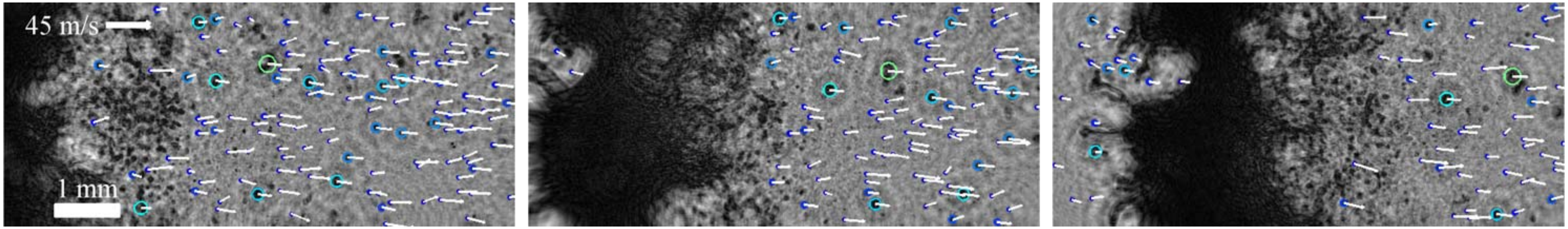
*Exceptional service in the national interest*

Sandia National Laboratories




# kHz Rate Digital In-line Holography Applied to Quantify Secondary Droplets from the Aerodynamic Breakup of a Liquid Column in a Shock-Tube

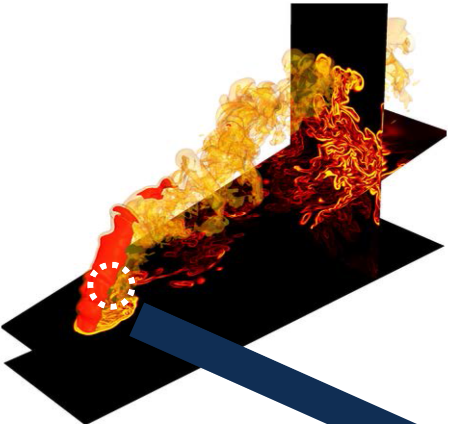
**Daniel R. Guildenbecher**, Justin L. Wagner, Joseph D. Olles, Yi Chen, Edward P. DeMauro, Paul A. Farias, Thomas W. Grasser, Paul E. Sojka

U.S. DEPARTMENT OF ENERGY

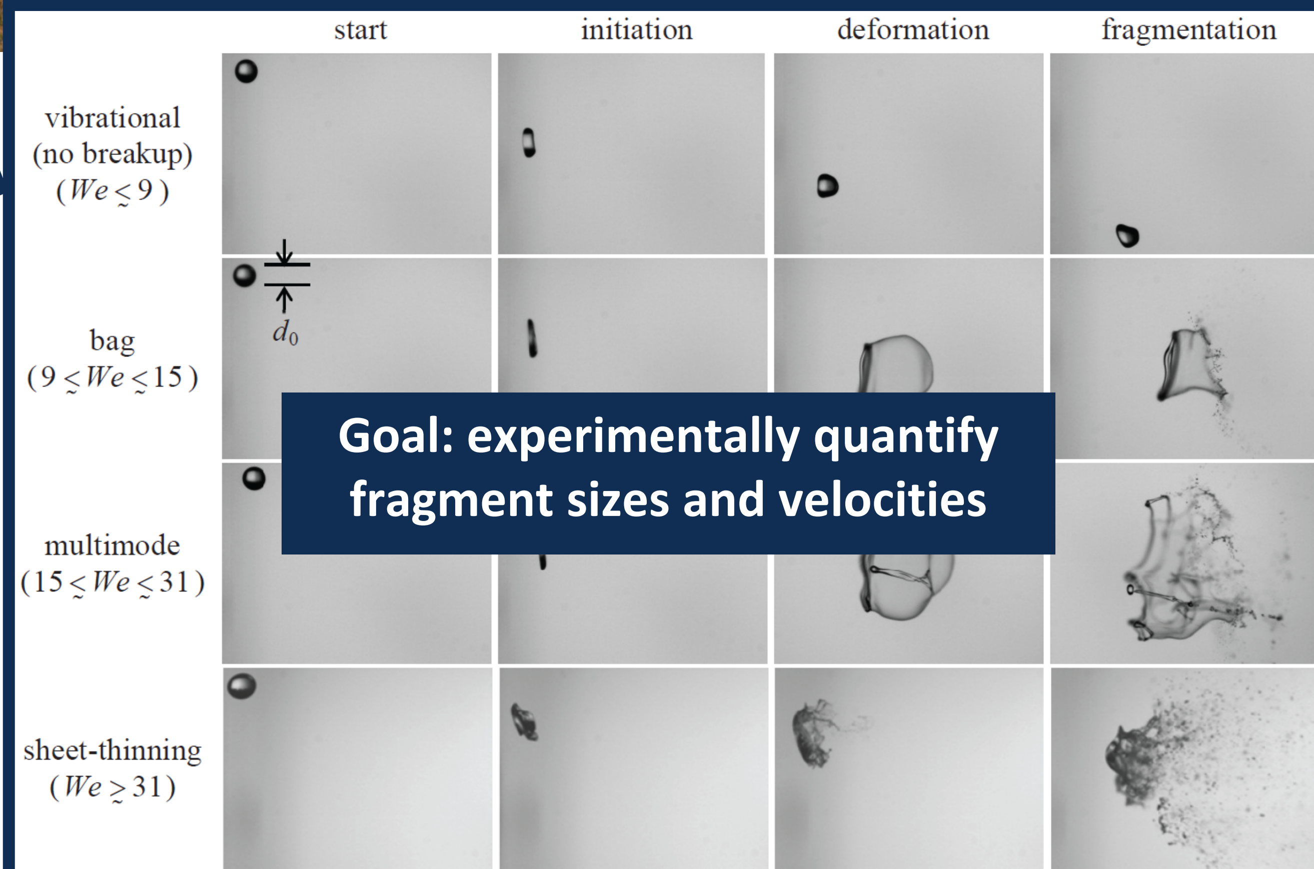
NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

# Motivation: Quantify liquid breakup



Oefeline et al, 2014



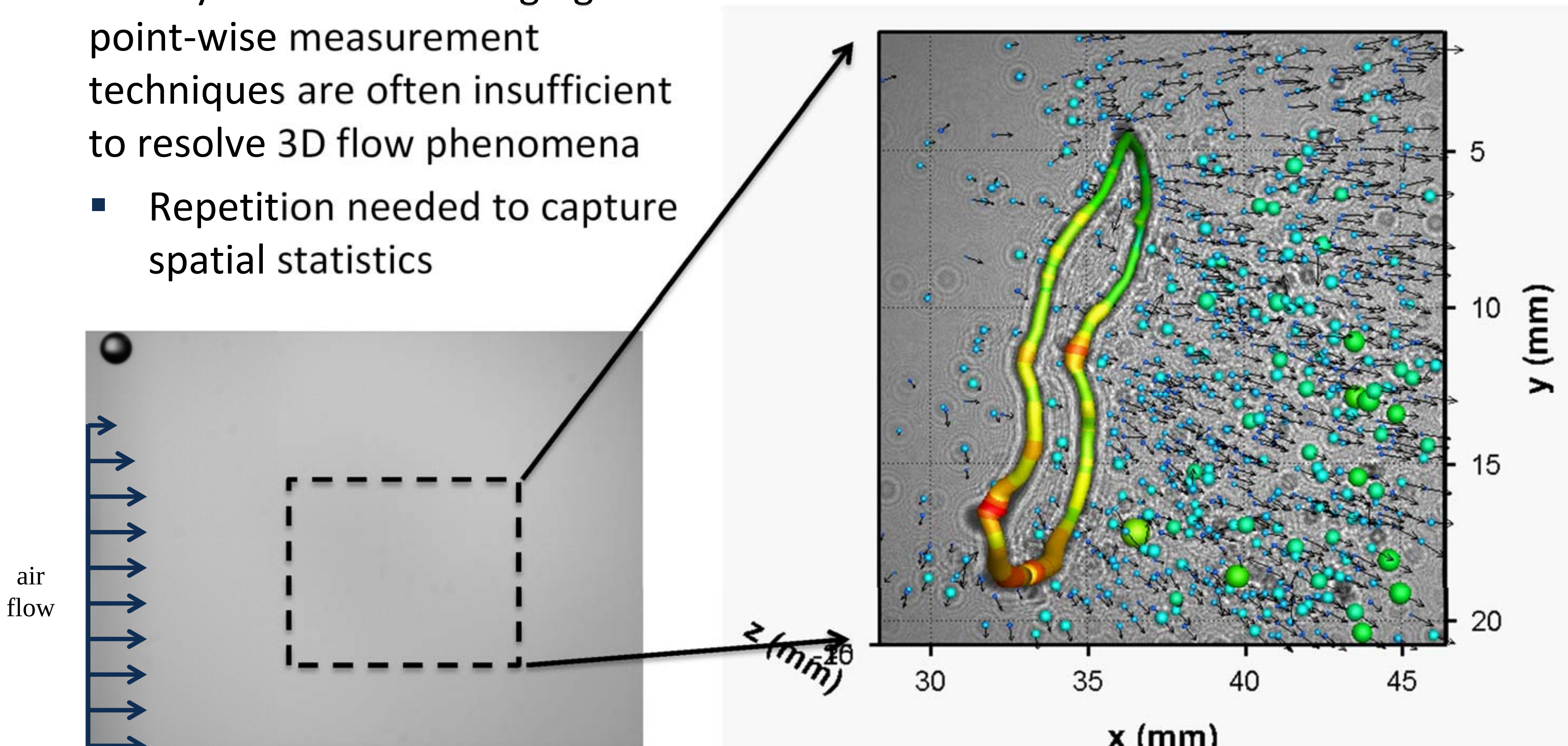

**Goal: experimentally quantify fragment sizes and velocities**

- Liquid atomization is critical many in multiphase flows
- Aerodynamic breakup is one important mechanism
  - $We = p_g u^2 d/\sigma$

# Motivation: 3D imaging for a 3D world

Widely available 2D imaging or point-wise measurement techniques are often insufficient to resolve 3D flow phenomena

- Repetition needed to capture spatial statistics



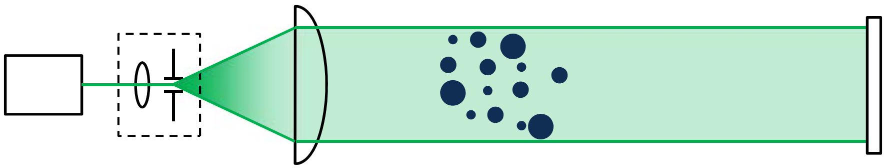

high-speed video of a ethanol drop in an air-stream

digital holographic measurement (Gao, Guildenbecher et al, 2013, *Opt. Lett.*)

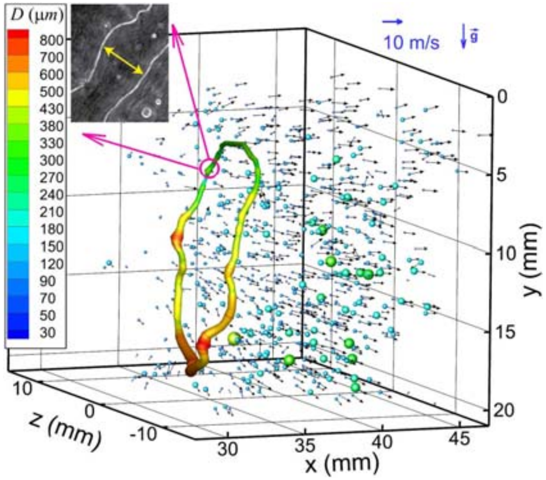
**Holography allows for 3D quantification of particle sizes and velocities**

