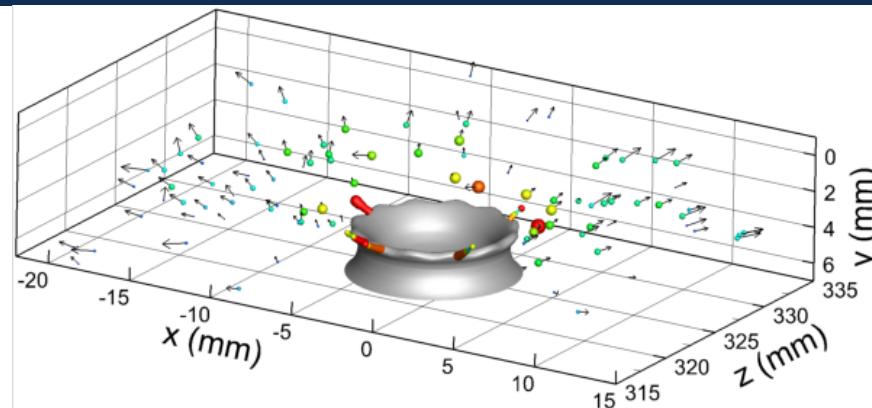
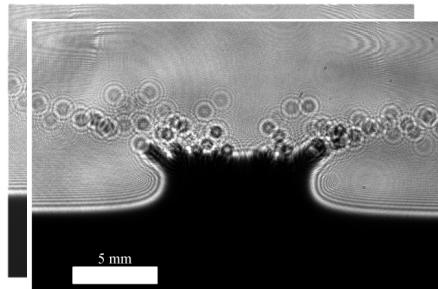


