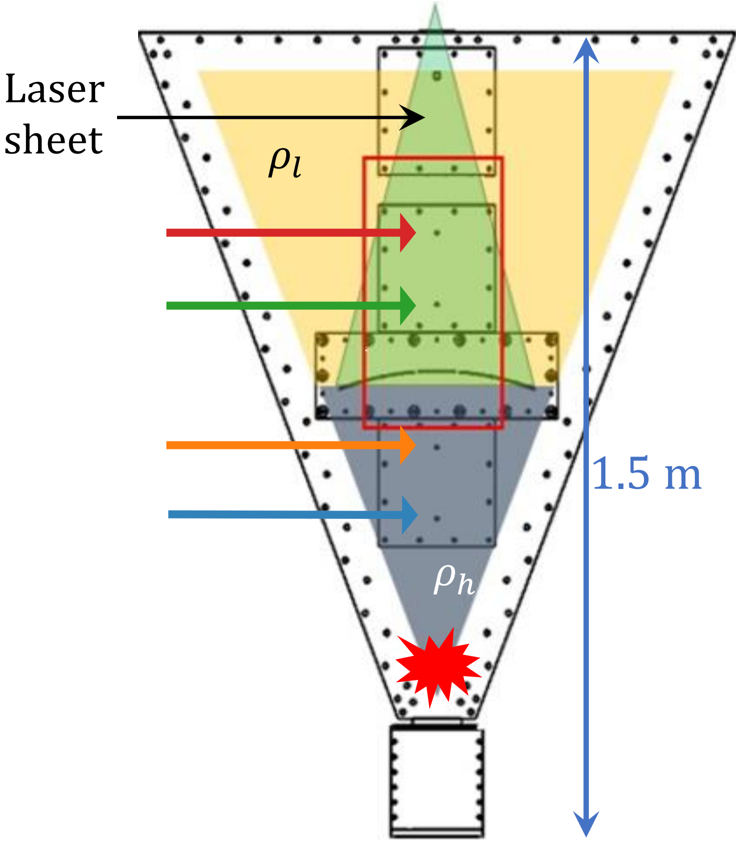
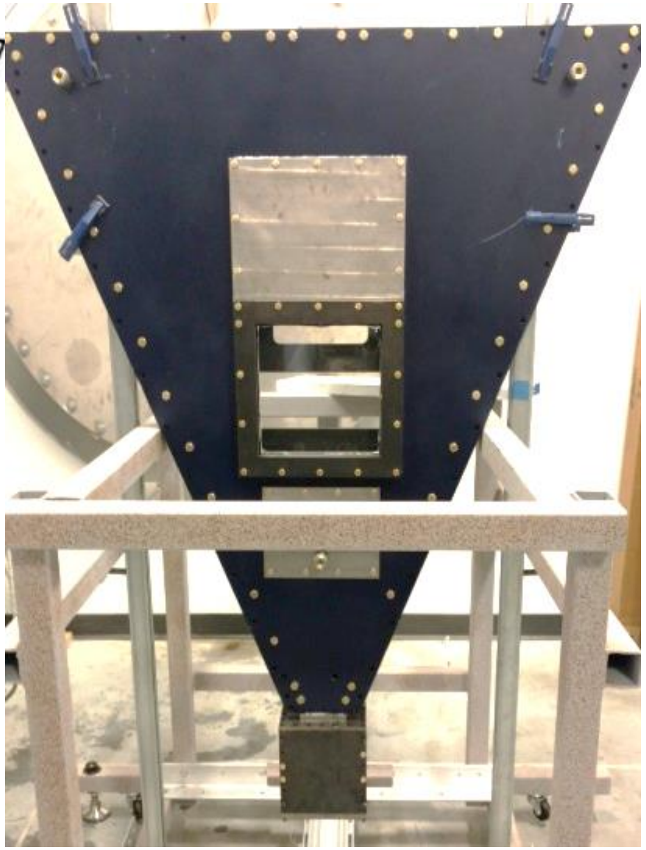
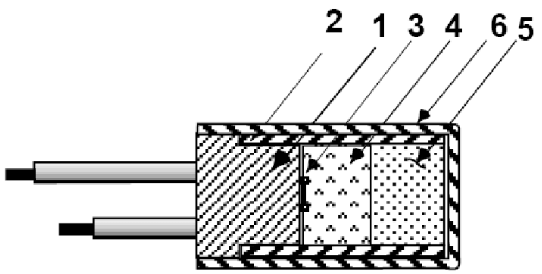
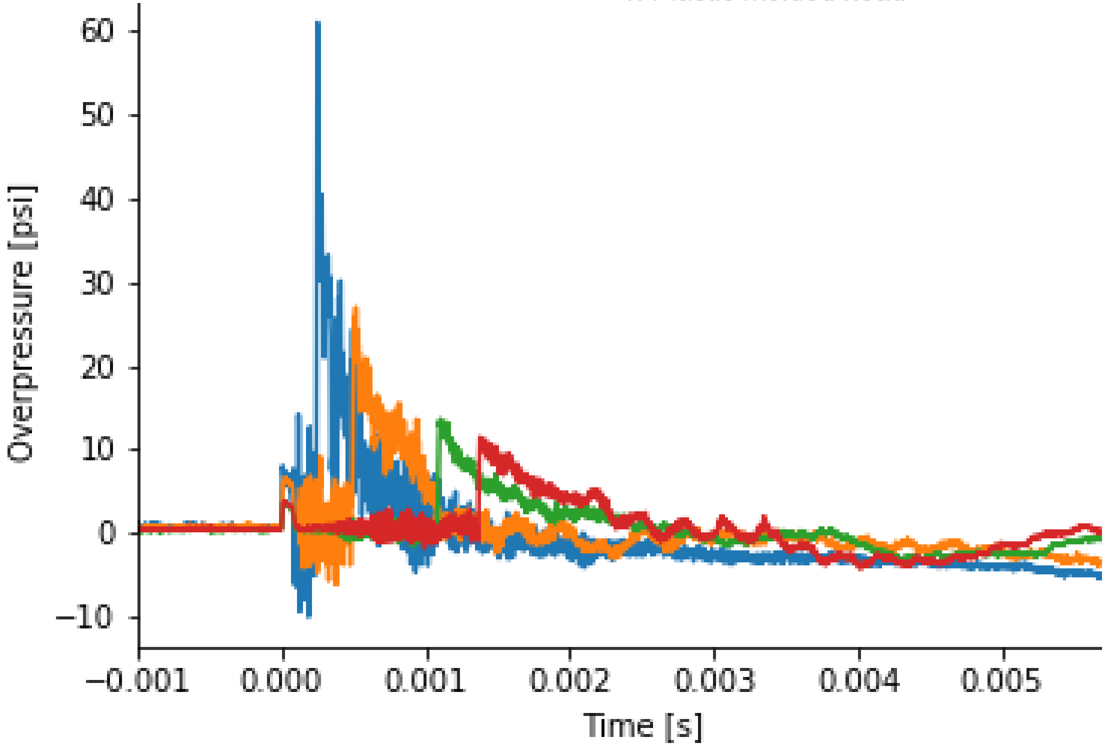