# Outline for talk

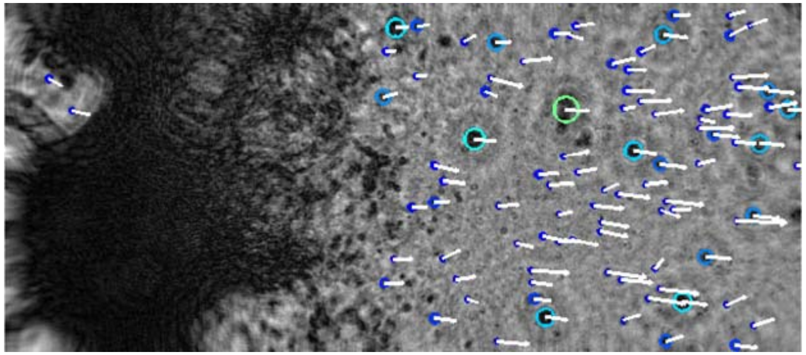
Introduction to holography for particle measurements



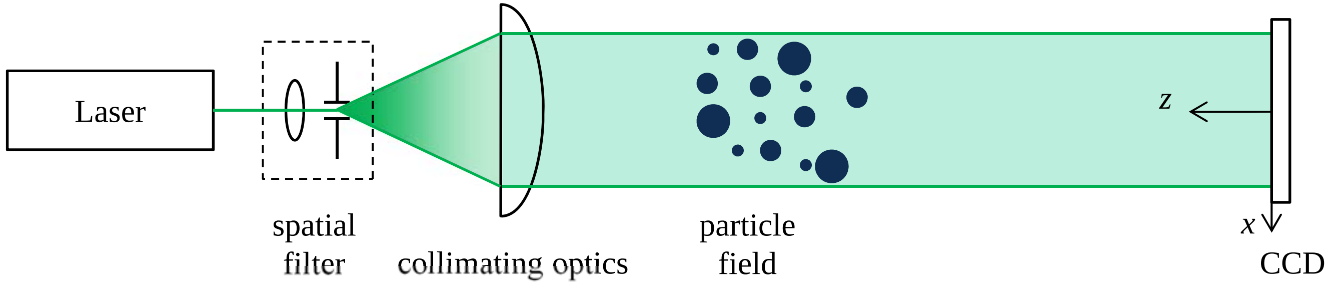
Challenges and opportunities for high-speed, 3D measurements

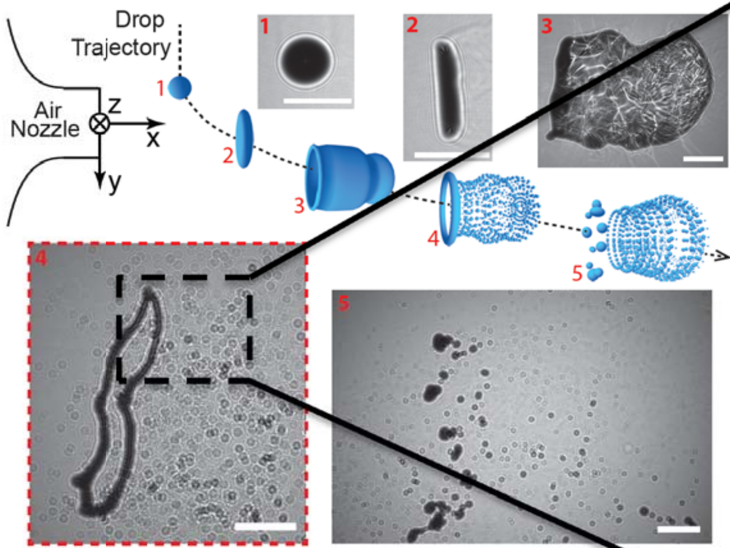



Quantitative investigation of aerodynamic breakup

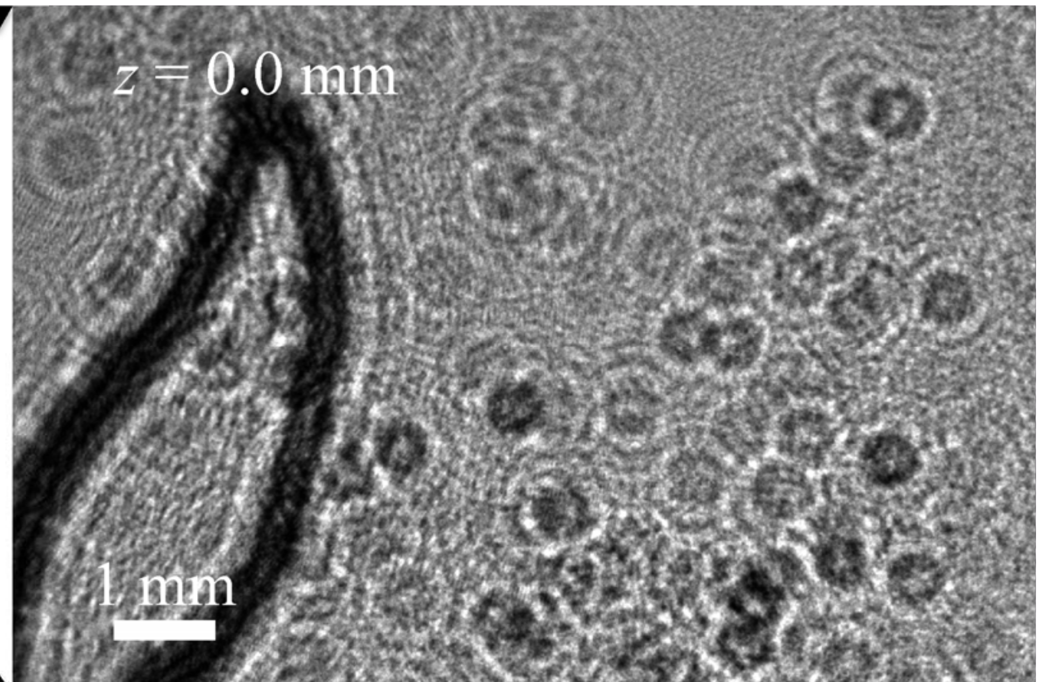


# Digital in-line holography (DIH)




digital holograms of the breakup of an ethanol drop in an air-stream (Gao, Guildenbecher et al 2013, *Opt. Lett.*)




recorded hologram: $h(\xi,\eta)$

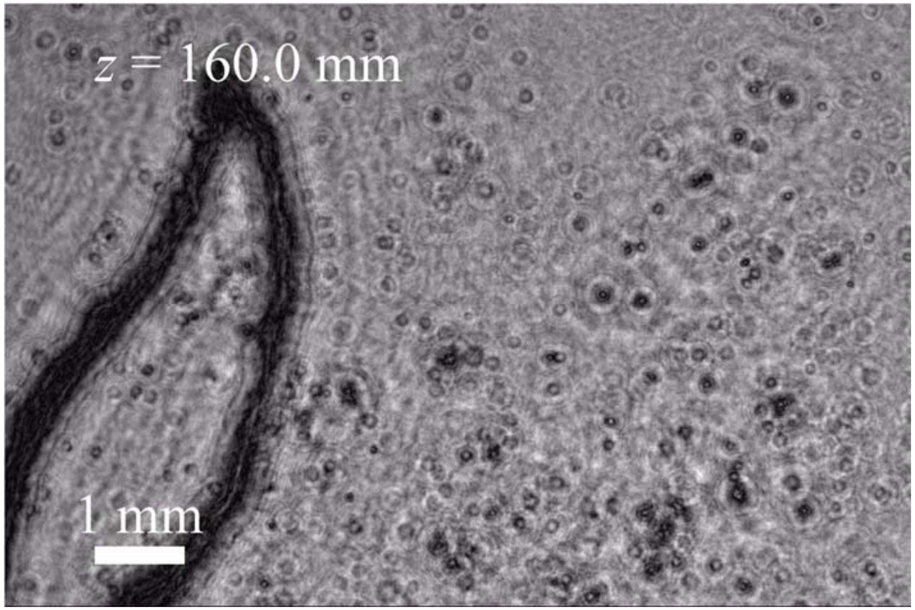
reconstructed amplitude through depth, $z$

Light is numerically back-propagated using the diffraction equation:

$$E(x,y,z) = \frac{1}{\lambda}\iint E(\xi,\eta,z=0)\frac{e^{-jkr}}{r}d\xi d\eta \quad \text{where: } r=\sqrt{(\xi-x)^2+(\eta-y)^2+z^2}$$

# Depth-of-focus problem

The spatial extent of the diffraction pattern limits the angular aperture, $\Omega$, from which a particle is effectively reconstructed (Meng et al, 2004, *Meas. Sci. Technol.*)




- From the central diffraction lobe → $\Omega \approx 2\lambda/d$
- Using the traditional definition of depth-of-focus, $\delta$, based on change of intensity within the particle center → $\delta \approx 4\lambda/\Omega^2$
- Therefore: for in-line holography, $\delta \approx d^2/\lambda$
  - Example: $d$ = 300 μm, $\lambda$ = 532 nm → $\delta \approx$ 170 mm!
- We can improve this to $\delta \approx$ O(600 μm) with image processing routines
  - E.g. Guildenbecher et al 2013, *Appl. Opt.;* Gao et al 2013, *Opt. Express;* Gao et al 2014, *Appl. Opt.*

**Nevertheless, we are always working to overcome to depth of focus problem**

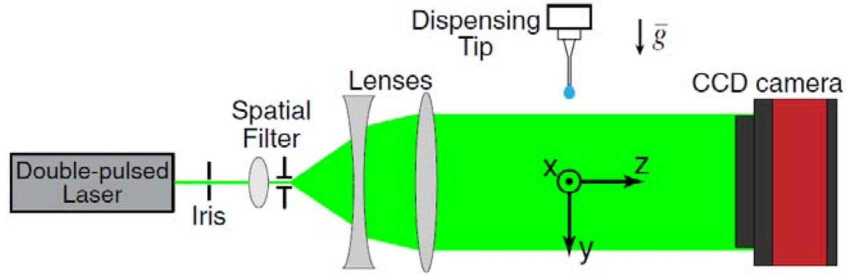
# Aerodynamic drop fragmentation

<u>Experimental configuration:</u> Double-pulsed laser and imaging hardware as typically used in PIV

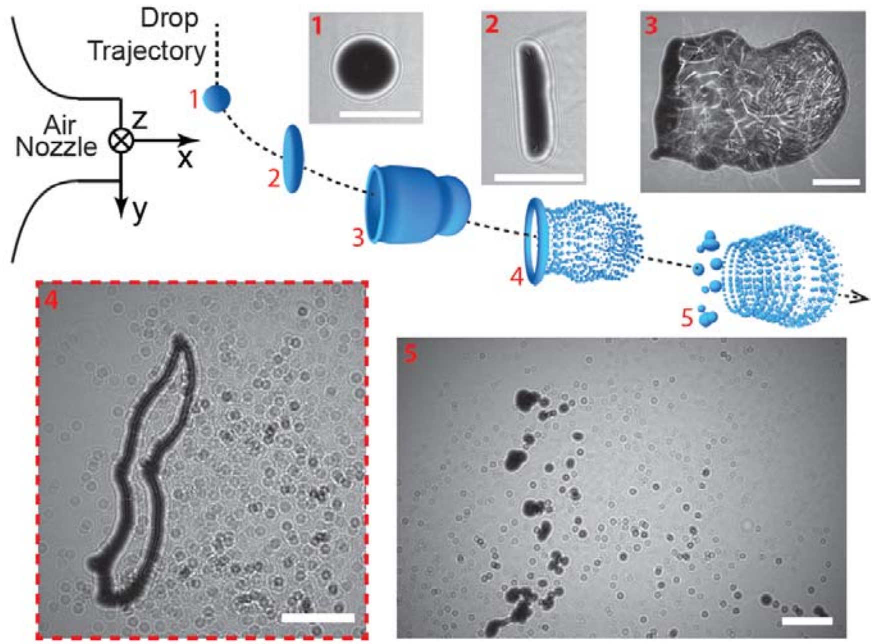
- $\lambda$ = 532 nm, 5 ns pulsewidth
- Interline transfer CCD (4008 × 2672, 9 μm pixel pitch)
- Temporal separation, $\Delta t$ = 62 μs, determined by laser timing

<u>Note:</u> without a separate reference wave, coherence length requirements in DIH are greatly relaxed.