*Exceptional service in the national interest*



# Digital In-line Holography (DIH) for 3D Quantification of Inert and Reacting Particle Fields

Daniel R. Guildenbecher  
May 19, 2015

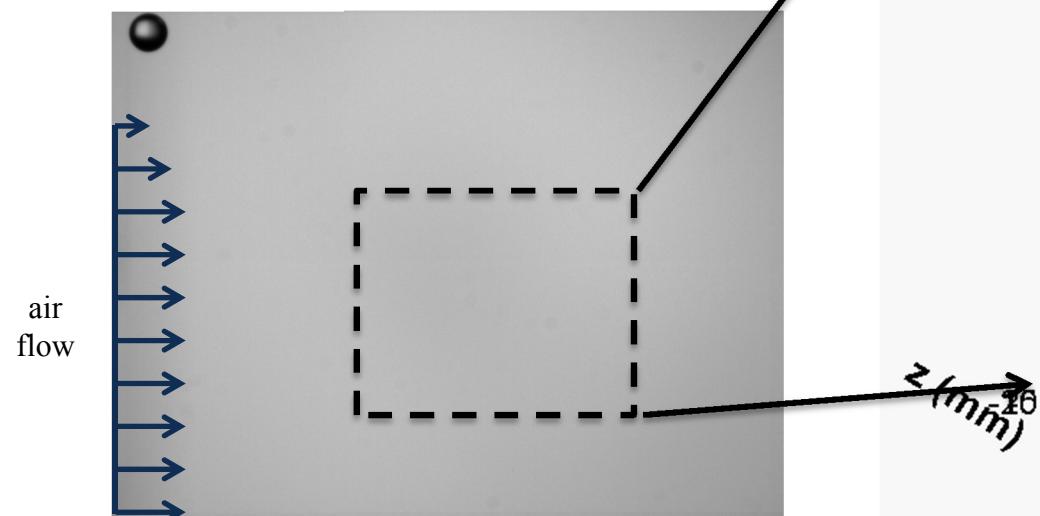


Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

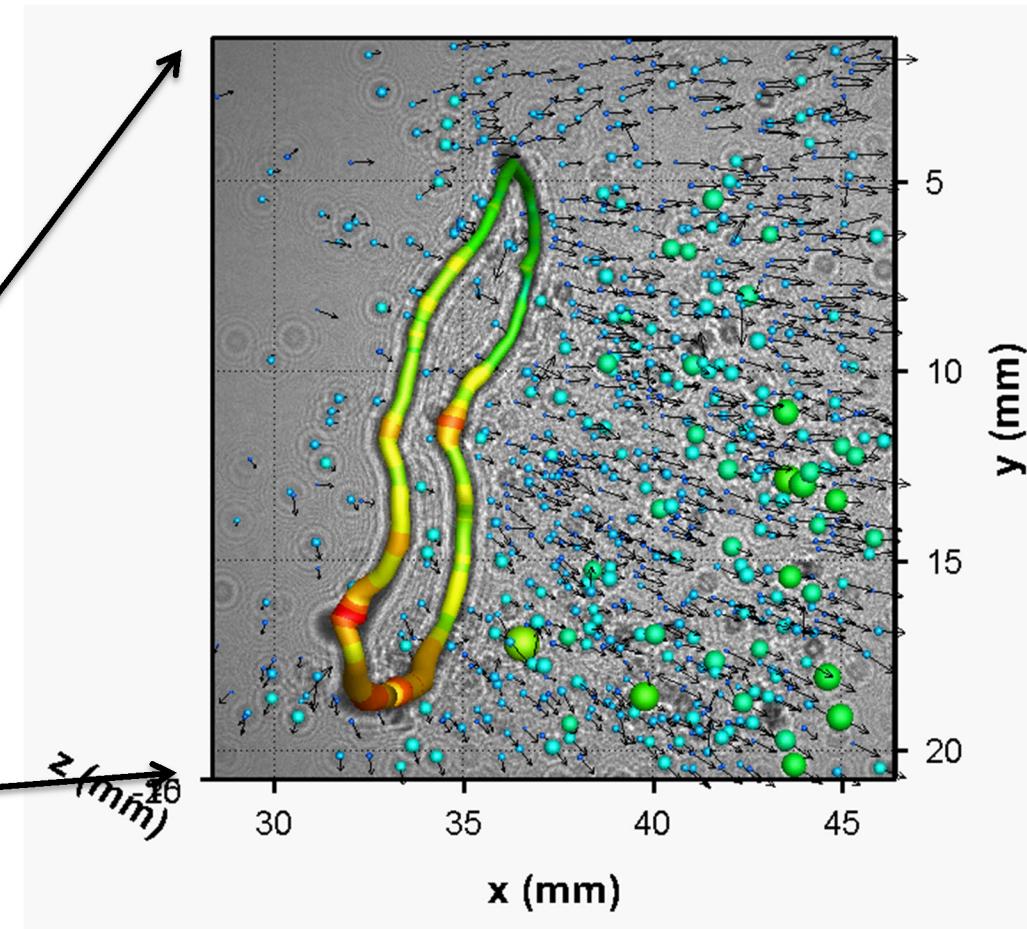
# Motivation: 3D imaging for a 3D world

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 an ethanol drop in an air-stream

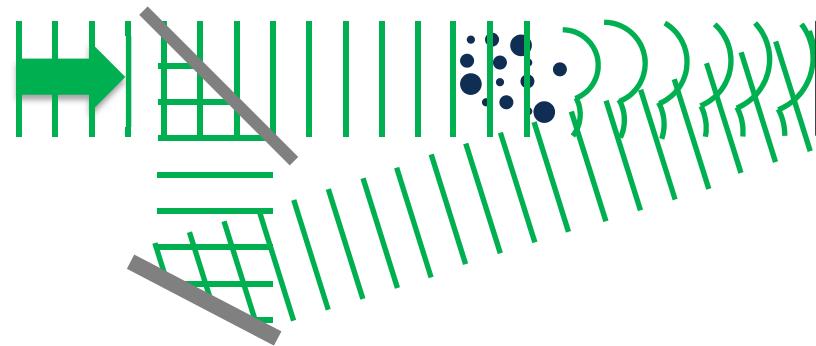


digital holographic measurement  
(Gao, Guildenbecher et al, 2013, *Opt. Lett.*)

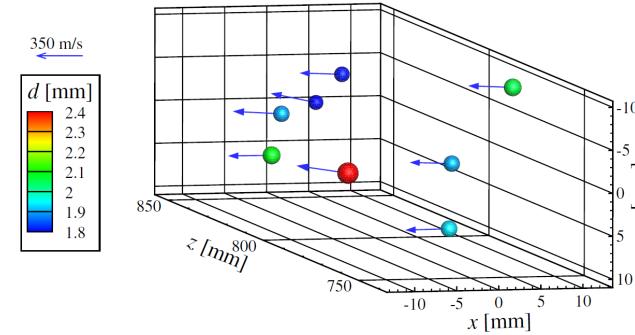
**Holography is an optical technique to record and reconstruct a 3D light field**

# Outline for talk

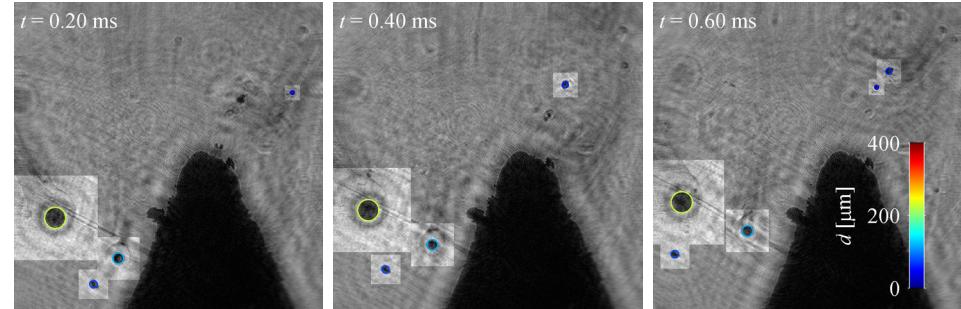
Introduction to holography and the “digital revolution”