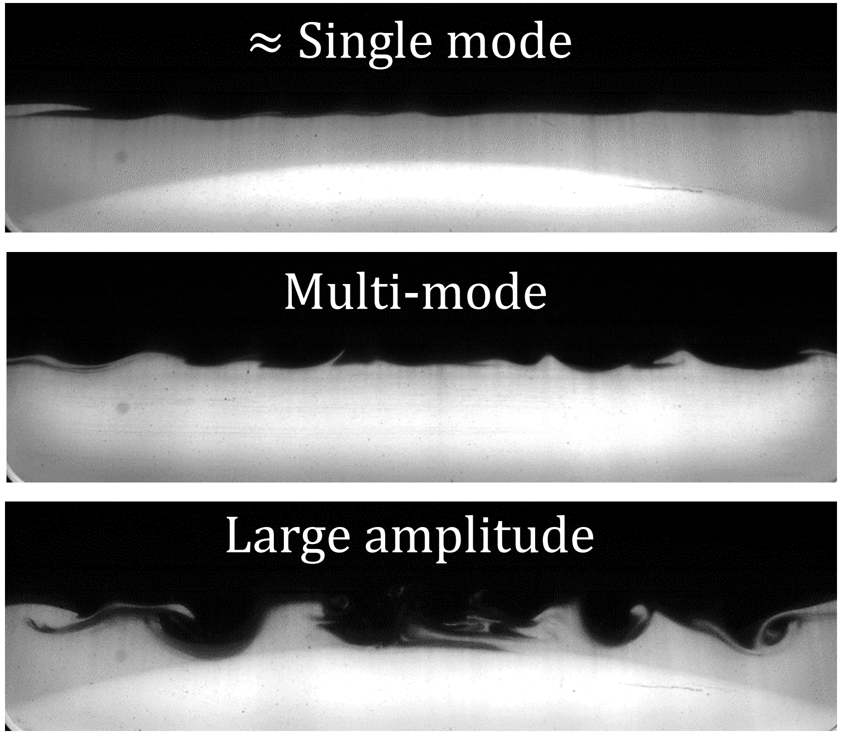


1. Plastic molded head



Interface Creation

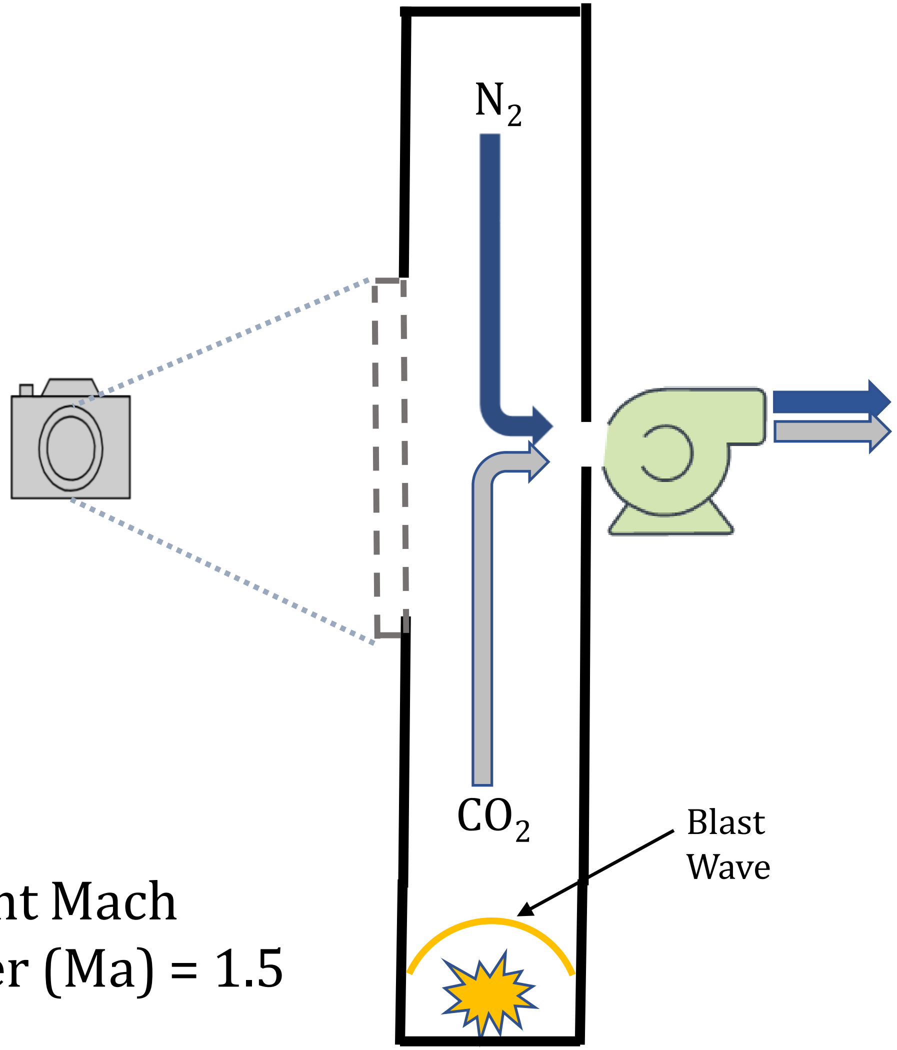
- Light gas (N_2 $- black$) enters from bottom
- Heavy gas (CO_2 $- white$) enters from top
- Fan exhausts gas in middle and perturbs interface
- Diagnostic used: **Mie Scattering**



$$k = \frac{2\pi}{wavelength}$$

$$a_o = \frac{1}{2} Peak\ to\ valley$$

SIDE VIEW



Incident Mach number (Ma) = 1.5

Experimental Parameter Sweep

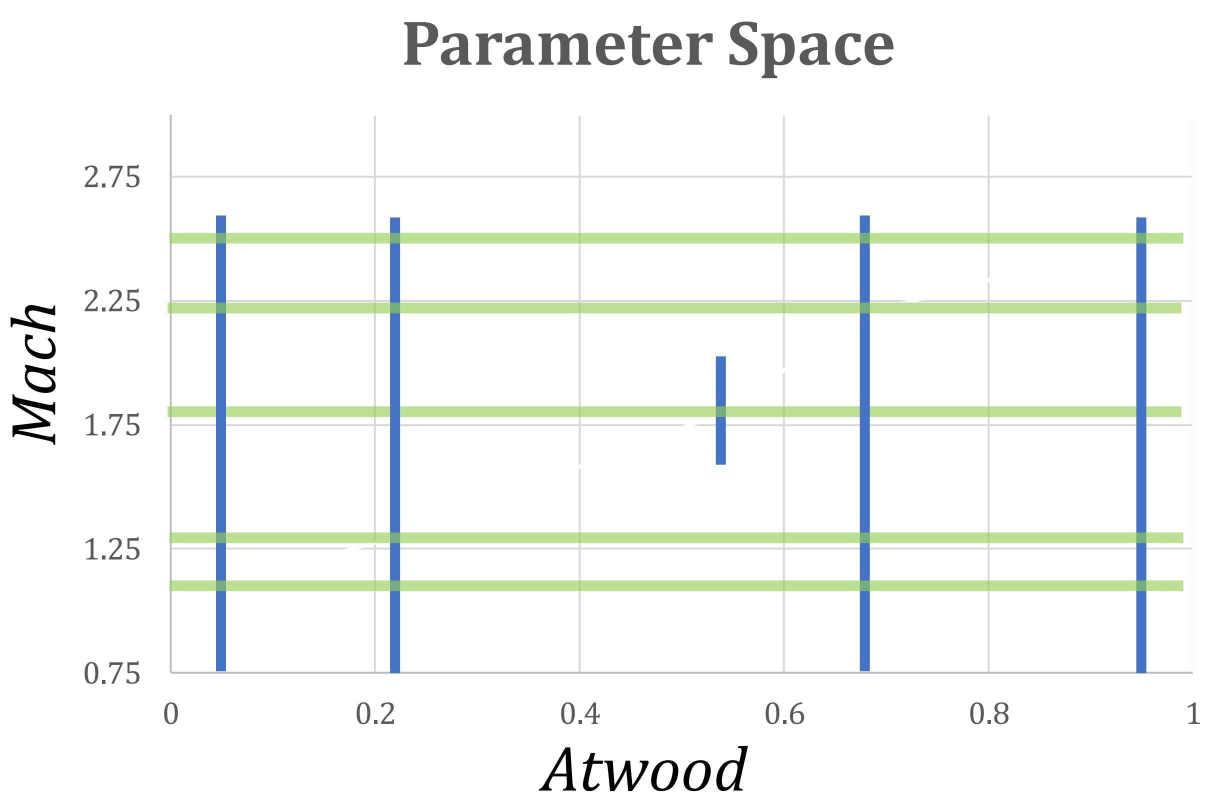
- Explore instability behavior by varying two governing parameters:
  - Detonator strength (incident Mach number)
  - Atwood number (density difference)

Atwood Number

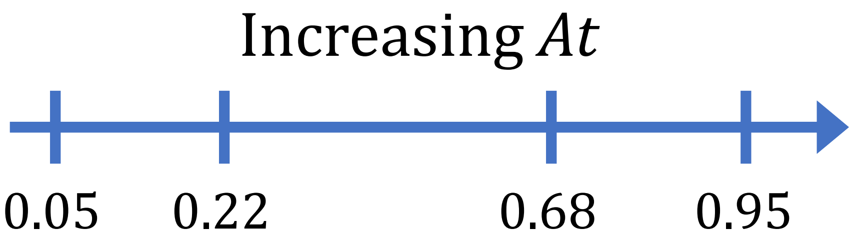
$$\mathcal{A} = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$$