- Expensive injection seeders are not always needed
- If you have a PIV system, you con probably do this experiment




Optical configuration (Gao, Guildenbecher et al 2013, *Opt. Lett.*)

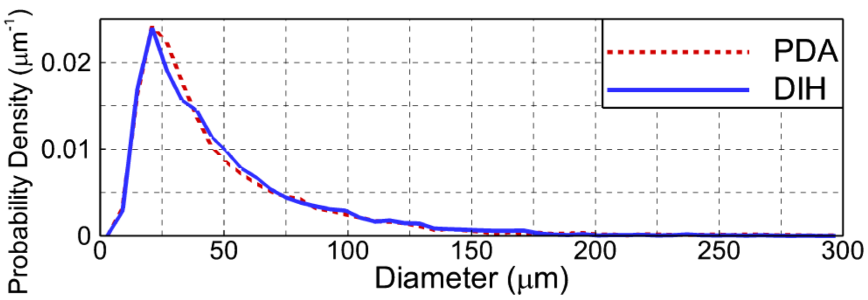



digital holograms of the breakup of an ethanol drop in an air-stream (Gao, Guildenbecher et al 2013, *Opt. Lett.*)

# Aerodynamic drop fragmentation

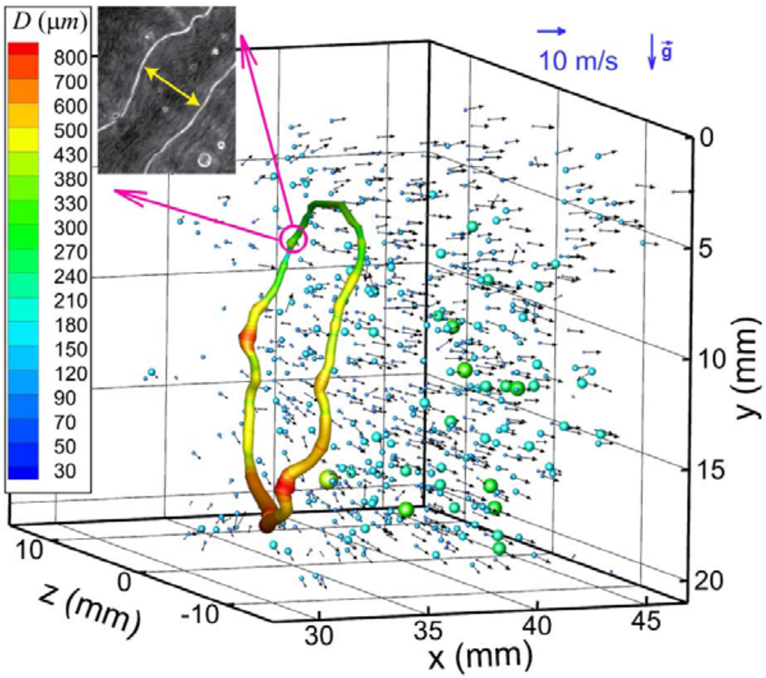
Secondary drop sizes/positions extracted by the hybrid method

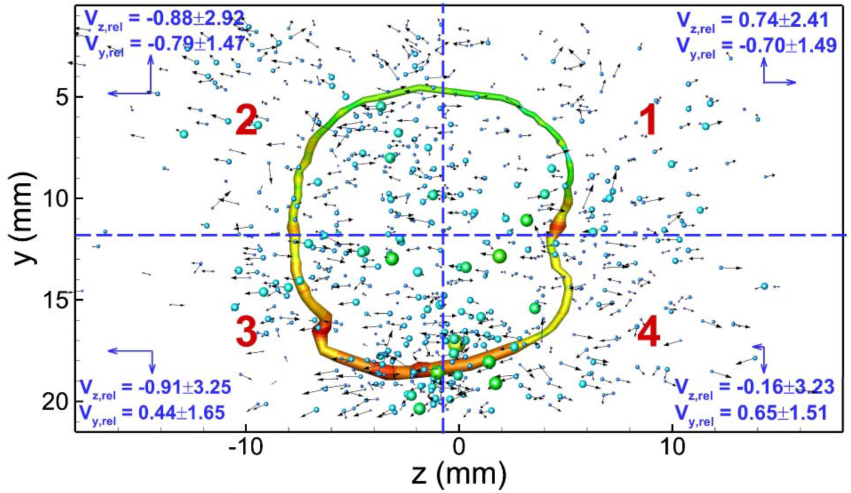
- Comparison with phase Doppler anemometer (PDA) data confirms accuracy of measured sizes