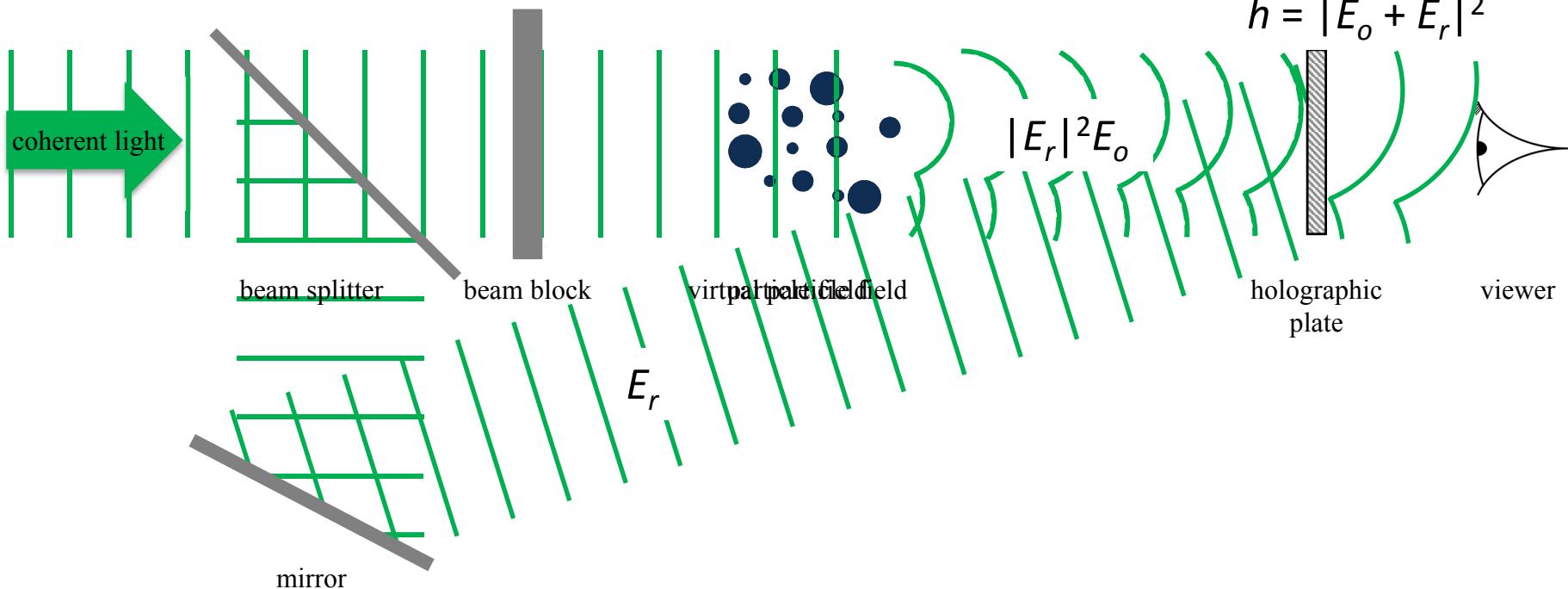
Particle measurements



Recent advancements



# 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

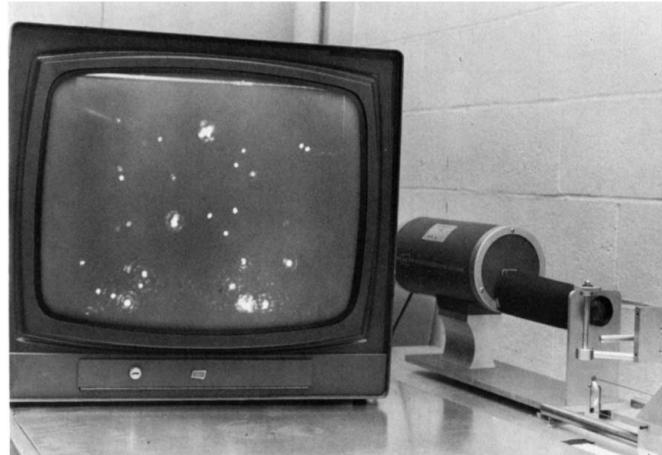
$$h \cdot E_r = \underbrace{(|E_o|^2 + |E_r|^2)E_r}_{\text{DC term}} + \underbrace{|E_r|^2 E_o}_{\text{virtual image}} + \underbrace{E_r^2 E_o^*}_{\text{real image}}$$