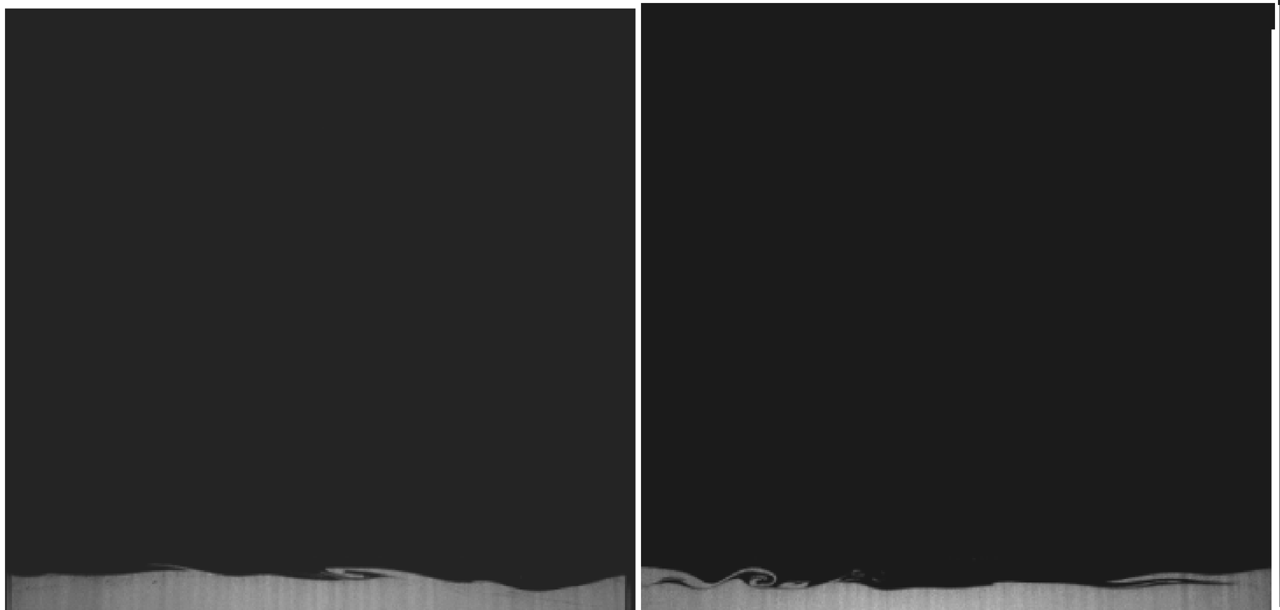
Mach Number

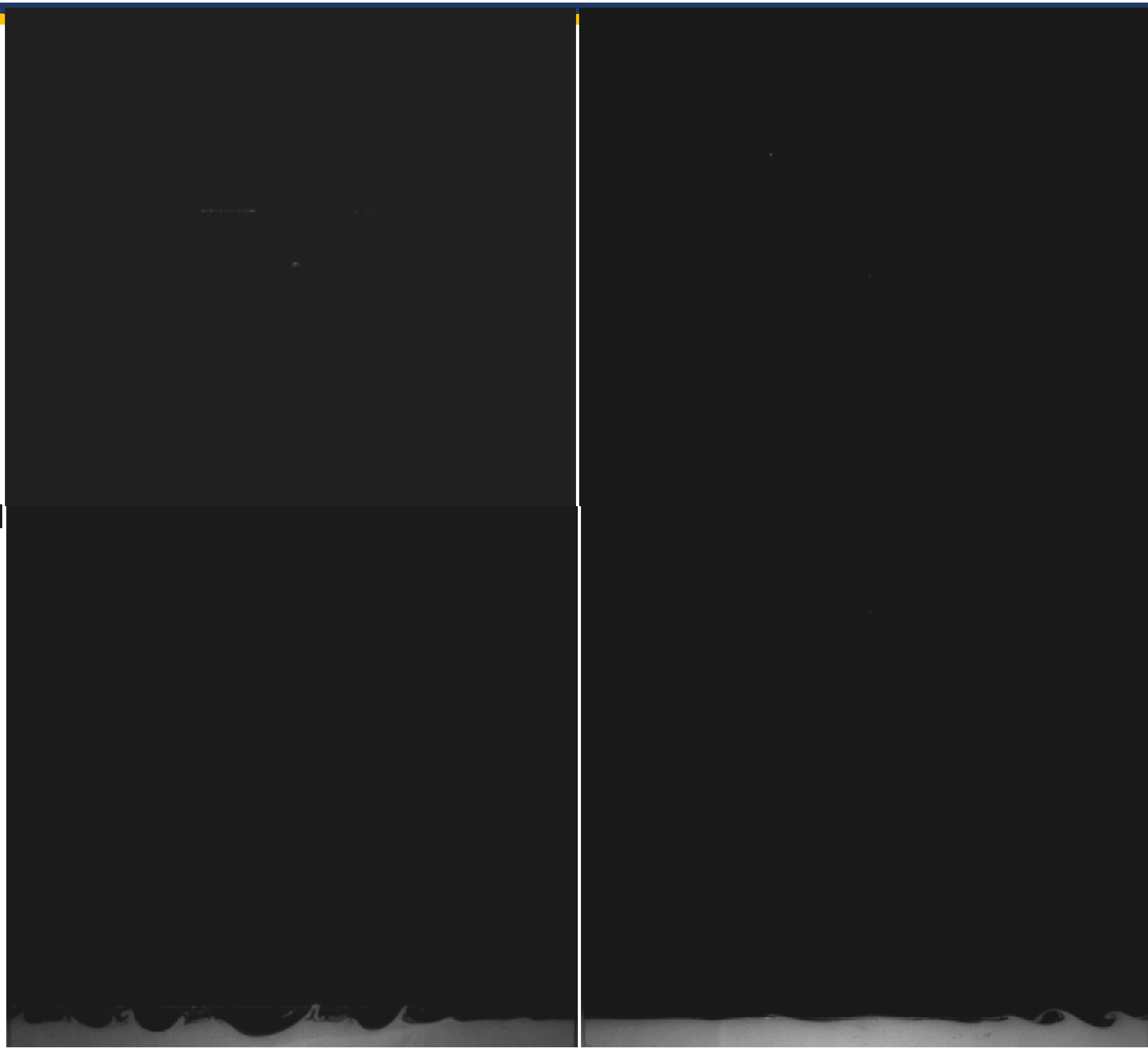
$$Ma = \frac{u_{blast}}{sound\ speed}$$



Mach = 1.8 / *At* = varying







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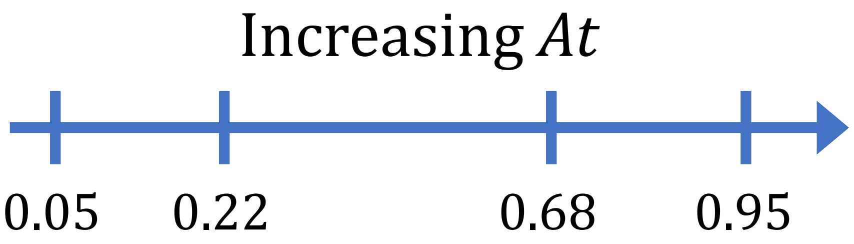
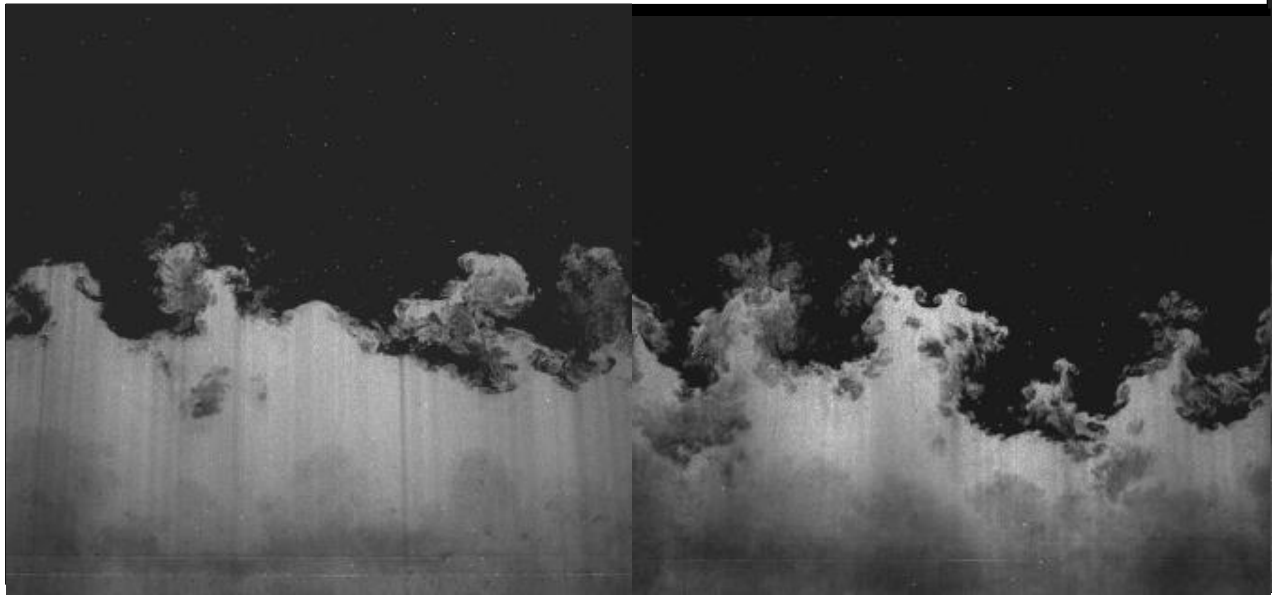
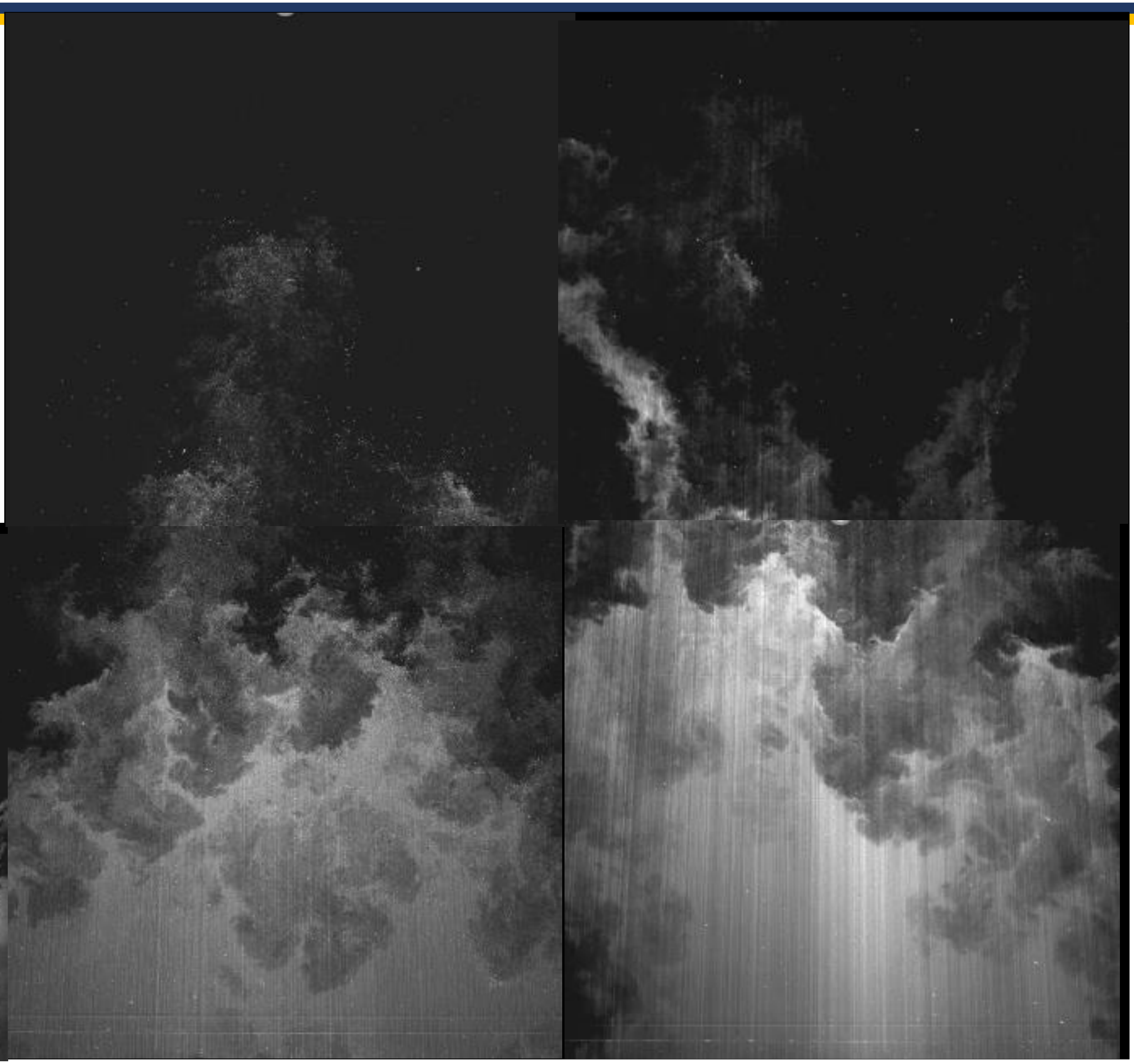
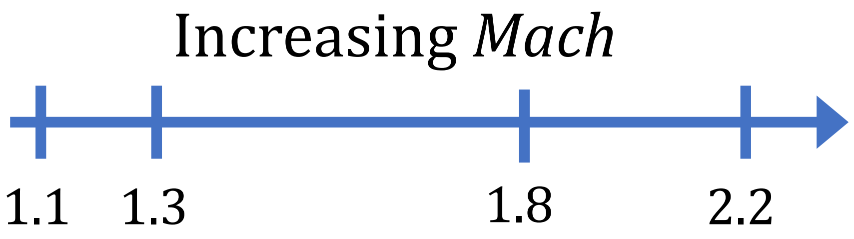
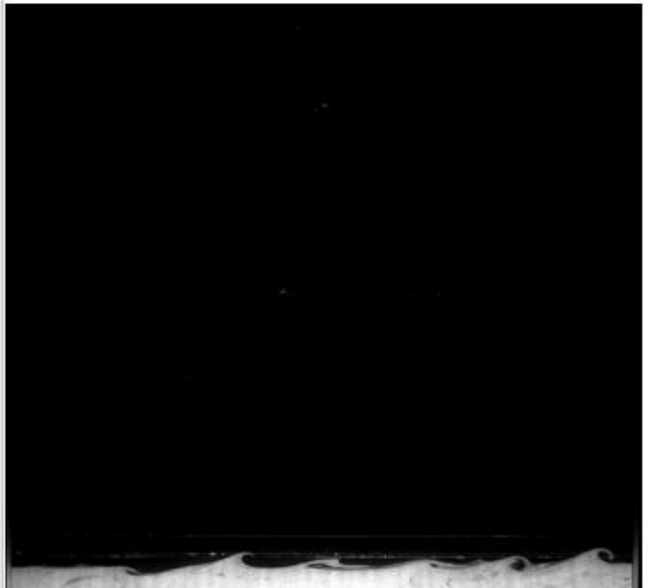