Ring measured from *z*-location of maximum image gradient

- Total volume of ring + secondary drops is within 2.2% of the initial volume

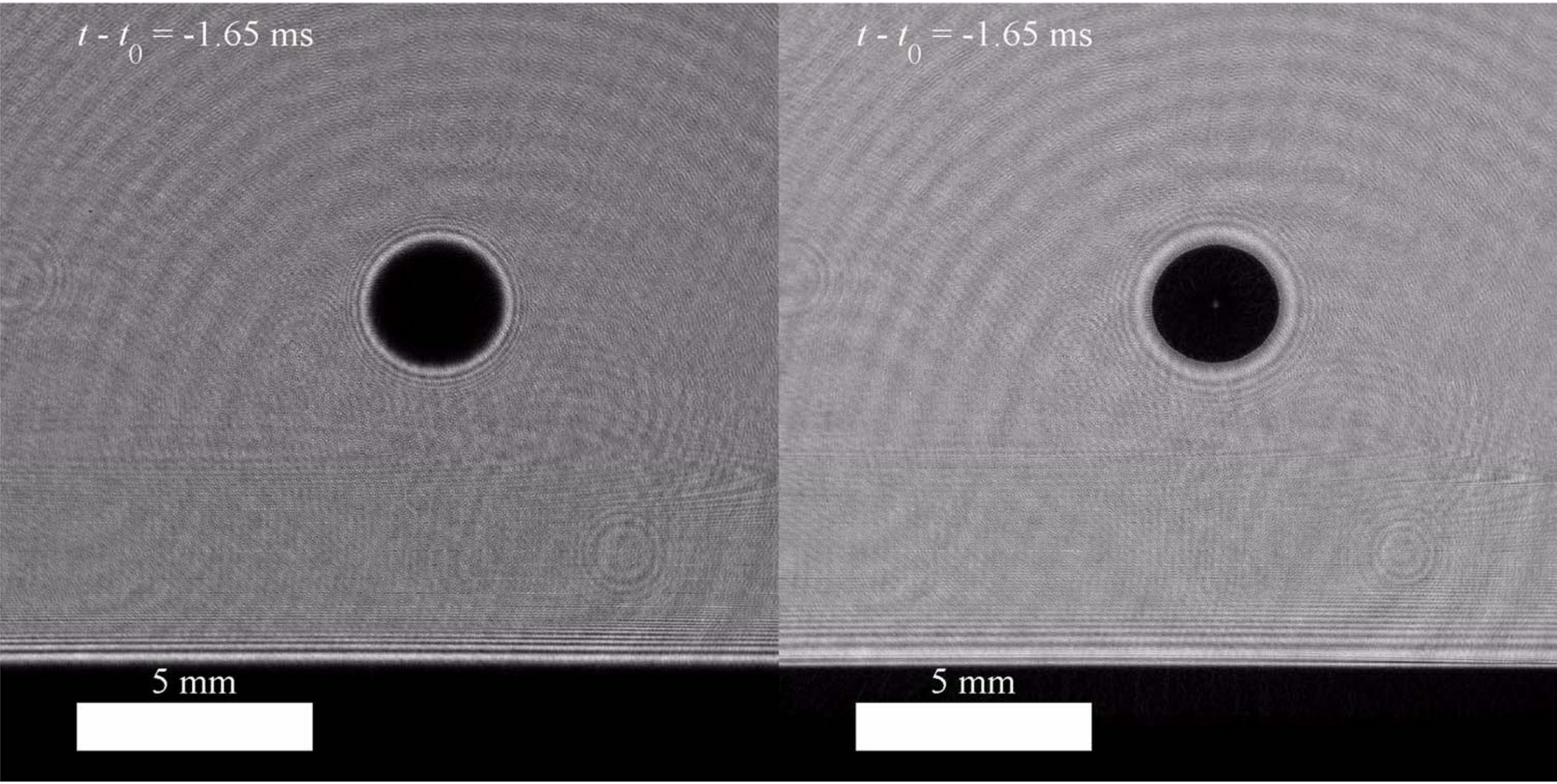


# DIH at kHz rates

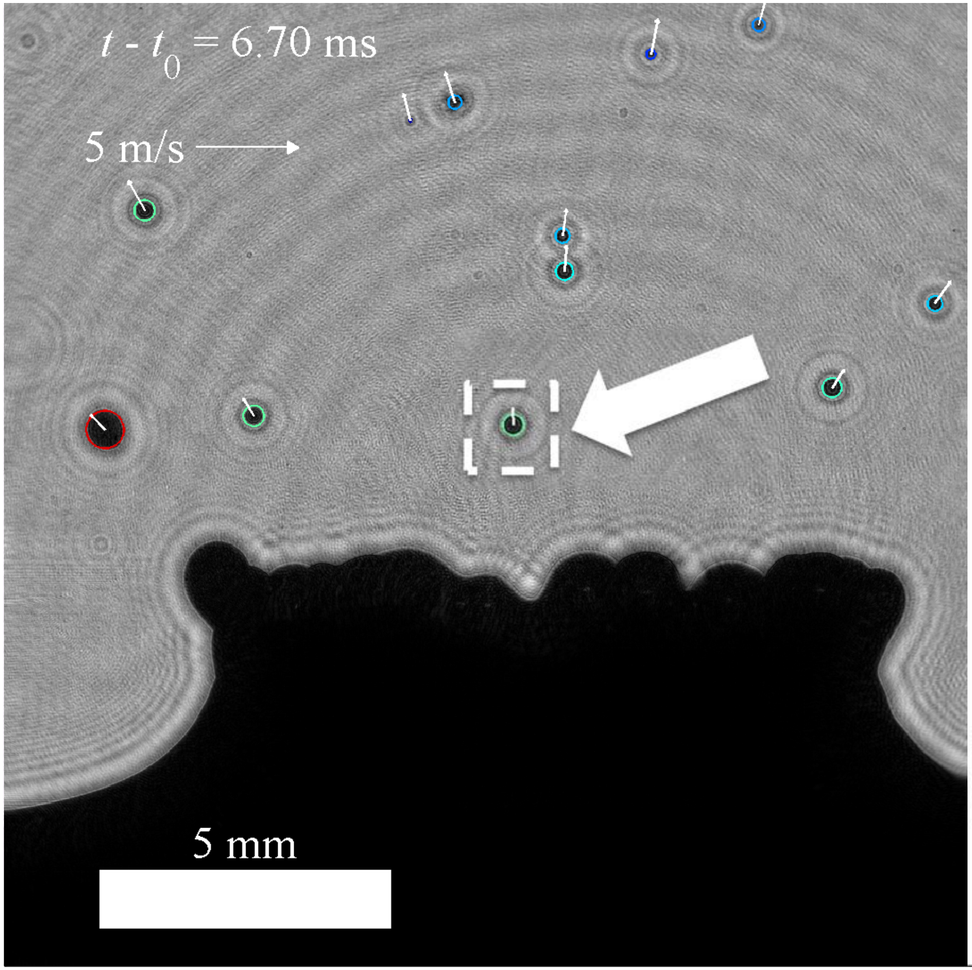
# High-speed (kHz) DIH

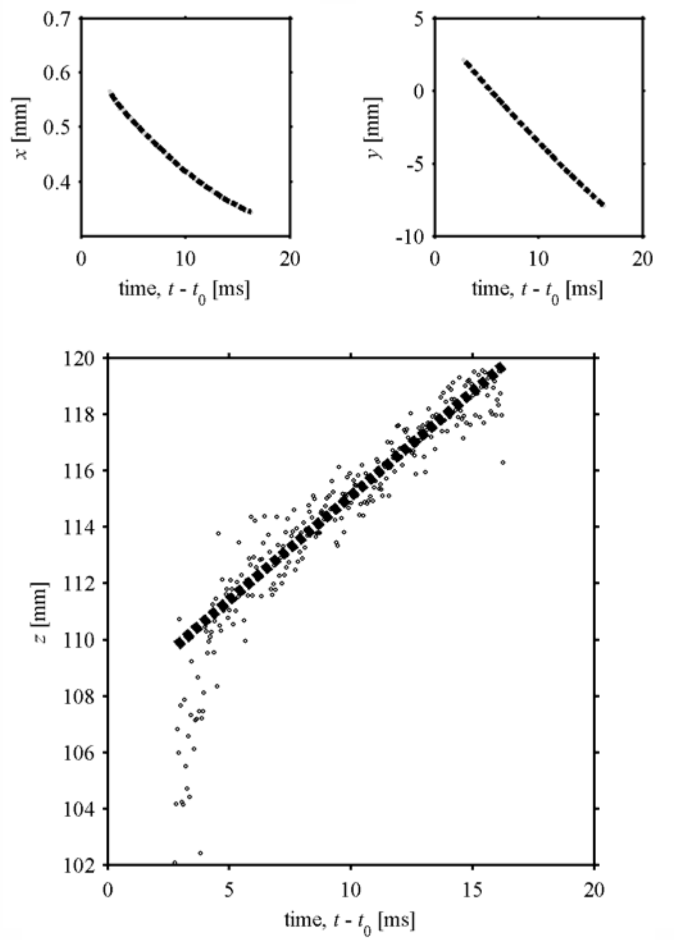
Increased temporal resolution is possible using high-speed (kHz rate) cameras




Challenges: (1) higher readout noise, fewer pixels, larger pixel pitches
(2) very large data sets (10s of Gb)

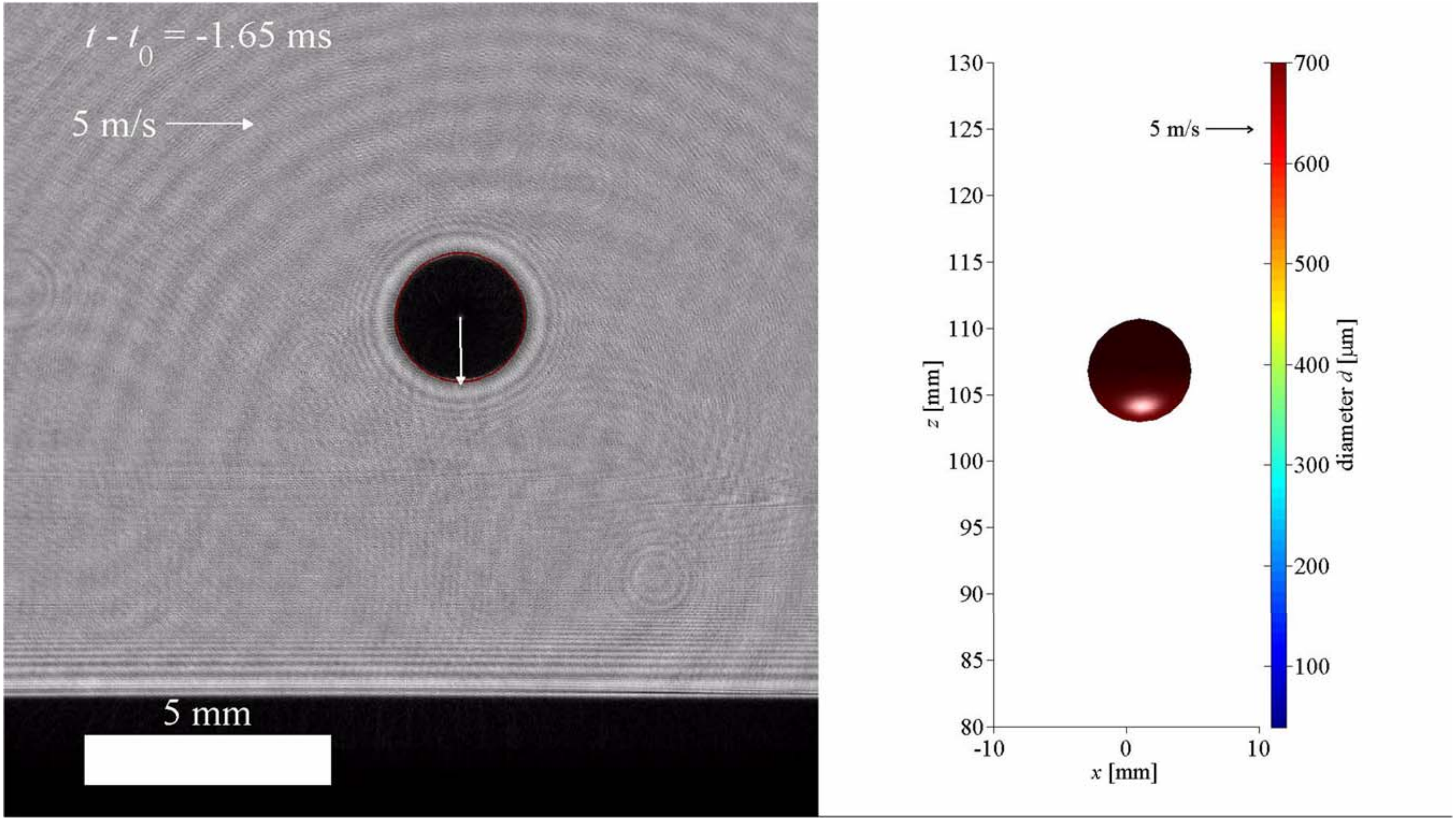
# High-speed (kHz) DIH




- Frame-to-frame particle matching illustrates the depth-of-focus problem
- With sufficient temporal resolution, particles trajectories can be fit to temporal models