# Analog holography

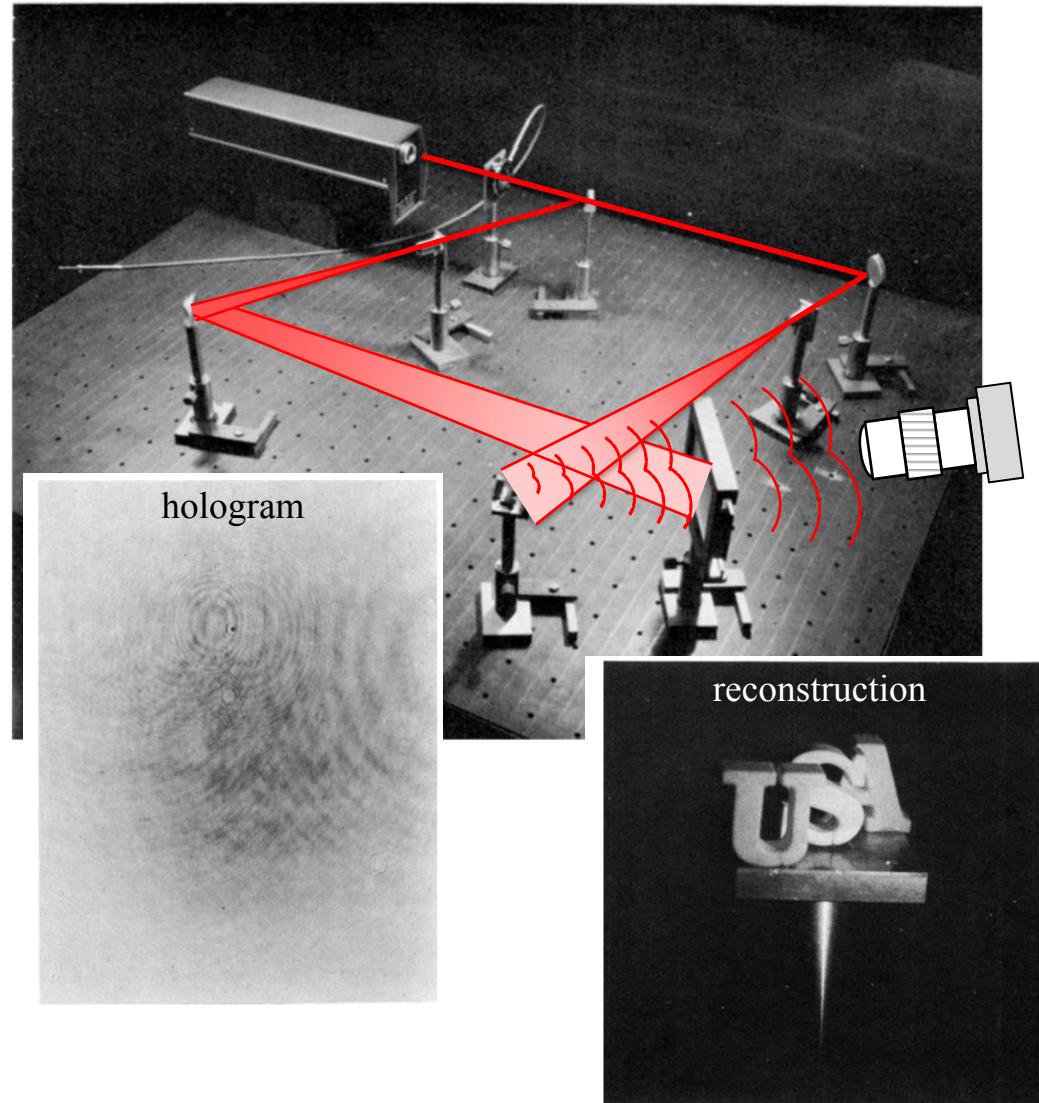
Applications of holography took off with invention of the laser in 1960