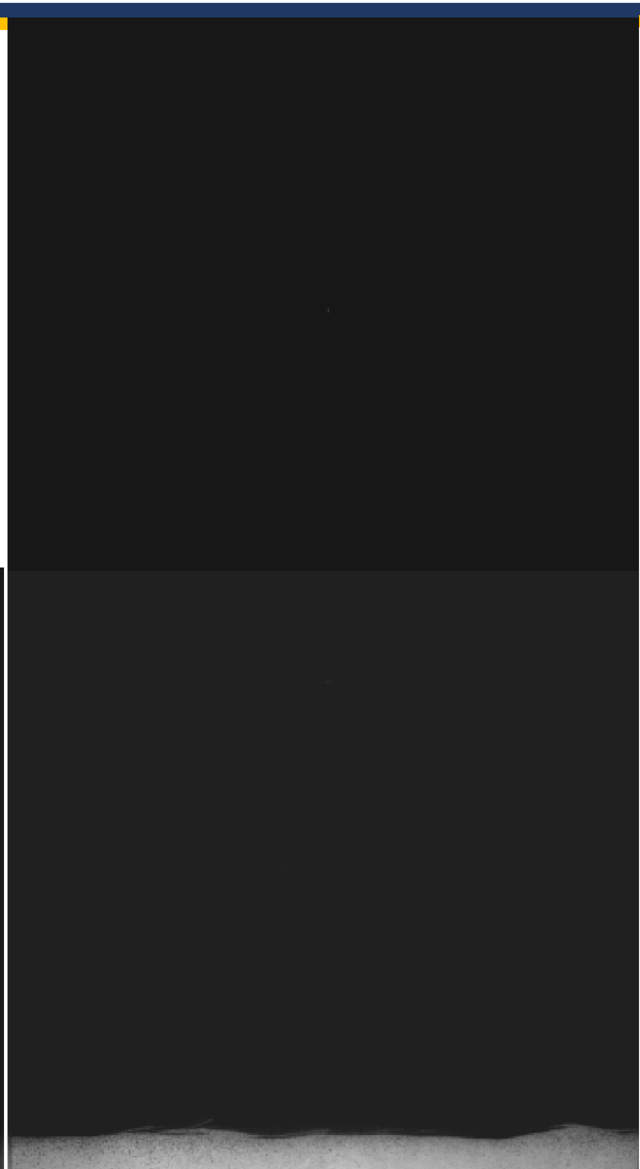




At = 0.95 / *Mach* = varying







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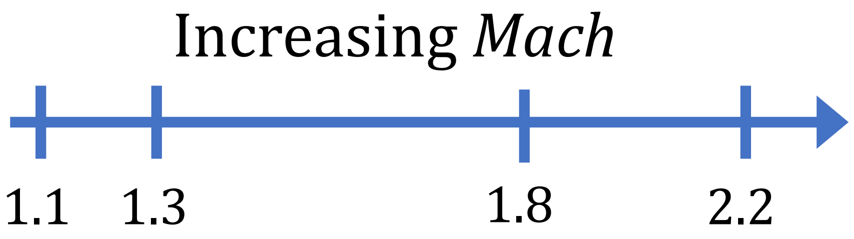
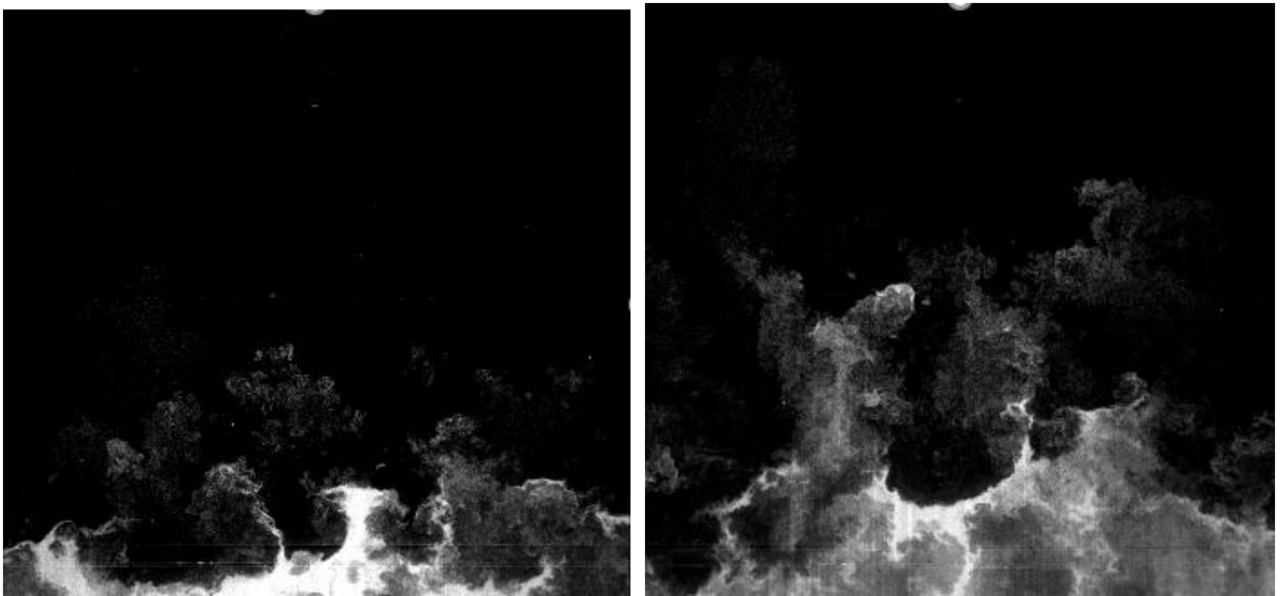
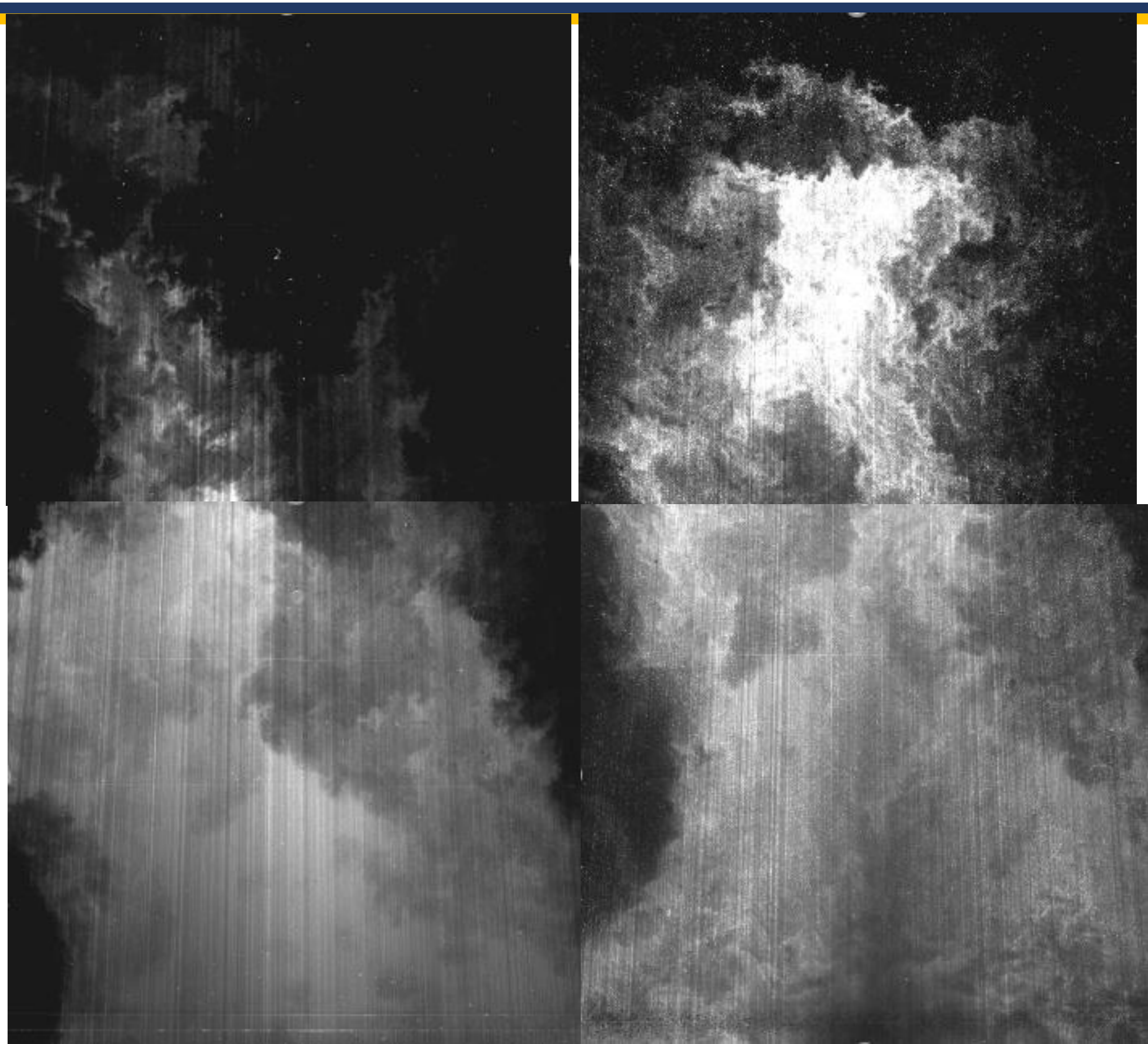
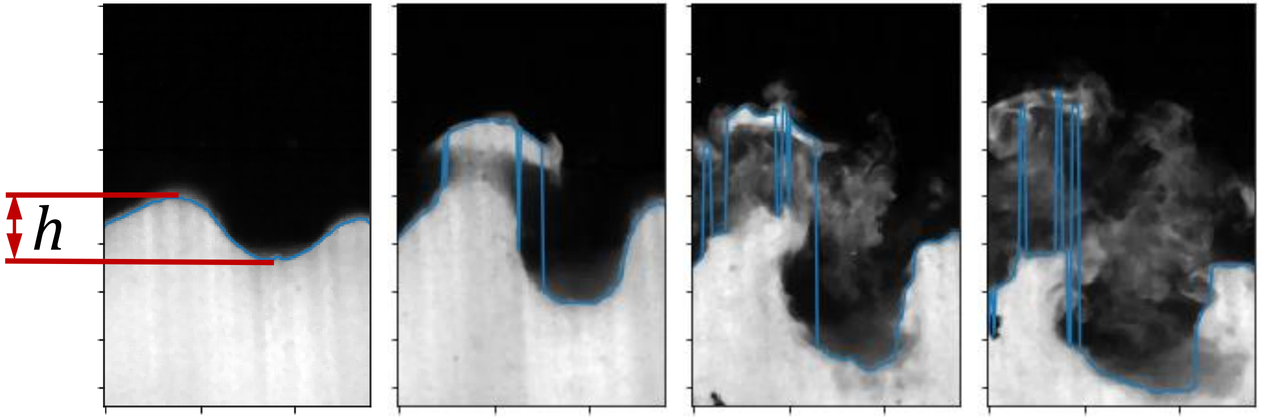