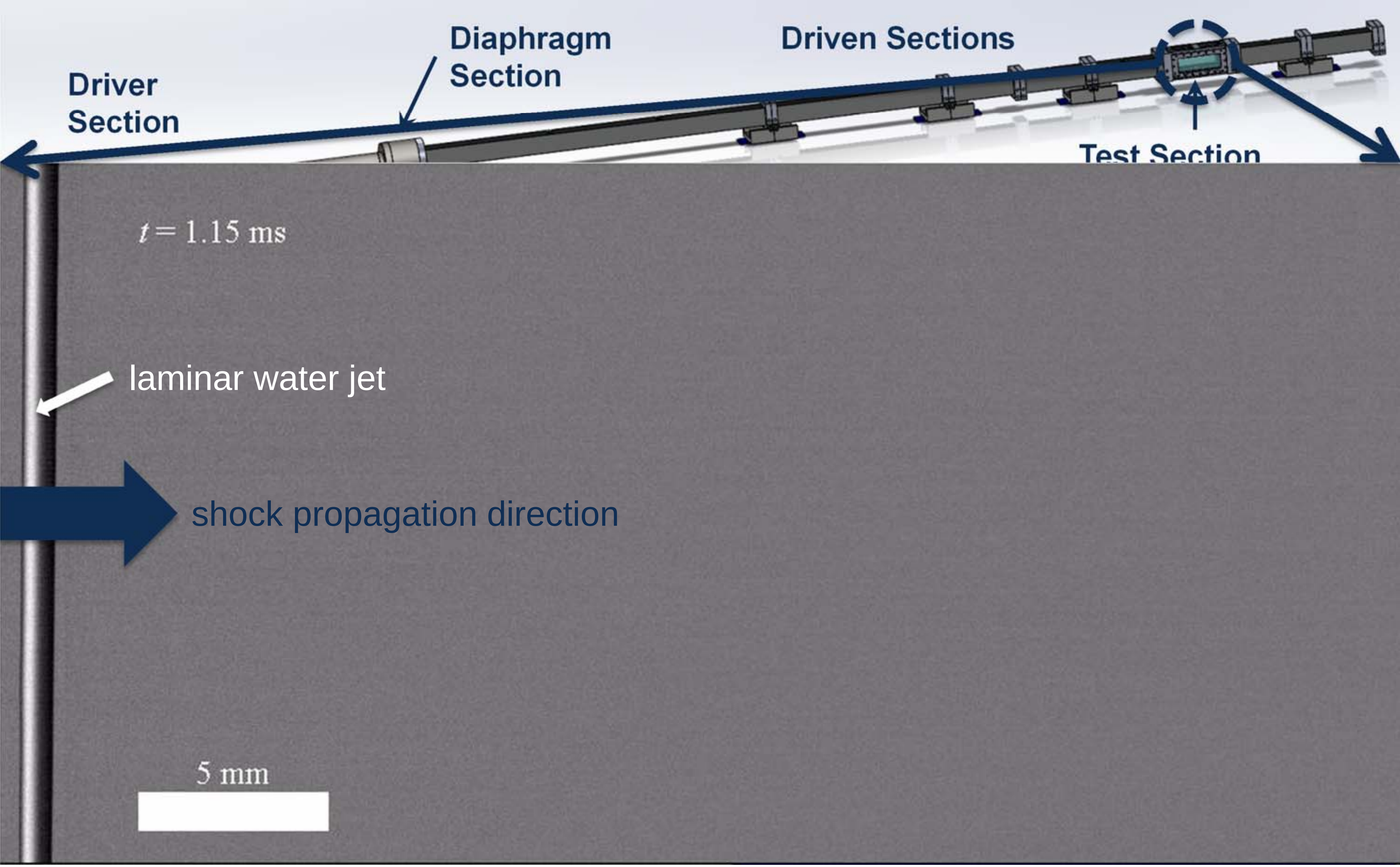
# High-speed (kHz) DIH



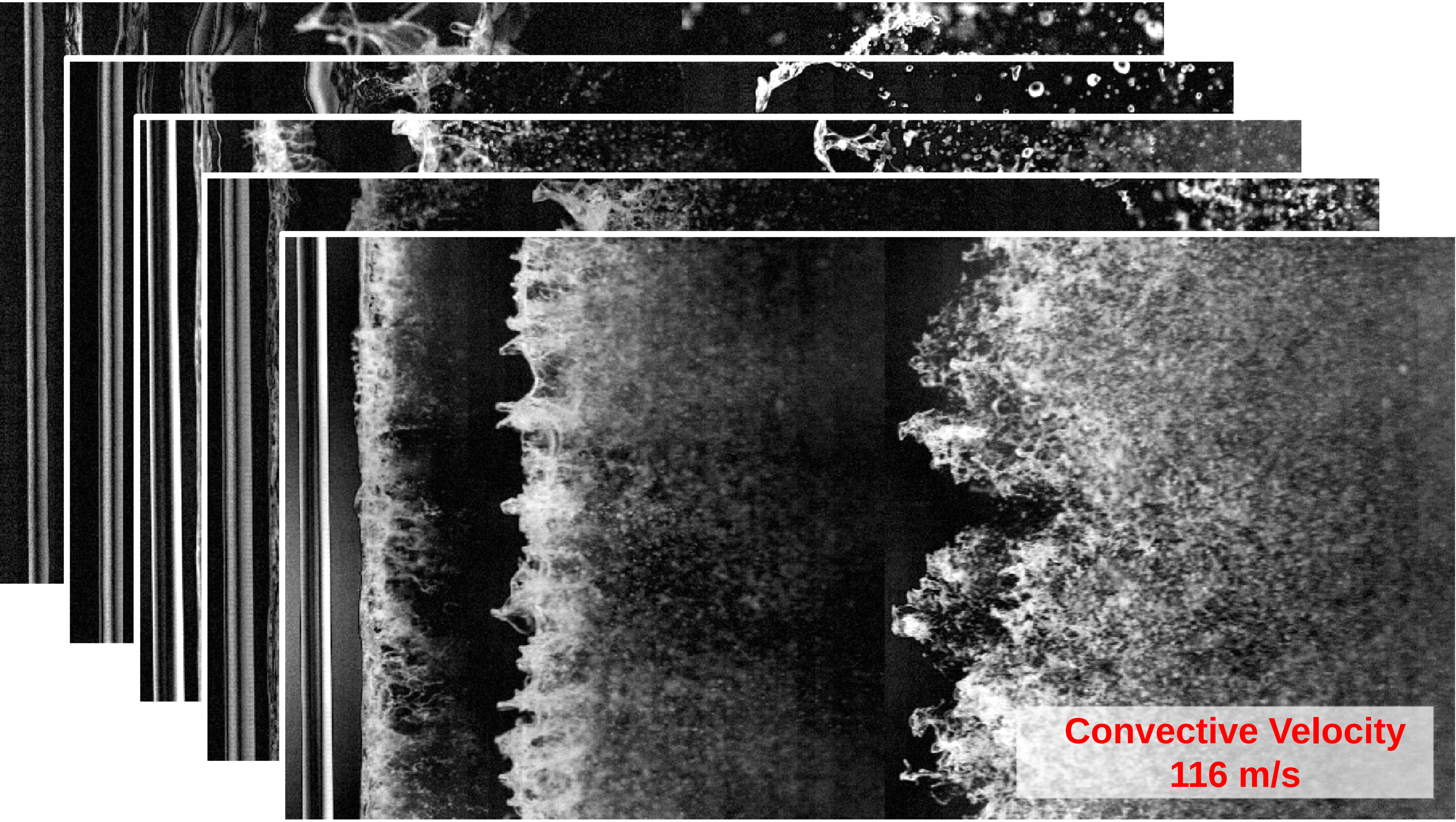

- Multi-frame trajectory fitting leads to a 36X reduction in *z*-uncertainty

# Quantification of liquid breakup

# Breakup of a water column in a shock-tube

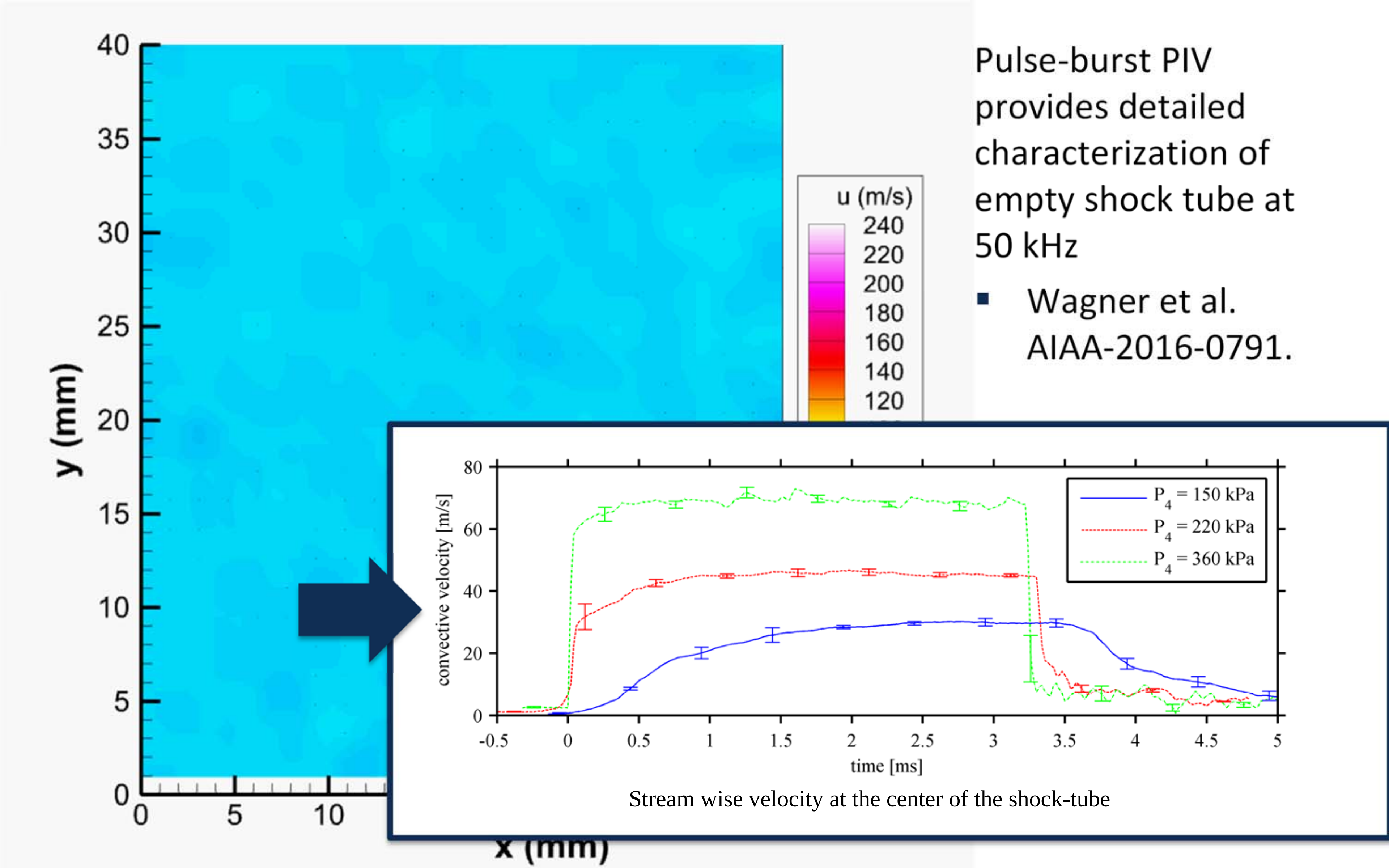


# Observed breakup morphologies




**Breakup morphologies similar to those observed for isolated drops**

# Well characterized boundary conditions

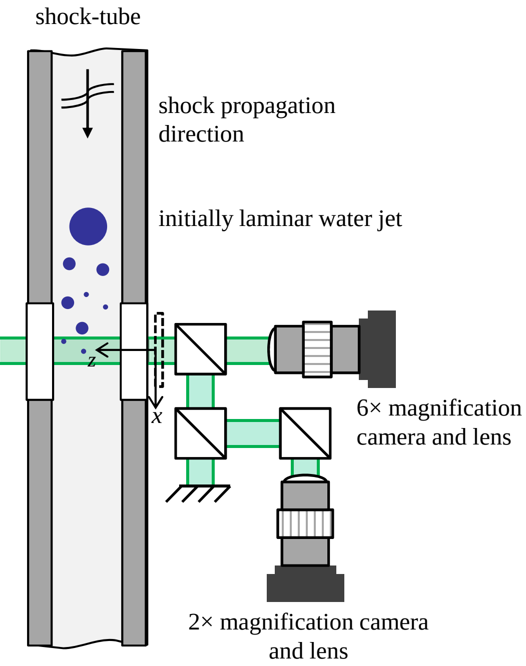


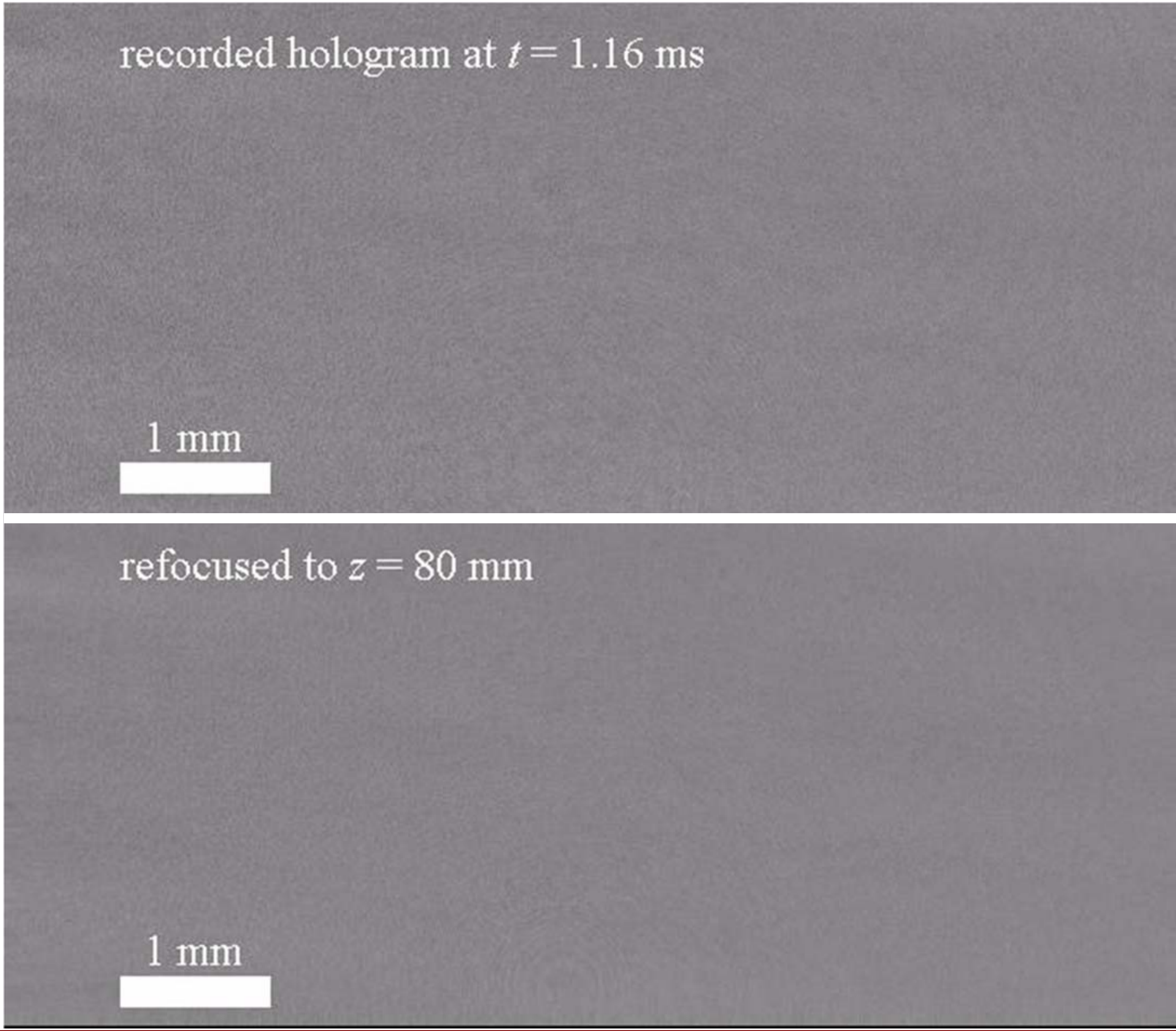

Stream wise velocity at the center of the shock-tube

Pulse-burst PIV provides detailed characterization of empty shock tube at 50 kHz

- Wagner et al. AIAA-2016-0791.