## Challenges:

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

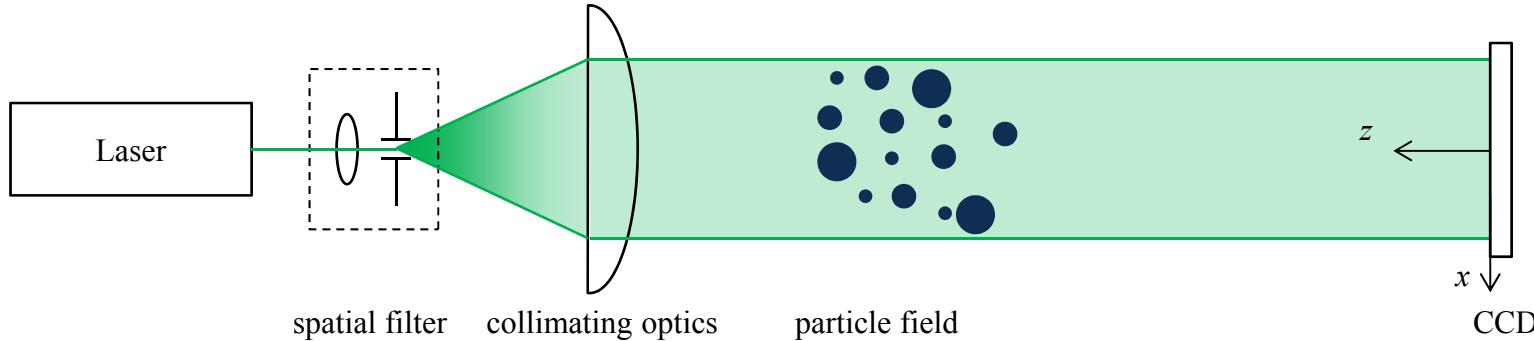


Thompson et al, 1967, *Appl. Opt.*



Collier et al, 1971, *Optical Holography*

# Digital in-line holography (DIH)



Holographic plate and wet-chemical processing replaced with digital sensor

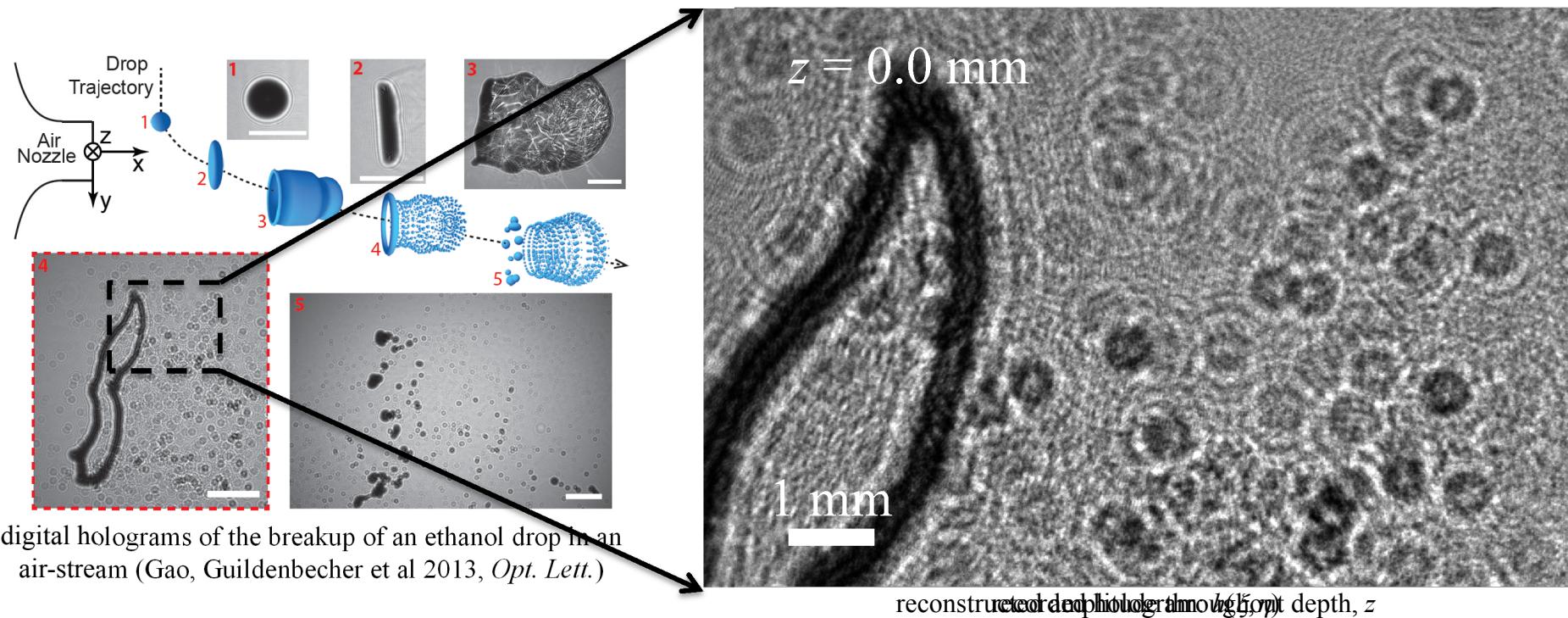
- First proposed by Schnars and Jüptner in '90s
- Advantages: (1) no darkroom, (2) temporal resolution is straight forward, (3) results can be numerically refocused and post-processed
- Challenge: Resolution of digital sensors (order 100 line pairs/mm) is much less than resolution of photographic emulsions (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

# Numerical refocusing

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

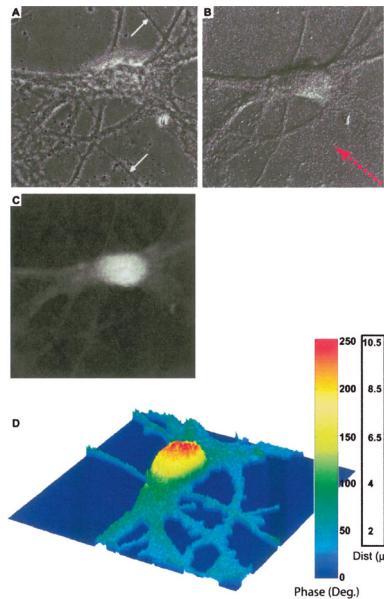
$$E(x, y, z) = \frac{1}{\lambda} \iint E(\xi, \eta, z=0) \frac{e^{-jkr}}{r} d\xi d\eta \quad \text{where: } r = \sqrt{(\xi - x)^2 + (\eta - y)^2 + z^2}$$