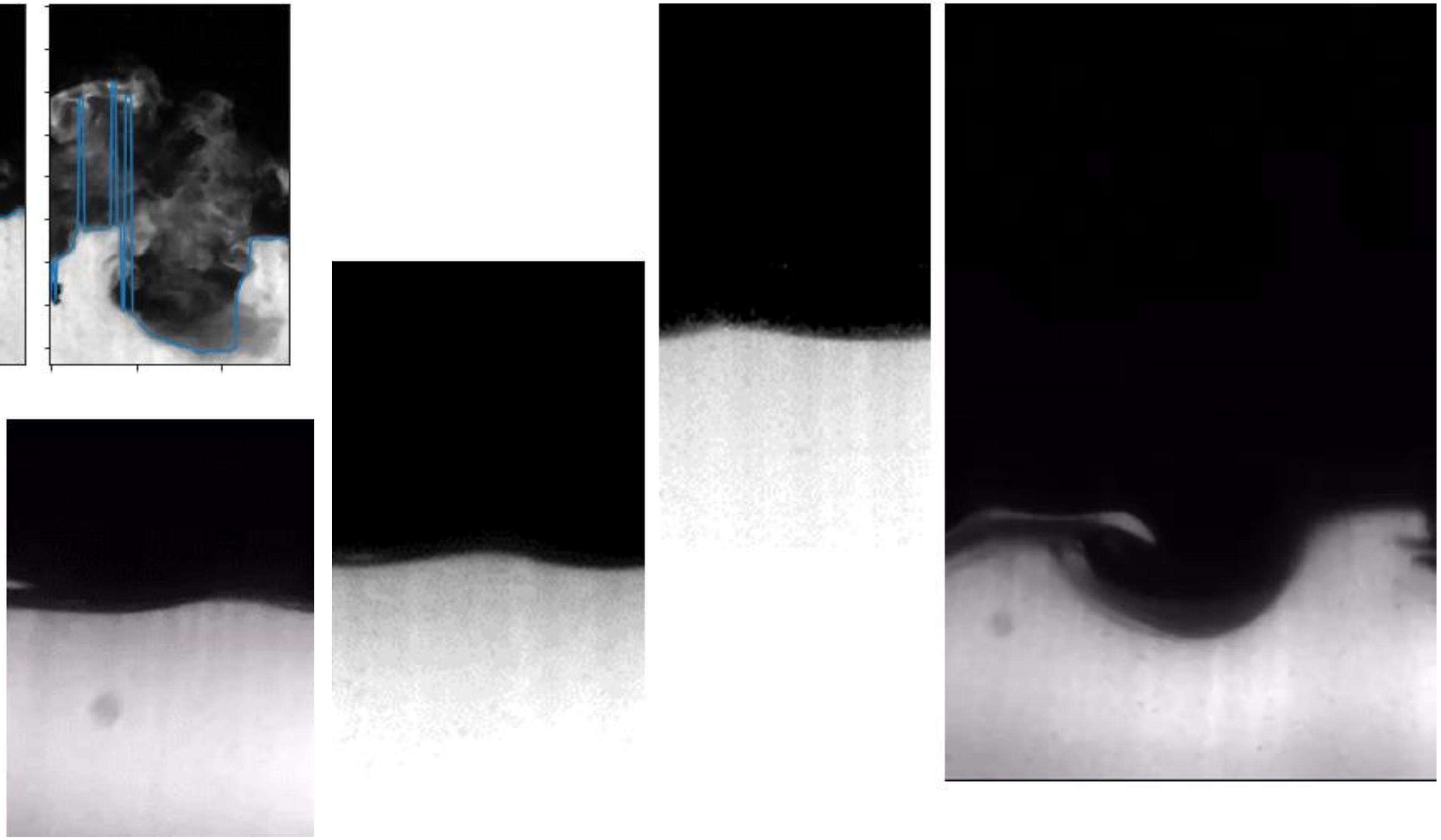


Individual Bubble Analysis – Processing

- Select several bubbles from each run → Track bubble with cross correlation → Detect maximum intensity gradient to trace interface shape → Extract mixed width data:



- Development tracked from IC to late time
- Allows for better characterization of a_o and λ



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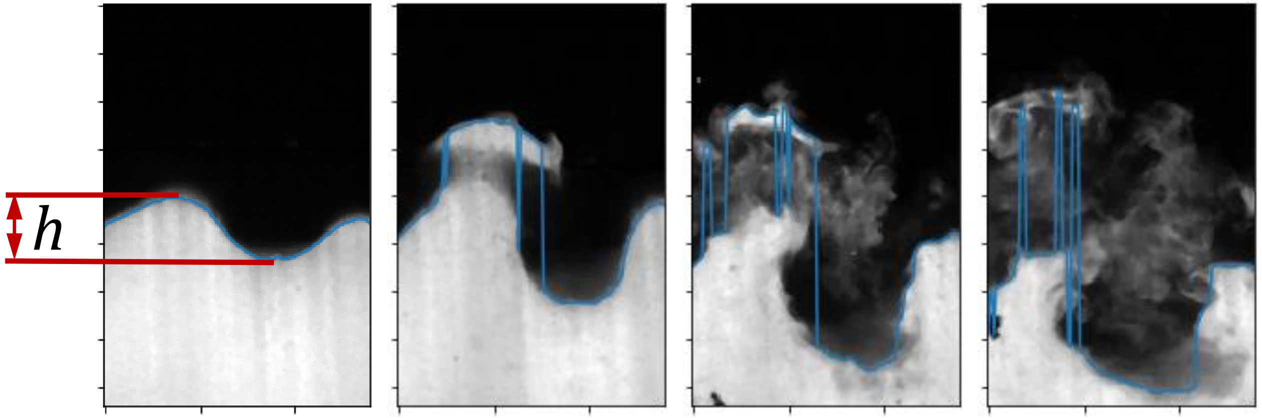

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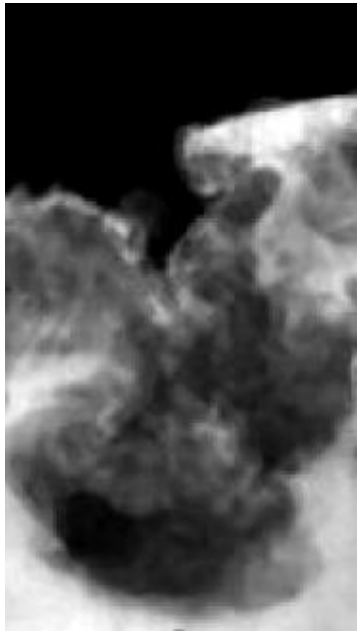
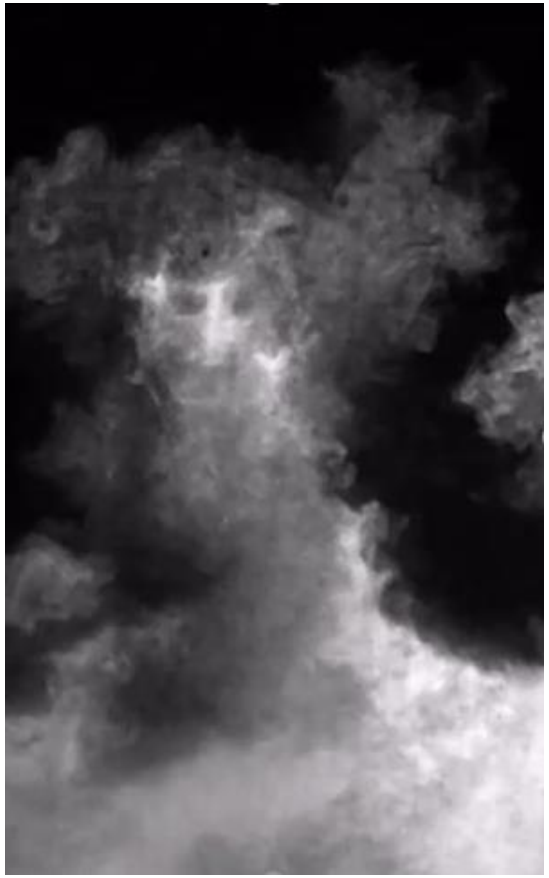


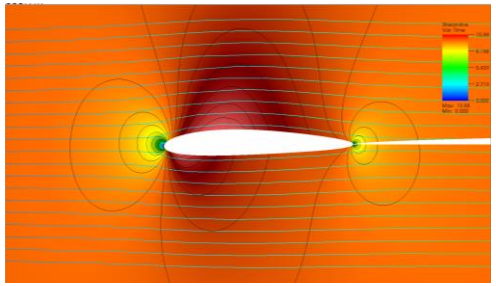


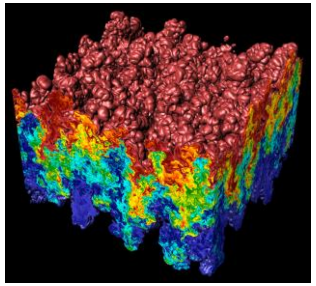
Simulation

- Create simulation “digital-twin”
- Use experimental data to validate commonly used mix models: RANS and LES
- Initiated by SSGF summer practicum at LLNL with CSGF alum Britton Olson

Simulation tool: Pyranda

- Pyranda is the open-source proxy-app for the LLNL Miranda code
  - Same high-order numerical methods - 10th order space / 4th order time
  - Available on github and constantly tested (https://github.com/LLNL/pyranda)
  - Python based and highly customizable for simple integration of new models
    - Domain, EOM, ICs, BCs
  - **Has ability to use both RANS and iLES models**

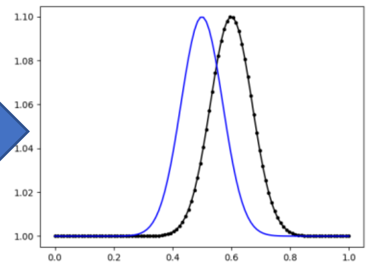




Python source for advection equation

```python
import sys
import time
import numpy
import matplotlib.pyplot as plt
from pyranda import pyrandaSim

# Define the domain/mesh
domain = "xdom = (0.0 , 1.0 , 100 )"

# Initialize a simulation object on a mesh
pysim = pyrandaSim('advection',domain)

# Define the equations of motion
pysim.EOM(" ddt(:phi:)  =  -:c: * ddx(:phi:) ")

# Initialize variables
ic = """
:phi: = 1.0 + 0.1 * exp( -(abs(meshx-.5)/.1 )**2 )
:phi0: = :phi:
:c:    = 1.0
"""
pysim.setIC(ic)

# Integrate in time
dt = .001
time = 0.0
while time < .1:
    time = pysim.rk4(time,dt)
```