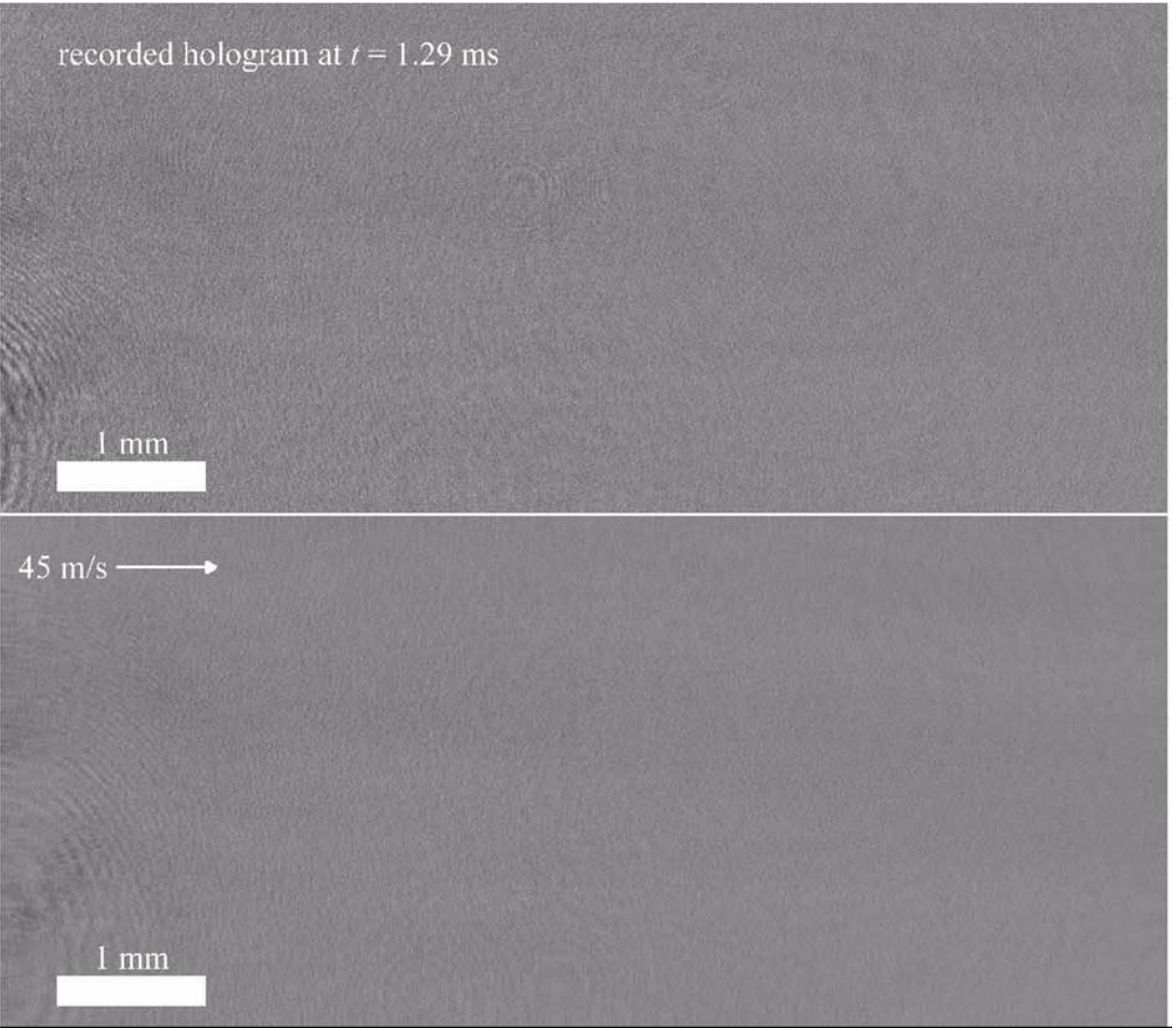
# DIH recorded at 100,000 fps



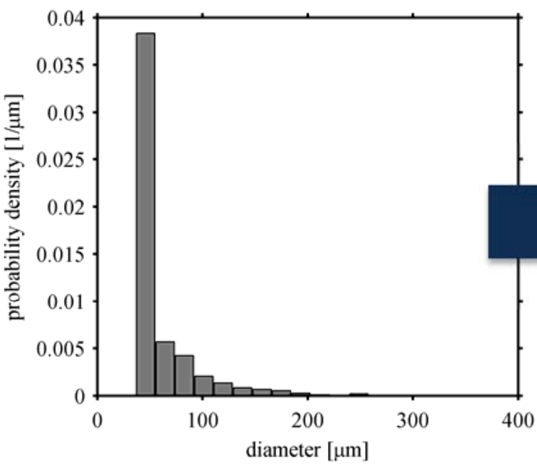



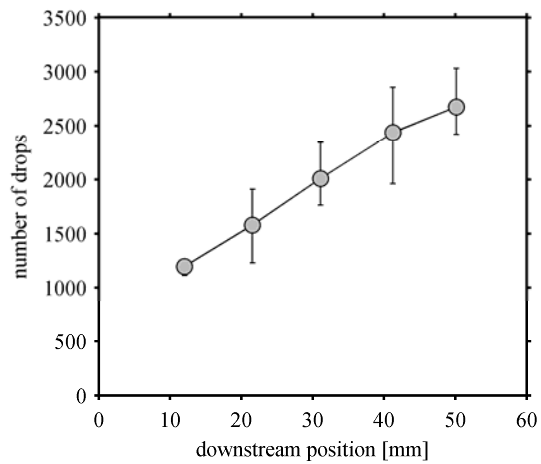
# Temporally resolved, 3D particle field

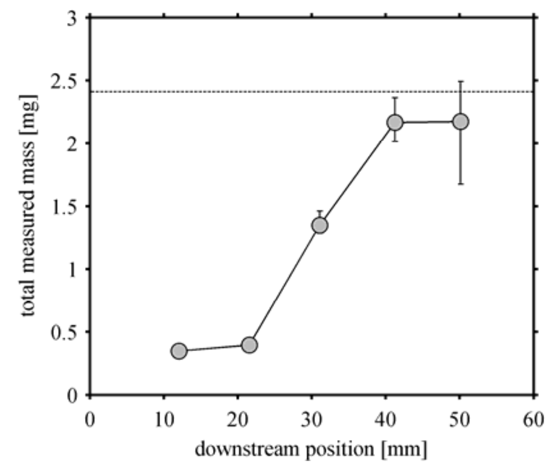
Data processing similar to drop impact experiment