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



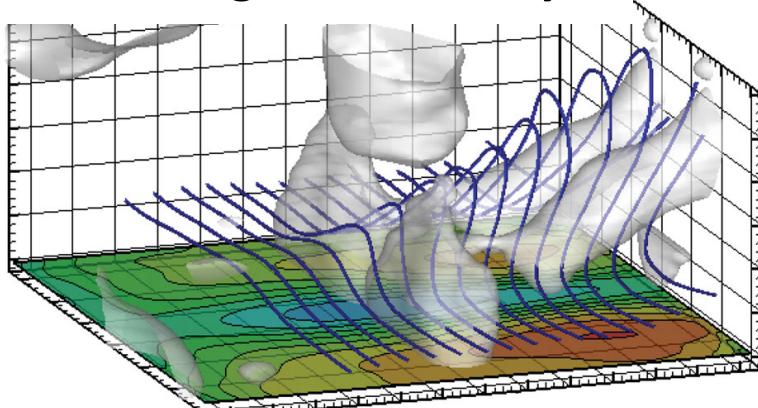
# DIH in the literature

## Microscopy



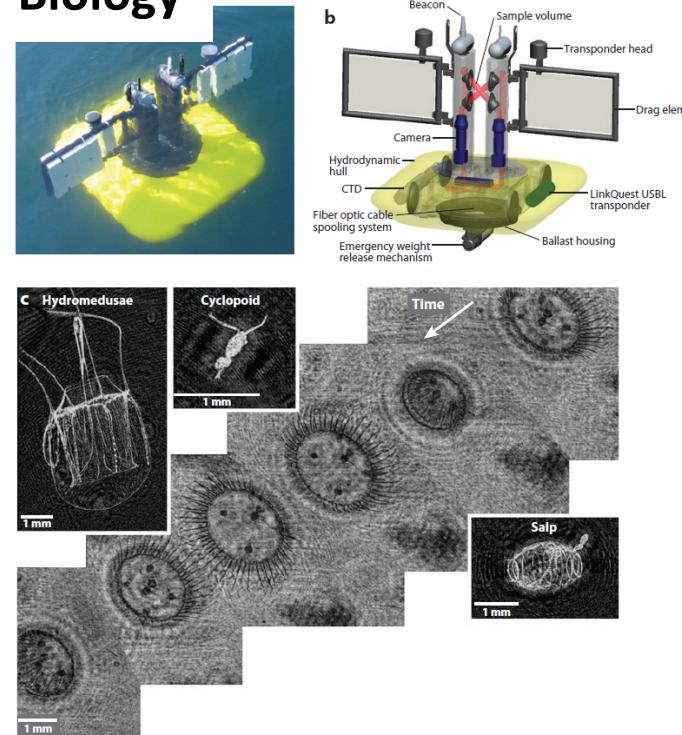
Marquet et al 2005, *Opt. Lett.*

## Particle Image Velocimetry



Sheng et al 2009, *J. Fluid Mech.*

## Biology

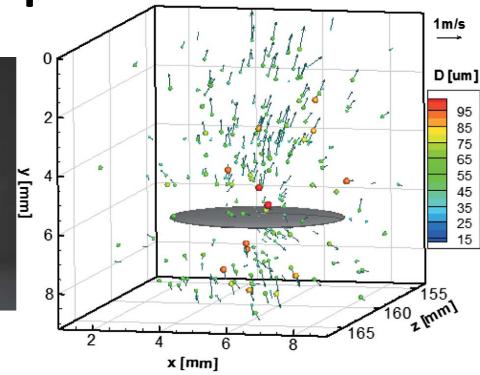


Katz and Sheng 2010, *Annu. Rev. Fluid Mech.*

## Multiphase Flows



Yao et al 2015, *Appl Opt.*



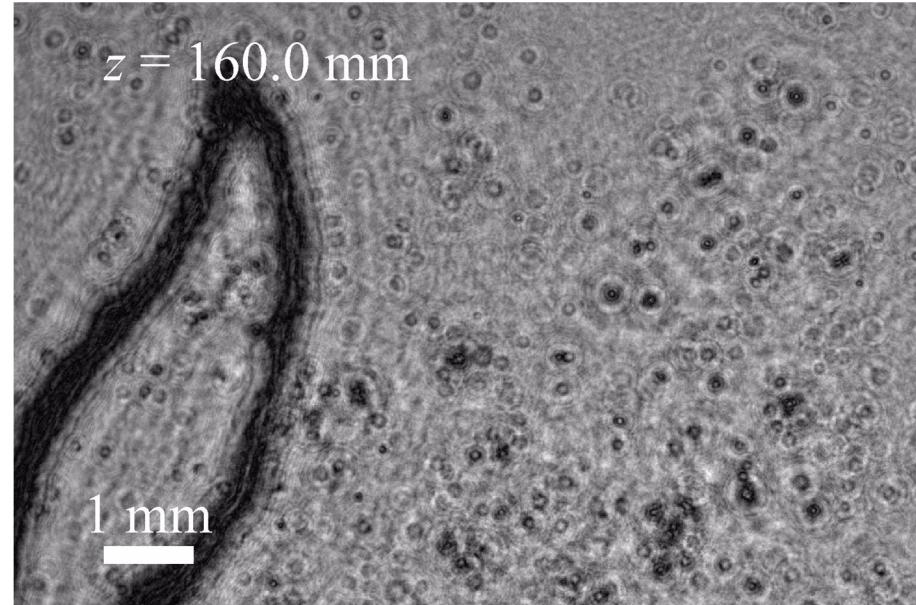
# Particle measurements

# Data processing

Acquisition and refocusing of a digital hologram is relatively straightforward.

However...

For quantitative measurements, methods are required to locate and measure particles.



## Challenge: 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  $\rightarrow \Omega \approx 2\lambda/d$
- Using the traditional definition of depth-of-focus,  $\delta$ , based on change of intensity within the particle center  $\rightarrow \delta \approx 4\lambda/\Omega^2$
- Therefore: for in-line holography,  $\delta \approx d^2/\lambda$ 
  - Example:  $d = 300 \mu\text{m}$ ,  $\lambda = 532 \text{ nm} \rightarrow \delta \approx 170 \text{ mm}!$