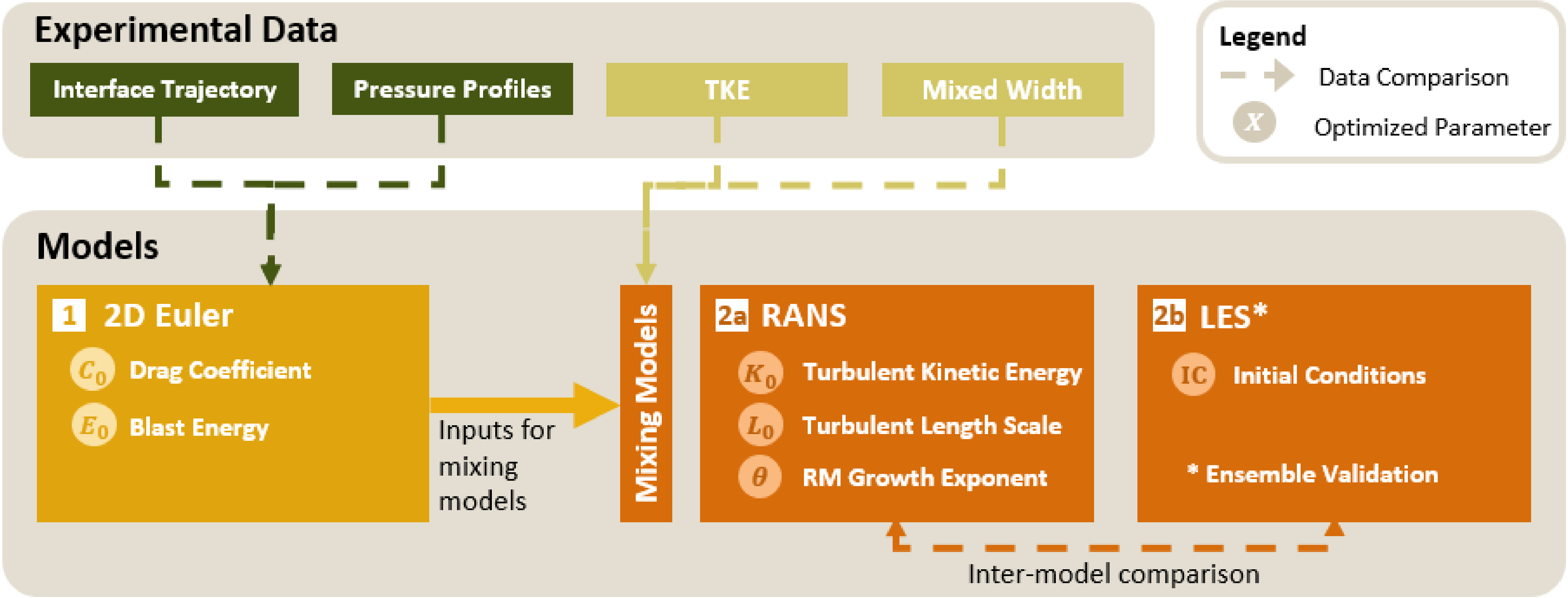
$$\frac{\partial}{\partial t}u = -c\frac{\partial}{\partial x}u$$



Scalar vs. x at initial/final times

High-level overview of work plan

- Framework for multi-fidelity verification of turbulent mixing models; RANS & LES.
- Staged approach to model validation:



Digital Twin – 2D Euler Simulation

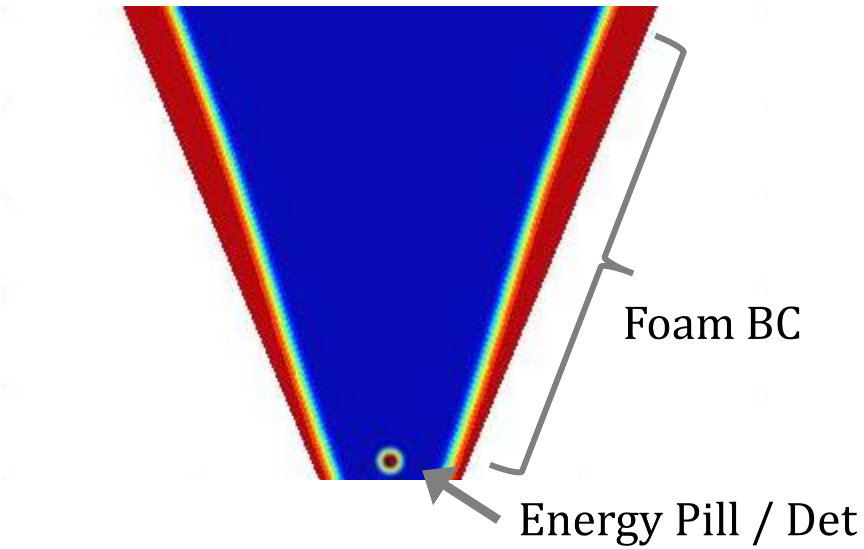
- Boundary Condition:
  No reflections off walls

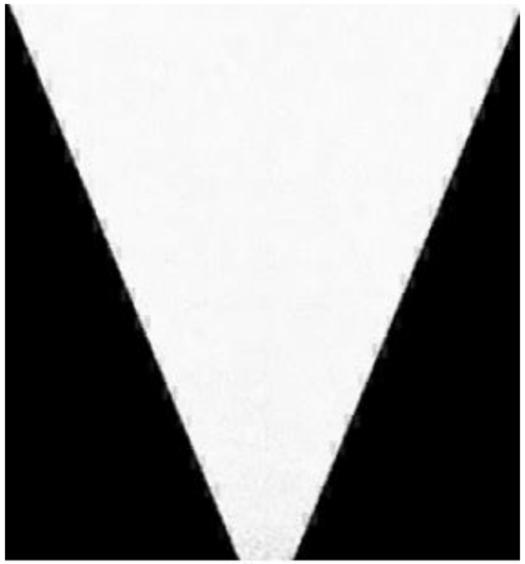
- Initial Condition:
  Large amount of energy released from small ball

- Model "losses" in experiment:
  - Boundary layer-based drag model

$$C_D = \frac{2C_{D0}\delta}{Width} \rightarrow \frac{d\delta}{dt} = a\, Re^b\, u_{mag}$$

- **Optimize with non-mixing data**





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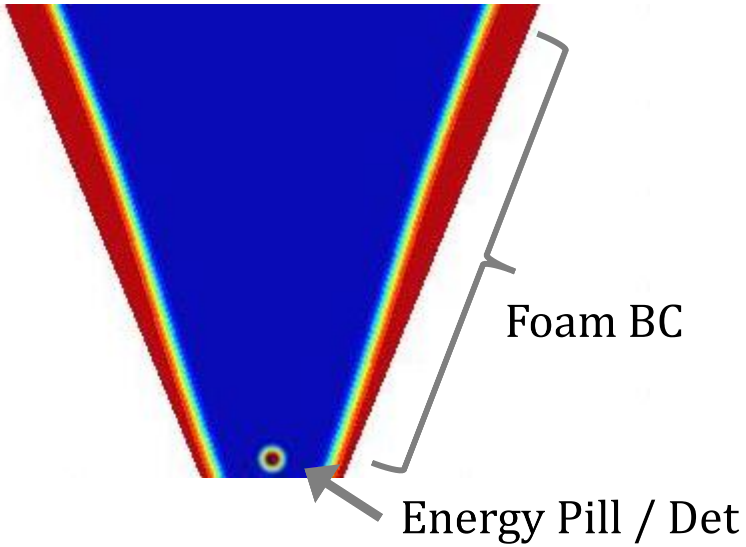
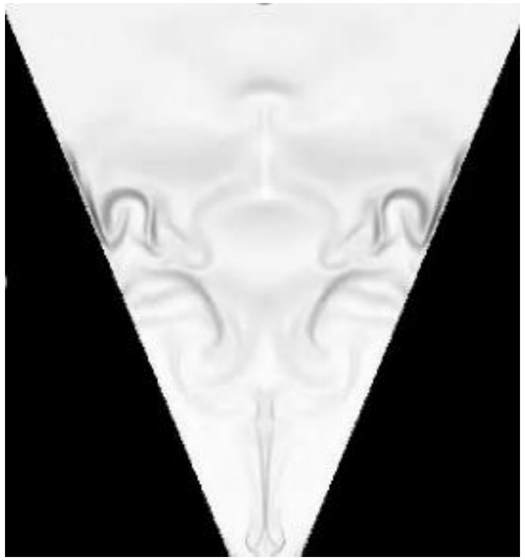


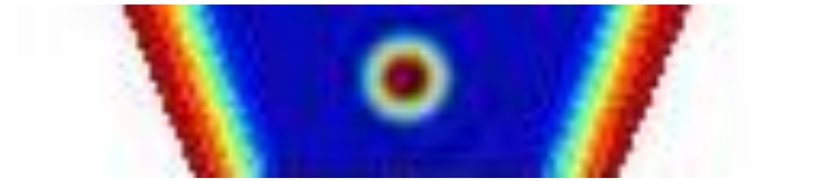


Euler Optimization

- Vary tuning parameters to maximize agreement with experimental data
- Tuning parameters:
  - Drag coefficient
  - Initial pill energy
- Experimental comparison:
  - Match pressure signal at probes
  - Match flat interface trajectory
- Optimize:
  - Gaussian Process to minimize error
  - Test and predict optimal parameters