# Multiple downstream fields of view

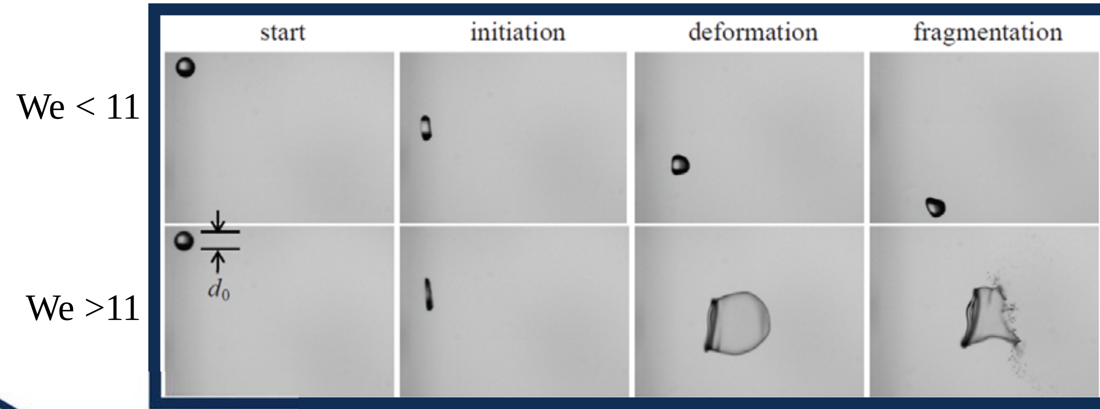



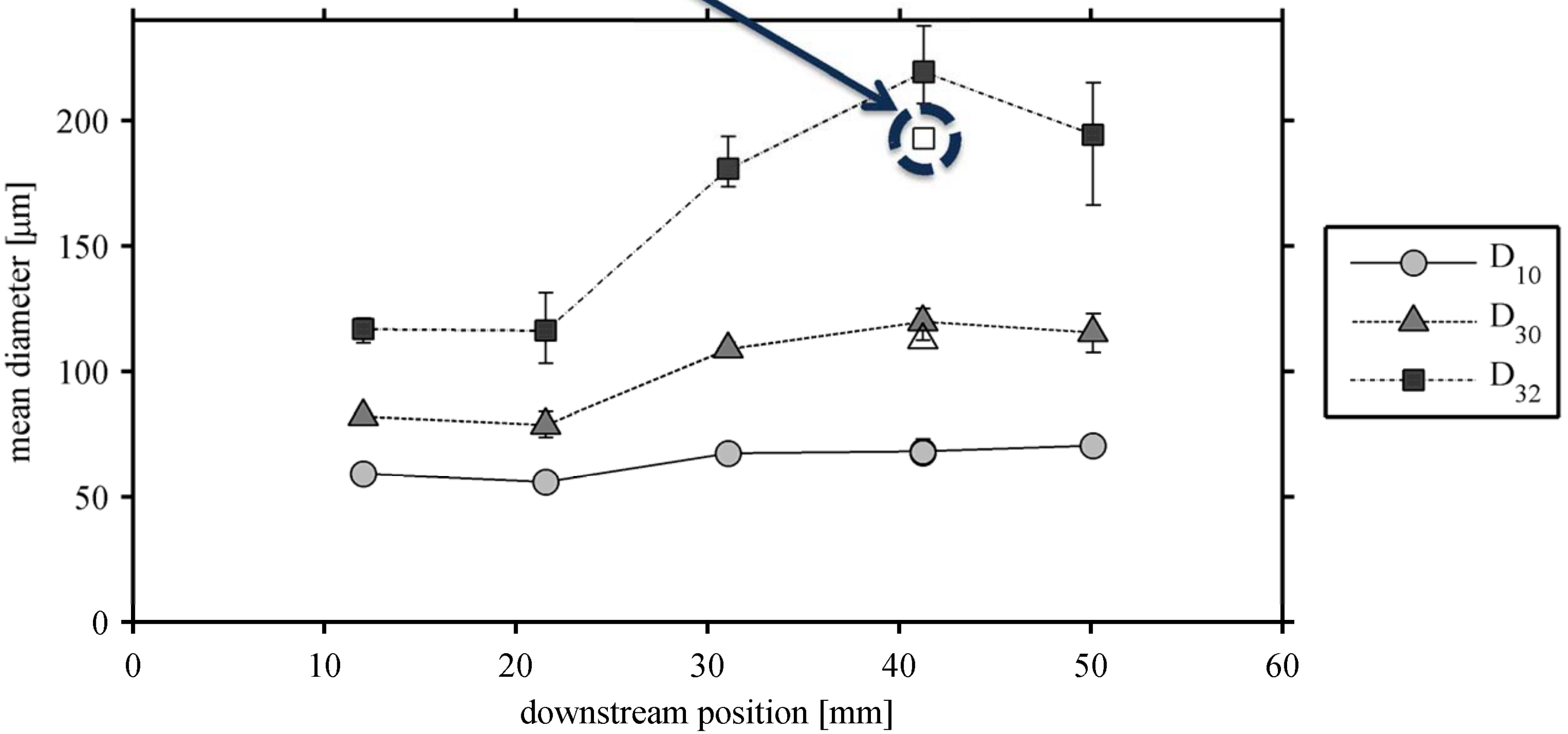



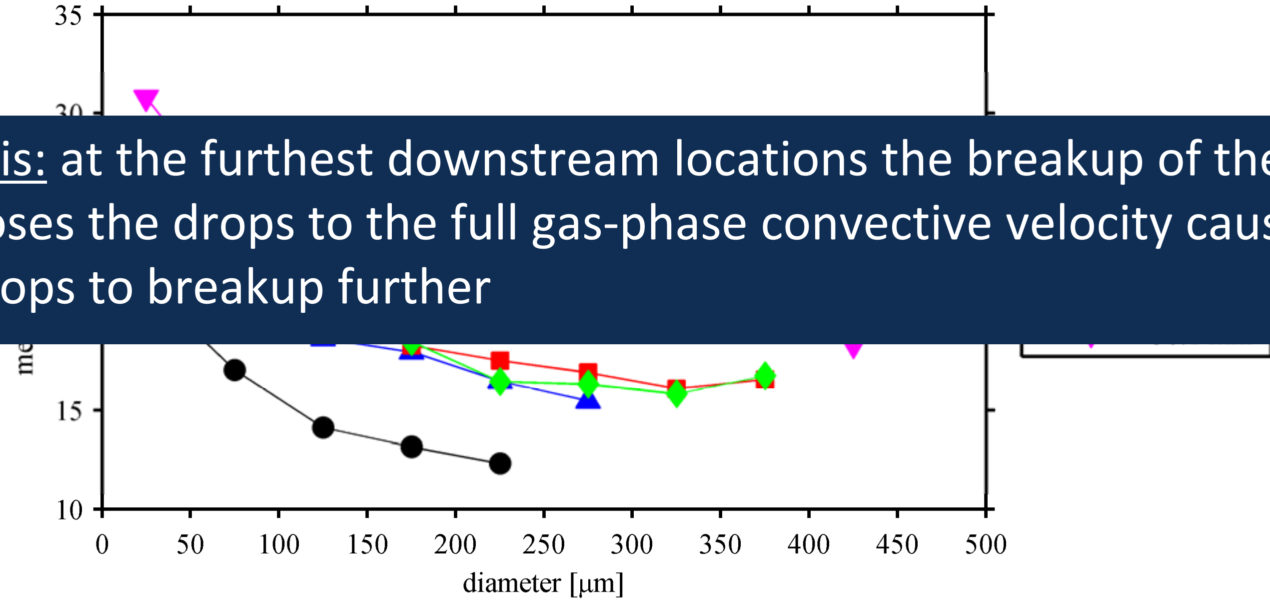
# Characteristic mean diameters

- Measured drops with relative *We*>11 are expected to be unstable and will break apart further
- Excluding drops with *We*>11 eliminates the unusual dip

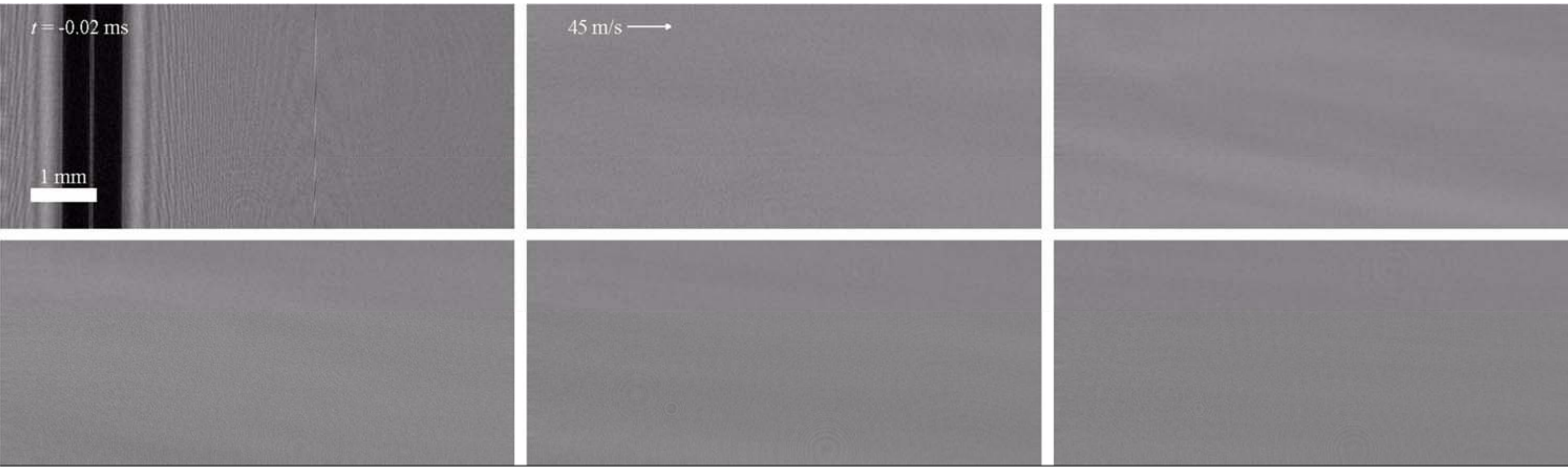


# Size-velocity correlations




Hypothesis: at the furthest downstream locations the breakup of the intact core exposes the drops to the full gas-phase convective velocity causing the largest drops to breakup further



# Conclusions

**100kHz digital in-line holography (DIH) enables detailed 3D, temporal characterization of fragment sizes and velocities very near the site of breakup**

Next steps:

- Investigate other flow conditions
- Leverage higher magnification FOV for improved size dynamic range
- Attempt to bound potential measurement biases

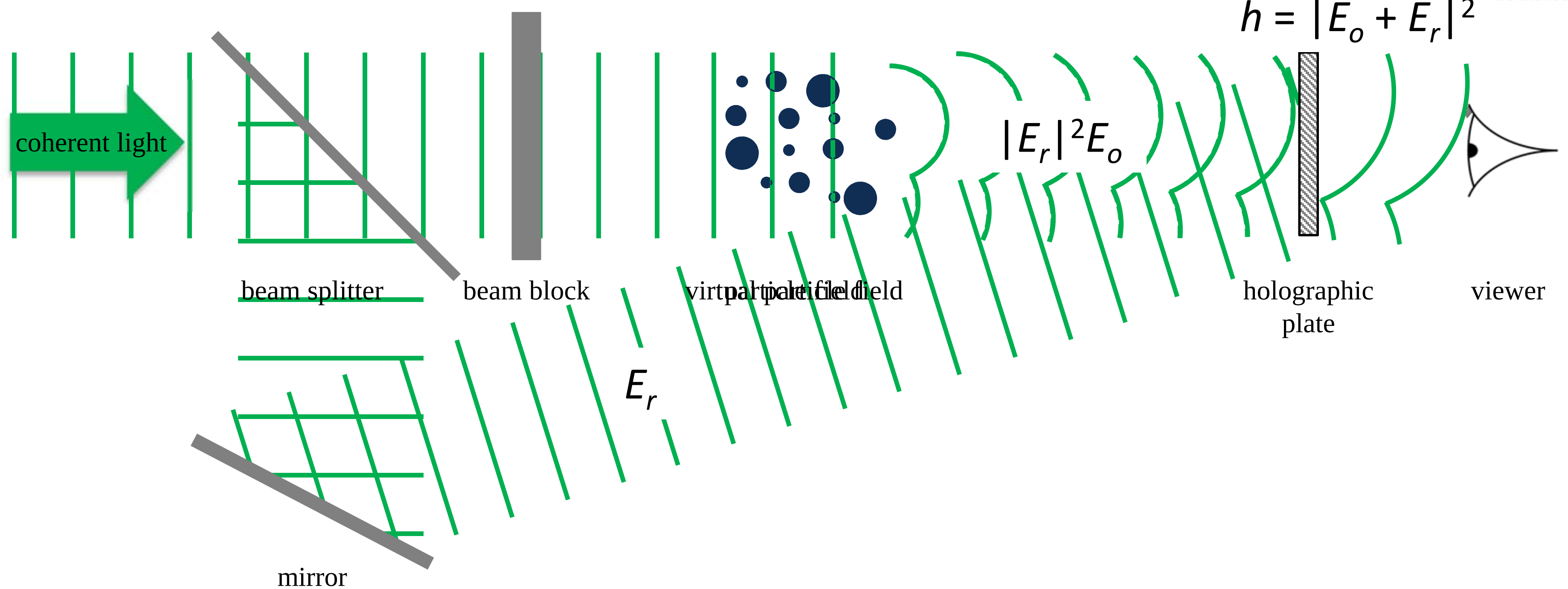
Acknowledgements:

This work was supported by the Laboratory Directed Research and Development and the Weapons Systems Engineering Assessment Technology program at Sandia National Laboratories (SNL)

**Questions**

# Backup slides

# What is holography?




Optical method first proposed by Gabor in 1948

1. Coherent light diffracted by particle field forms the object wave, $E_o$
2. Interference with a reference wave, $E_r$, forms the hologram: $h = |E_o+E_r|^2$
3. Reconstruction with $E_r$ forms virtual images at original particle locations

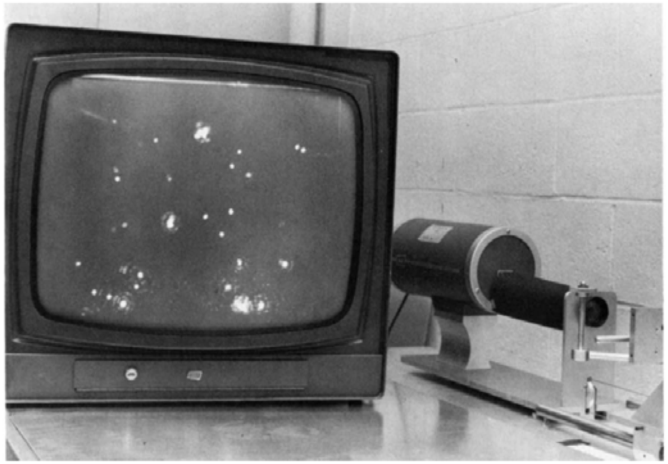
$$h \cdot E_r = \underbrace{(|E_o|^2 + |E_r|^2)E_r}_{\text{DC term}} + \underbrace{|E_r|^2 E_o}_{\text{virtual image}} + \underbrace{E_r^2 E_o^*}_{\text{real image}}$$