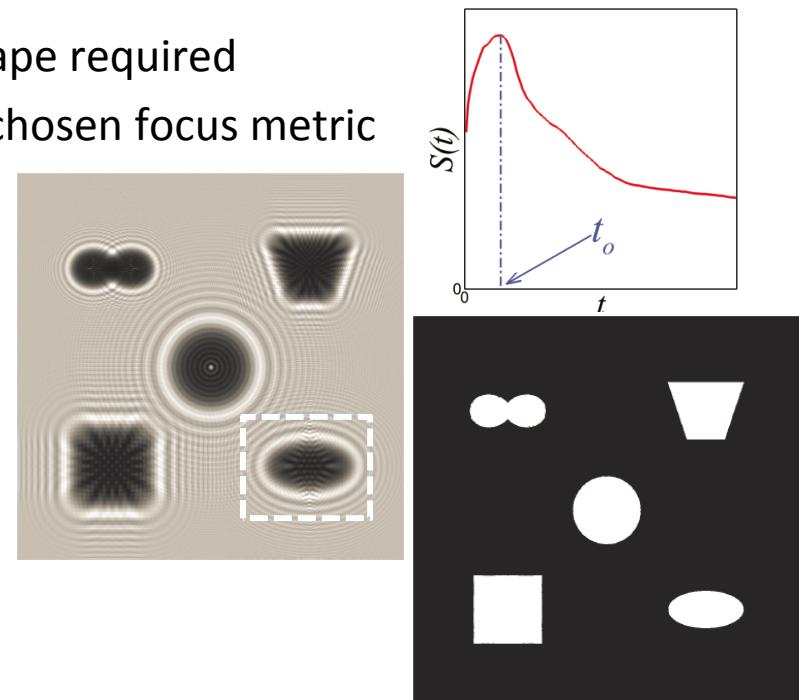
# Data processing

Literature contains two basic methods to find the focal plane:

1. Fit a model to the observed diffraction patterns (inverse method)
  - Generally accurate with small depth uncertainty
  - Limited to objects with known diffraction patterns (spheres)
2. Reconstruct the amplitude (or intensity) throughout depth and apply a focus metric to find “in-focus” objects
  - No *a-priori* knowledge of particle shape required
  - Accuracy is a strong function of the chosen focus metric

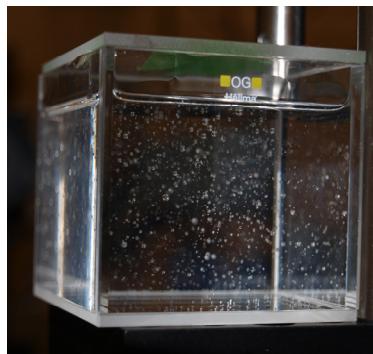
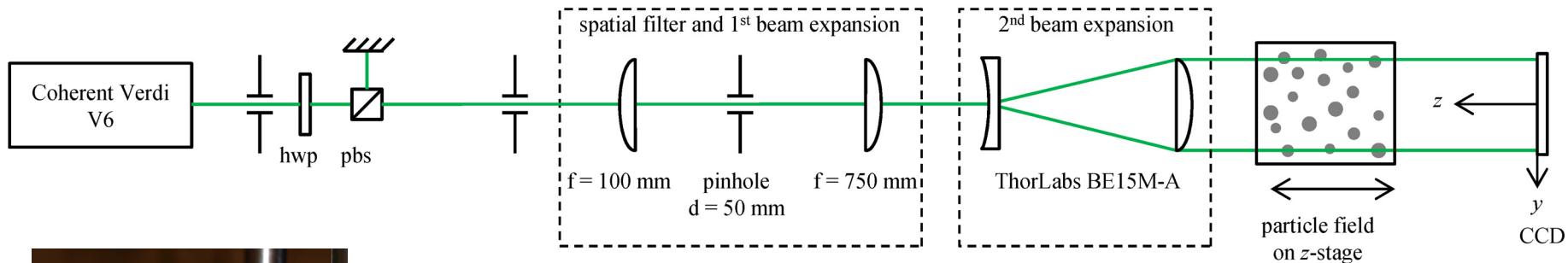
Hybrid method:

- Focus metric is a combination of amplitude minimization and edge sharpness maximization
  - Details in Guildenbecher et al 2013, *Appl. Opt.*; Gao et al 2013, *Opt. Express*; Gao et al 2014, *Appl. Opt.*