$$C_D = \frac{2\boldsymbol{C_{D0}}\delta}{Width}$$

$$\rightarrow \frac{d\delta}{dt} = a\,Re^{b}\,u_{mag}$$



- **Optimized parameters are set as constants for use in mix models**

Euler Optimization

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- Tuning parameters:
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  - Initial pill energy
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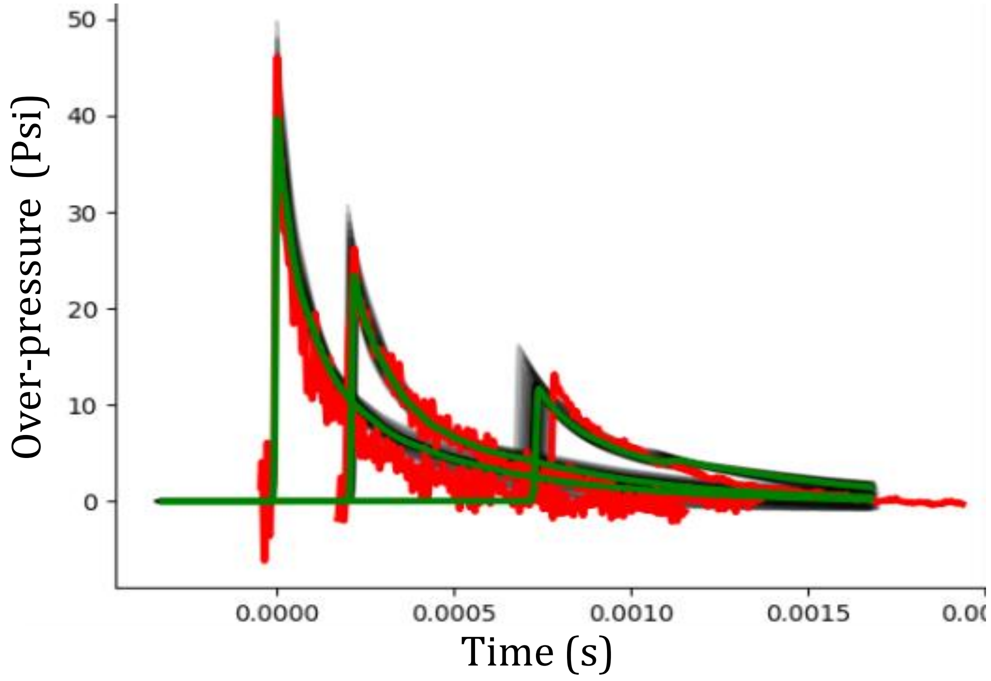
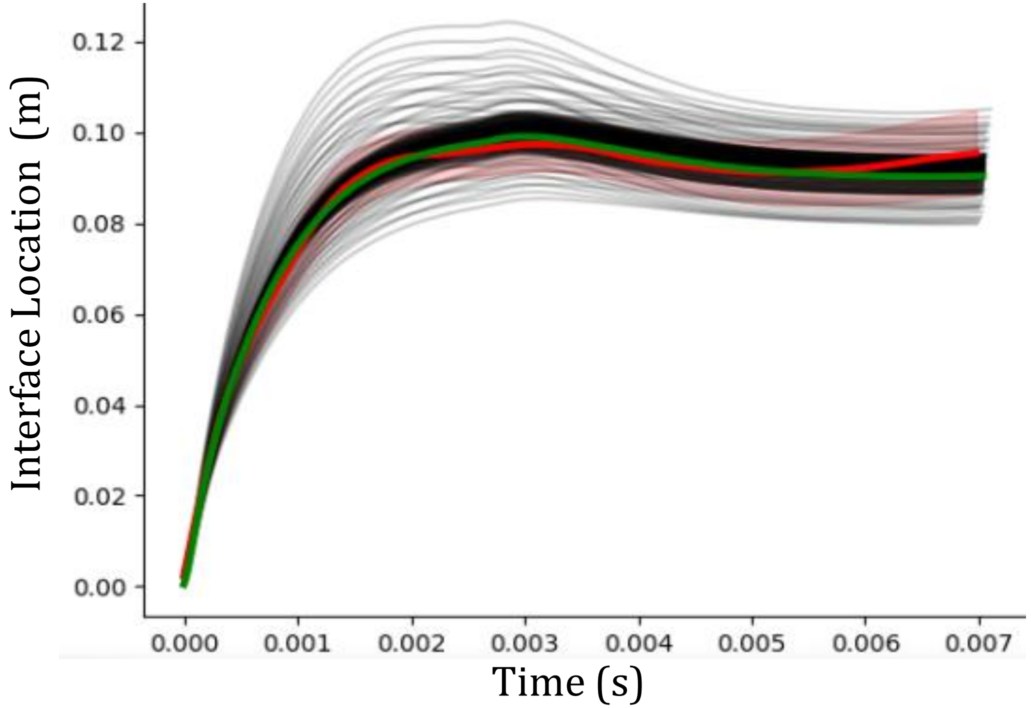
  - Match pressure signal at probes
  - Match flat interface trajectory
- Optimize:
  - Gaussian Process to minimize error
  - Test and predict optimal parameters

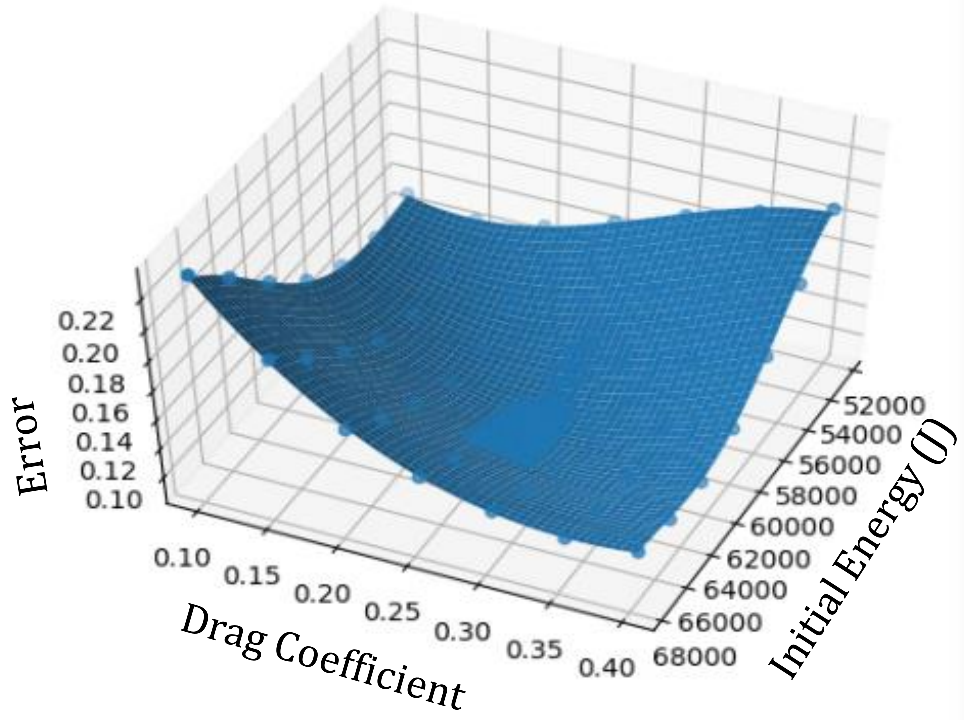


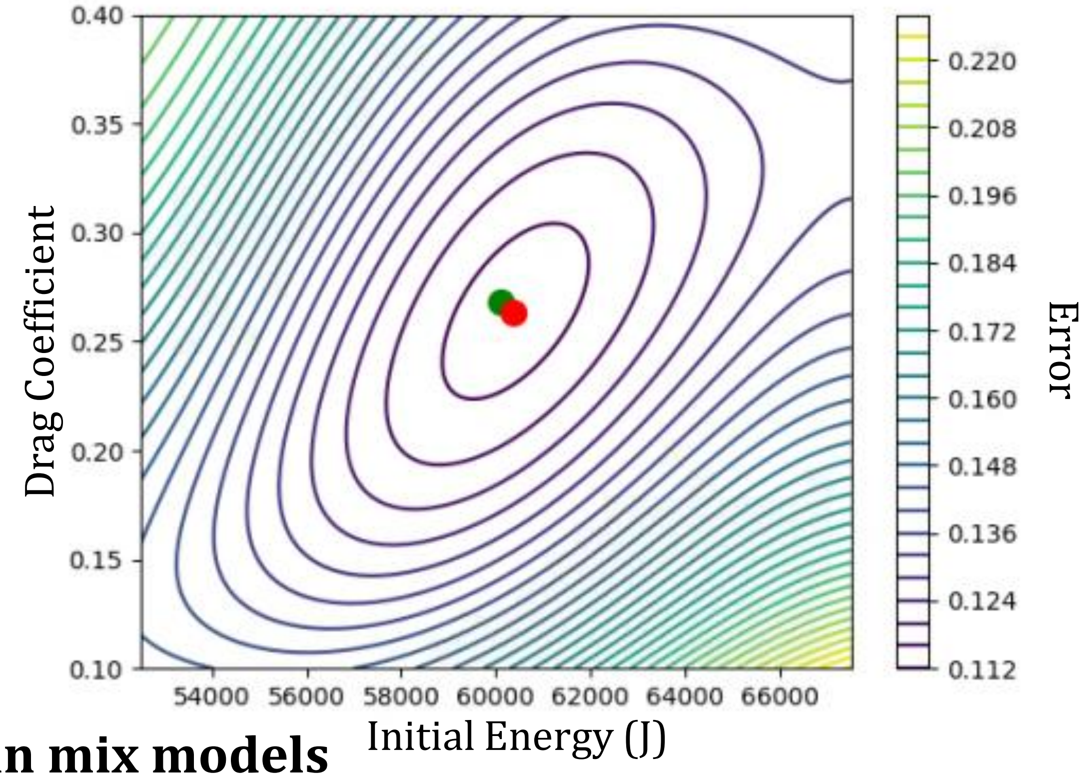


- **Optimized parameters are set as constants for use in mix models**

Euler Optimization

- Vary tuning parameters to maximize agreement with experimental data
- Tuning parameters:
  - Drag coefficient
  - Initial pill energy
- Experimental comparison:
  - Match pressure signal at probes
  - Match flat interface trajectory
- Optimize:
  - Gaussian Process to minimize error
  - Test and predict optimal parameters