# Analog holography

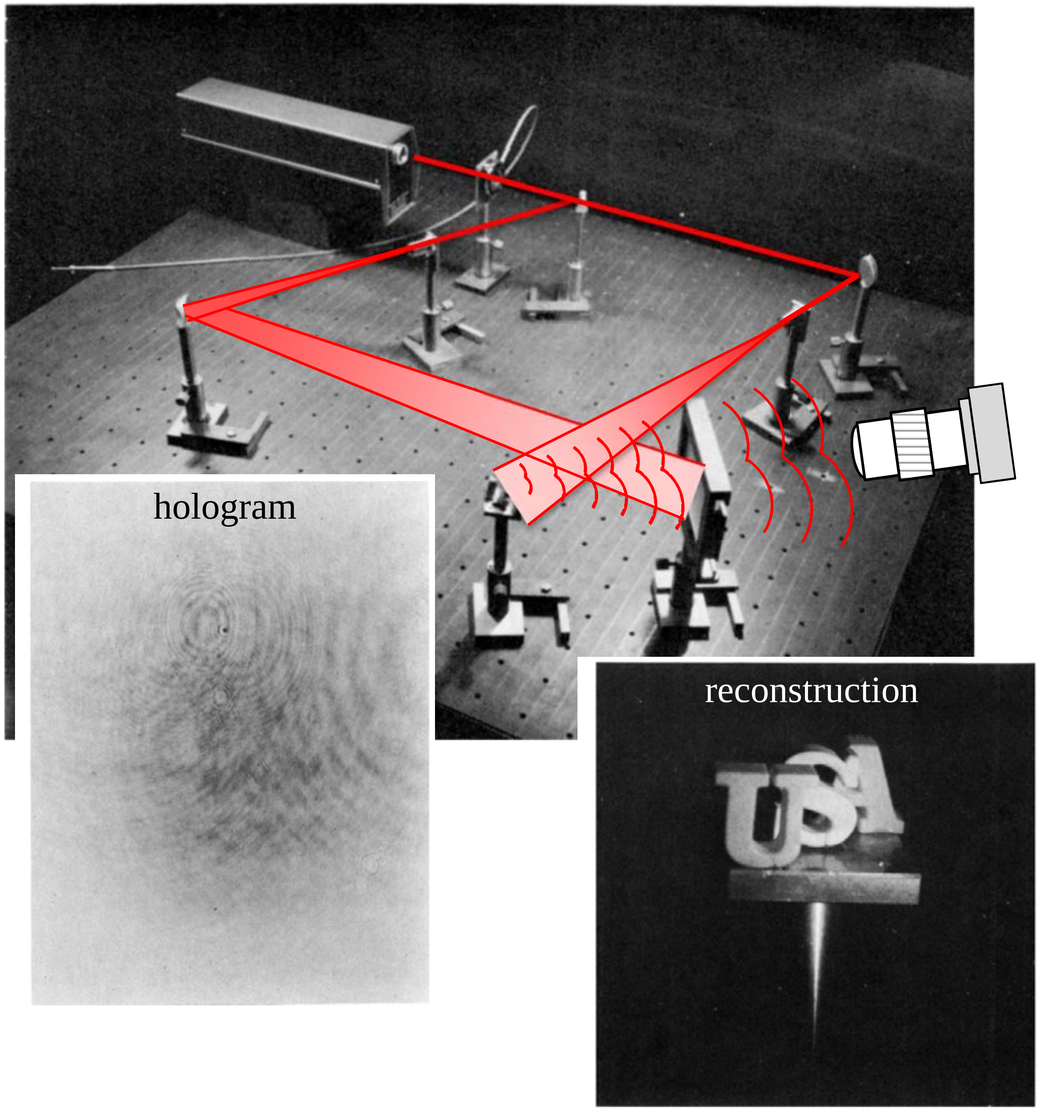
Applications of holography took off with invention of the laser in 1960

<u>Challenges:</u>

- Darkroom needed to process the hologram
- Limited temporal resolution
- Manual post processing

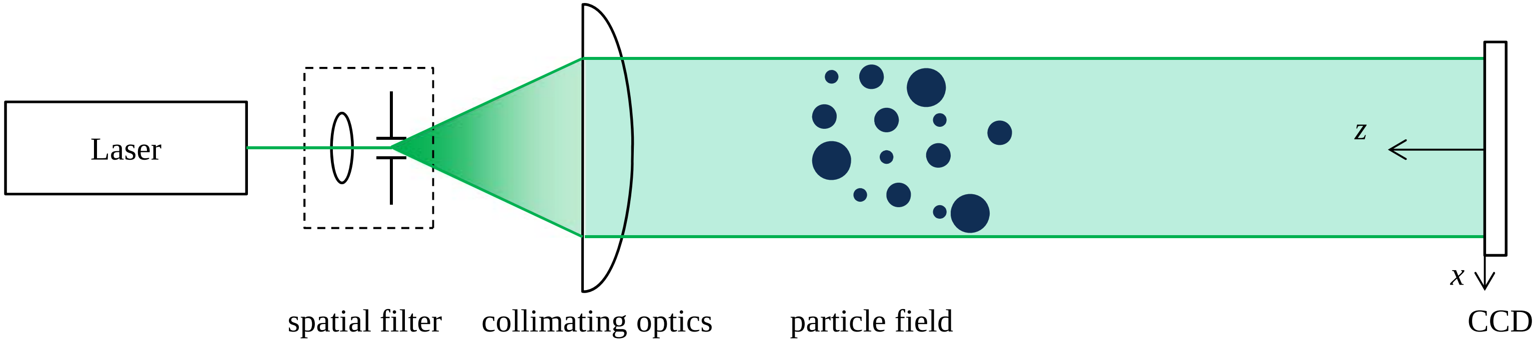


Thompson et al, 1967, *Appl. Opt.*




Collier et al, 1971, *Optical Holography*

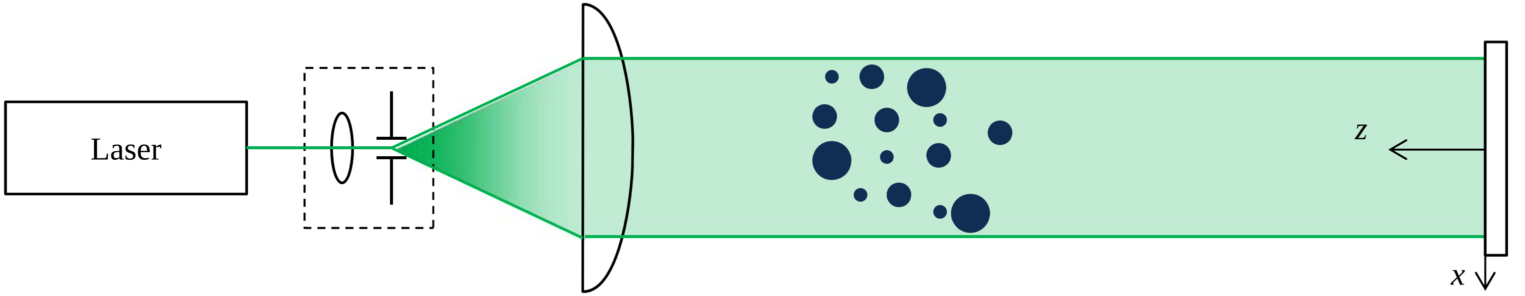
# Digital in-line holography (DIH)




Holographic plate and wet-chemical processing replaced with digital sensor

- First proposed by Schnars and Jüptner in ‘90s
- <u>Advantages:</u> (1) no darkroom, (2) temporal resolution is straight forward, (3) results can be numerically refocused and post-processed
- <u>Challenge:</u> Resolution of digital sensors (order 100 line pairs/mm) is much less than resolution of photographic emulsions (order 5,000 line pairs/mm)
  - For suitable off axis angles, $\theta$, the fringe frequency, $f$, is typically too large to resolve with digital sensors ($f = 2\sin(\theta/2)/\lambda$)
  - Rather, the in-line configuration ($\theta = 0$) is typically utilized

# Where is the reference wave?




Hologram is the combination of object and reference waves: $h = |E_o+E_r|^2$

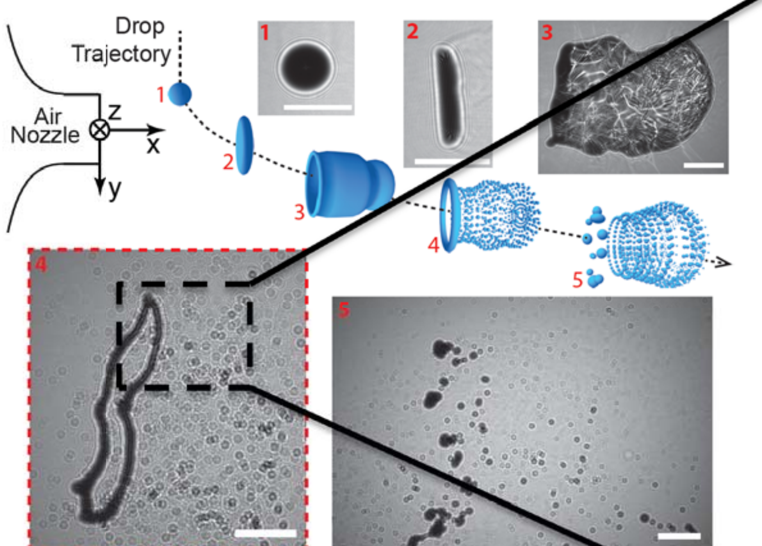
- Reconstruction with $E_r$ gives: $h \cdot E_r = \underbrace{(|E_o|^2 + |E_r|^2)E_r}_{\text{DC term}} + \underbrace{|E_r|^2 E_o}_{\text{virtual image}} + \underbrace{E_r^2 E_o^*}_{\text{real image}}$
  - In off-axis holography, these terms are spatially separated and we attempt to reconstruct the original object wave, $E_o$
- In in-line holography, we actually want to reconstruct the combination of the reference wave and object wave, $E_o+E_r$
  - Rearranging: $h \cdot E_r = \underbrace{|E_o|^2 E_r}_{\text{DC term}} + \underbrace{|E_r|^2(E_o+E_r)}_{\text{virtual image}} + \underbrace{E_r^2 E_o^*}_{\text{real image}}$

# Numerical refocusing

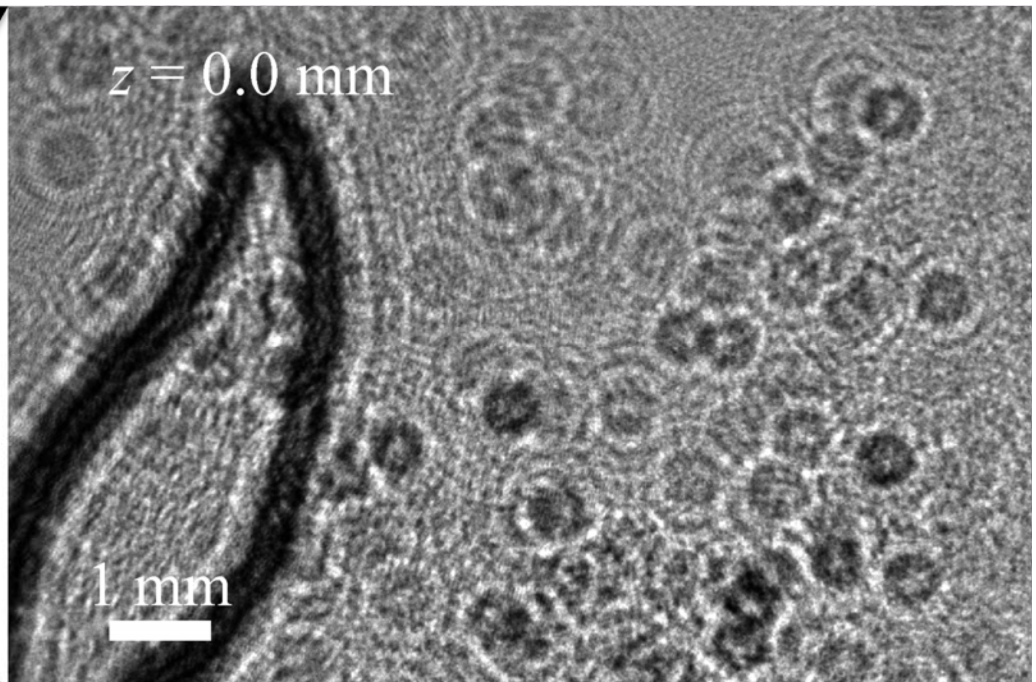
Light propagation in a non-absorbing, constant index of refraction medium is described by the diffraction integral equation:

$$E(x,y,z) = \frac{1}{\lambda}\iint E(\xi,\eta,z=0)\frac{e^{-jkr}}{r}d\xi d\eta \quad \text{where: } r = \sqrt{(\xi - x)^2 + (\eta - y)^2 + z^2}$$

- $E(\xi,\eta,0)$ ≡ complex amplitude at hologram plane = $h(\xi,\eta)\cdot E_r^*$
- $E(x,y,z)$ ≡ refocused complex amplitude at optical depth $z$




digital holograms of the breakup of an ethanol drop in an air-stream (Gao, Guildenbecher et al 2013, *Opt. Lett.*)




reconstructed amplitude at depth, $z$
recorded hologram: $h(\xi,\eta)$