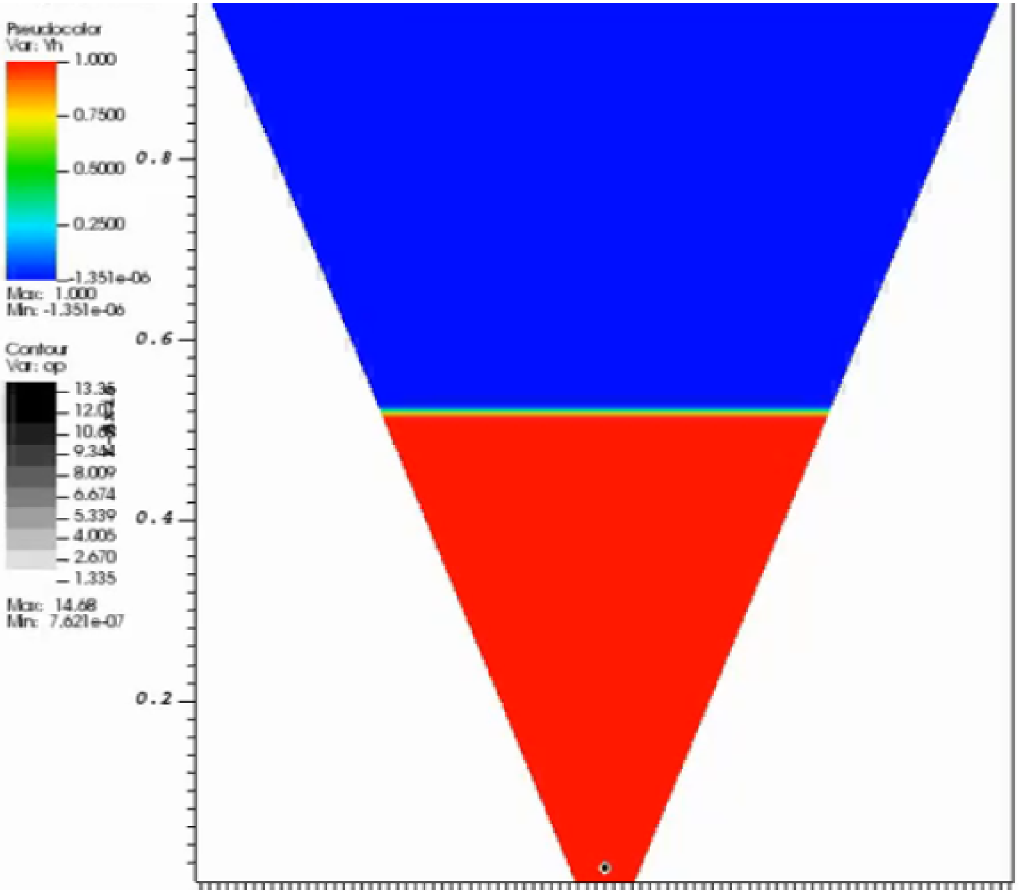


- **Optimized parameters are set as constants for use in mix models**

Simulation Results

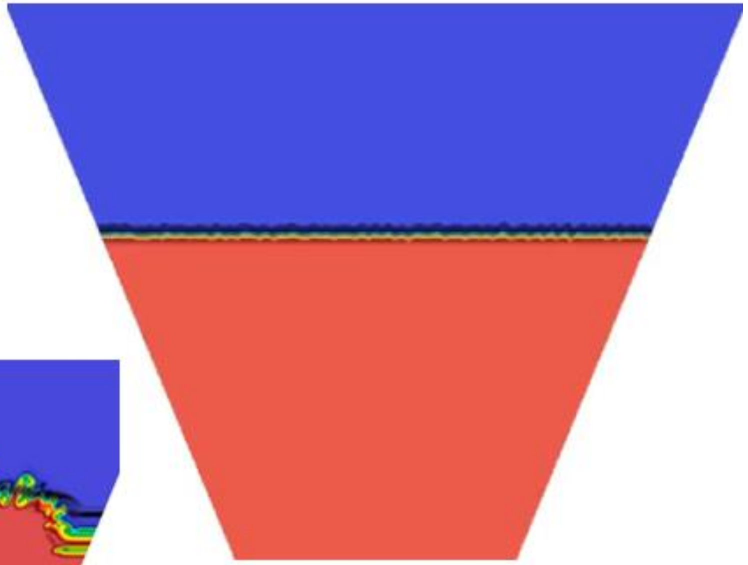
RANS Results

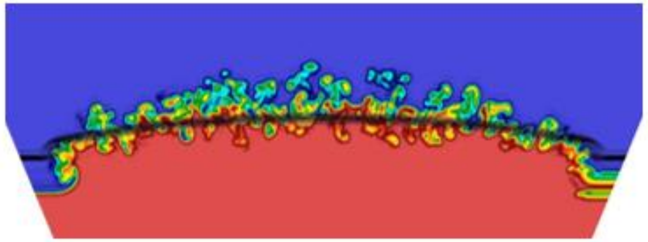
- “k-L” model in RANSBOX library
- Written by Brandon Morgan of LLNL

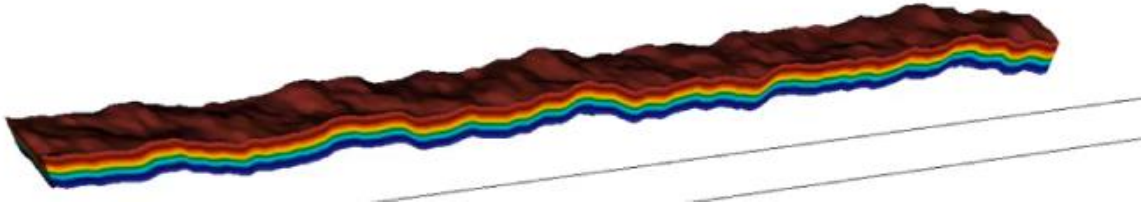


LES Results

- Use hybrid 2D/3D domain
- AFLES method of Miranda







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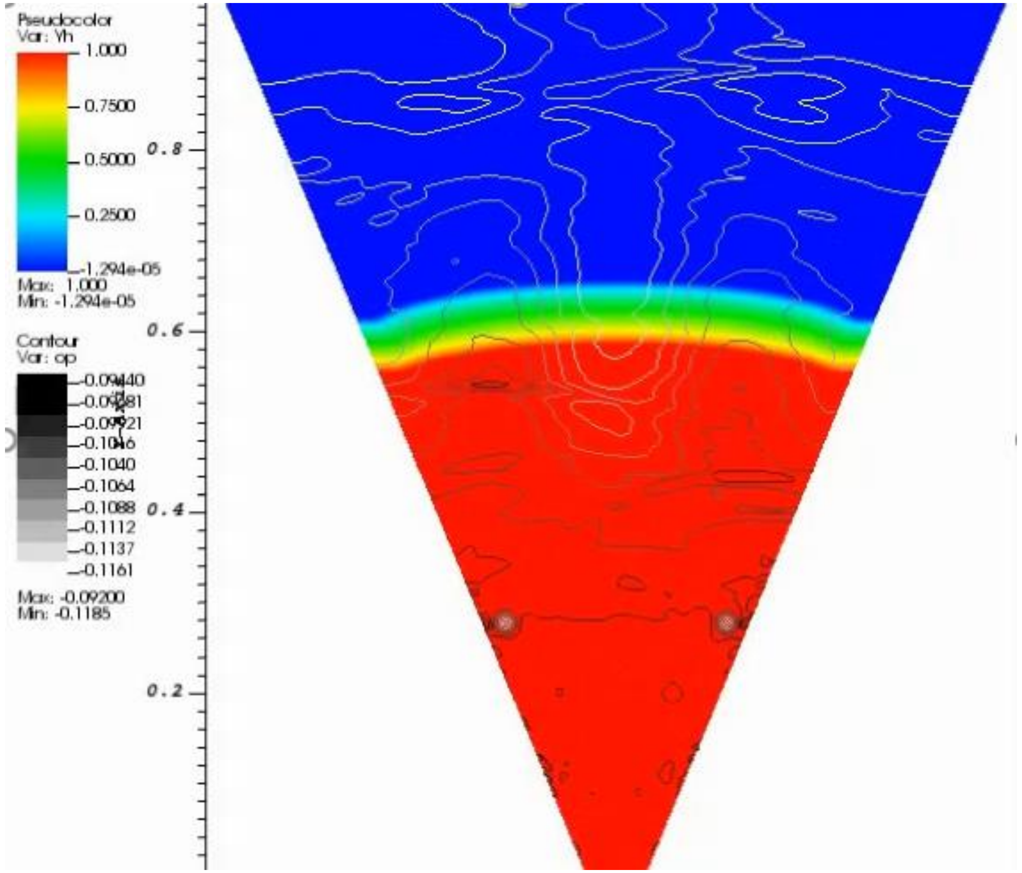

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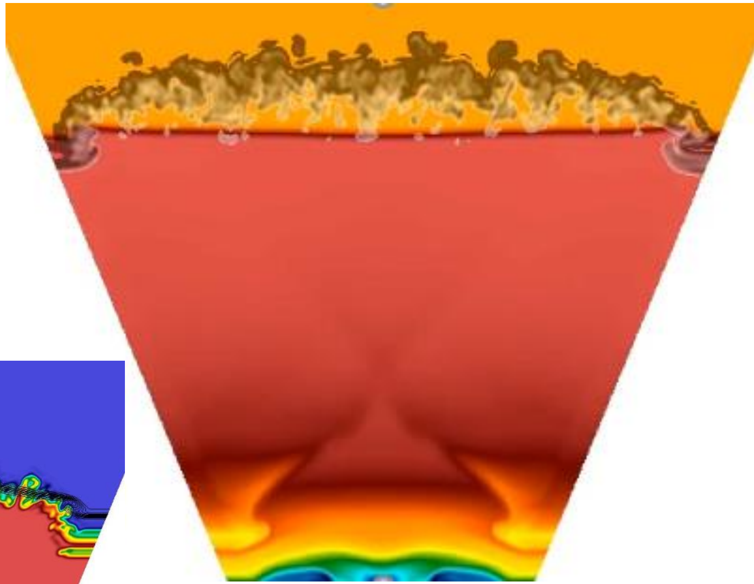

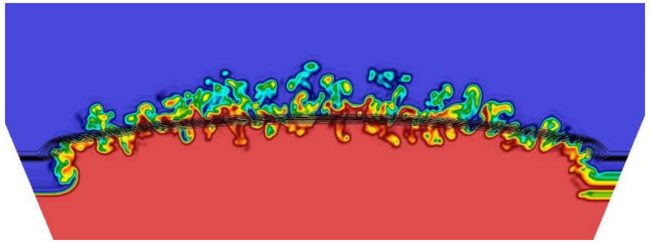

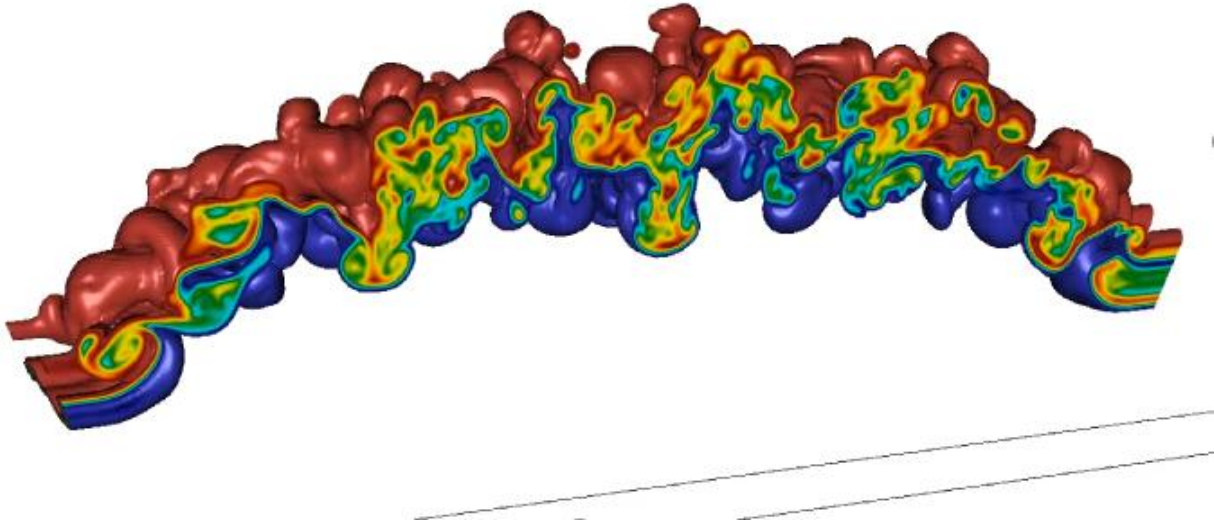

Questions