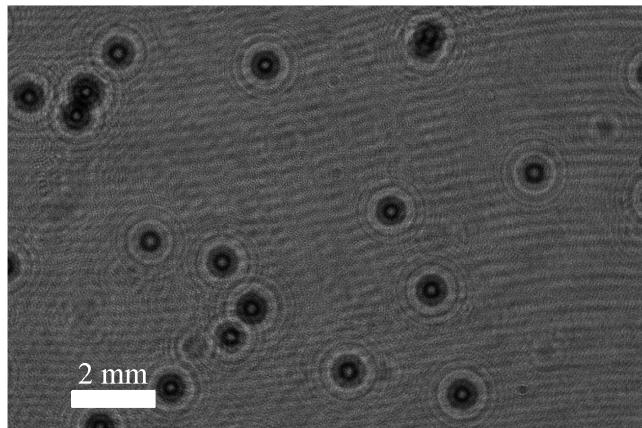
Gao et al 2014, *Appl. Opt.*

# Experimental validation

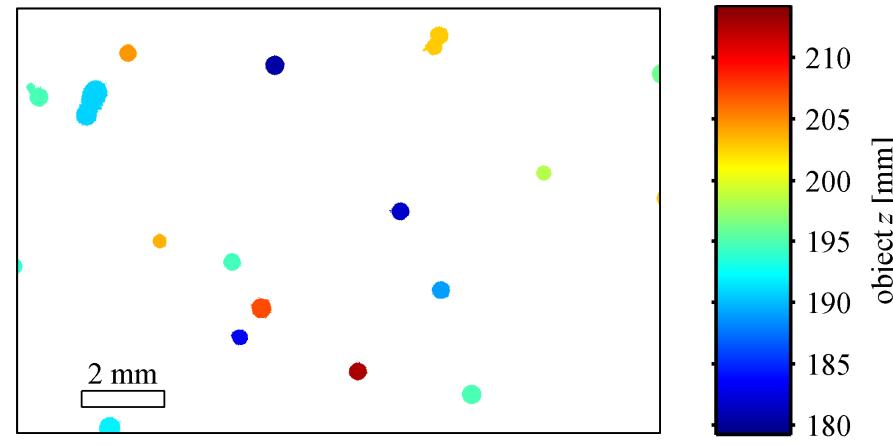


particle field

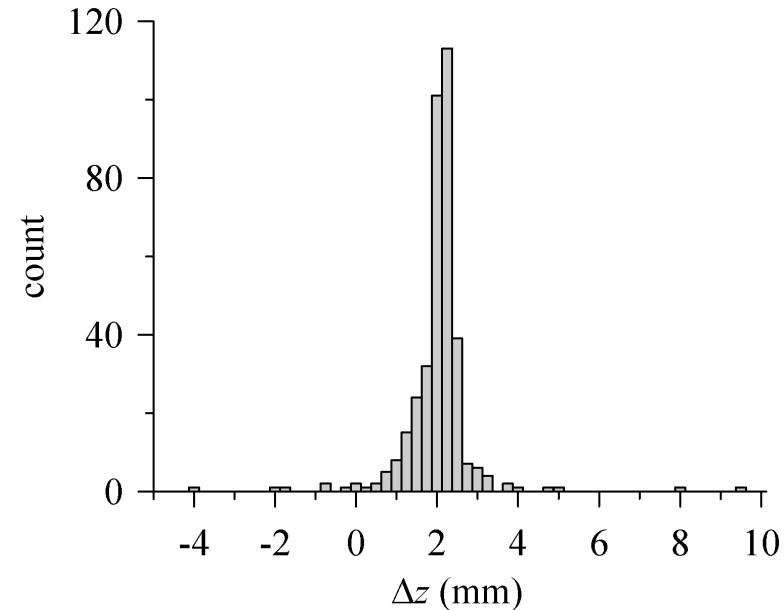
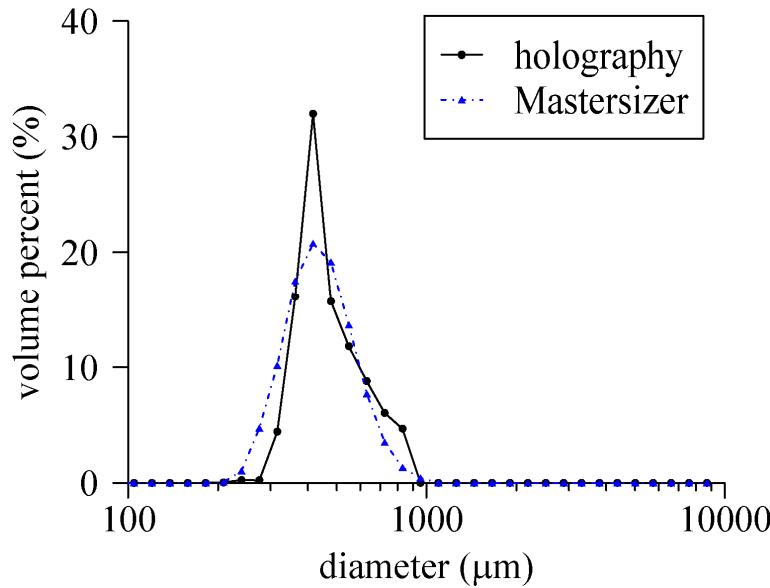
- Quasi-stationary particle field
  - Polystyrene beads ( $\bar{d} \approx 465 \mu\text{m}$ ) in 10,000 cSt silicone oil
  - Settling velocity  $\approx 0.8 \mu\text{m/s}$
- Multiple holograms recorded, displacing the particle field 2 mm in the z-direction between each acquisition



hologram



# Experimental validation



Diameter measured from area of the detected 2D morphology

- Actual mass median diameter = 465  $\mu\text{m}$
- Measured mass median diameter = 474  $\mu\text{m}$ 
  - Error of 2.0% with respect to actual value

Displacement found by particle matching between successive holograms

- Actual displacement = 2.0 mm
- Mean detected displacement = 1.91 mm  $\pm$  0.81 mm
- Standard deviation of 1.74 times mean diameter

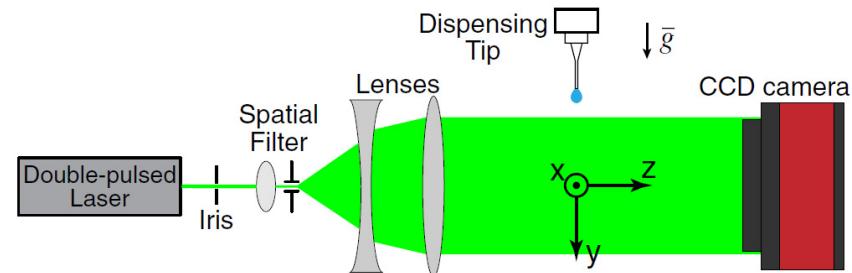
# Aerodynamic drop fragmentation

Experimental configuration: Double-pulsed laser and imaging hardware as typically used in PIV

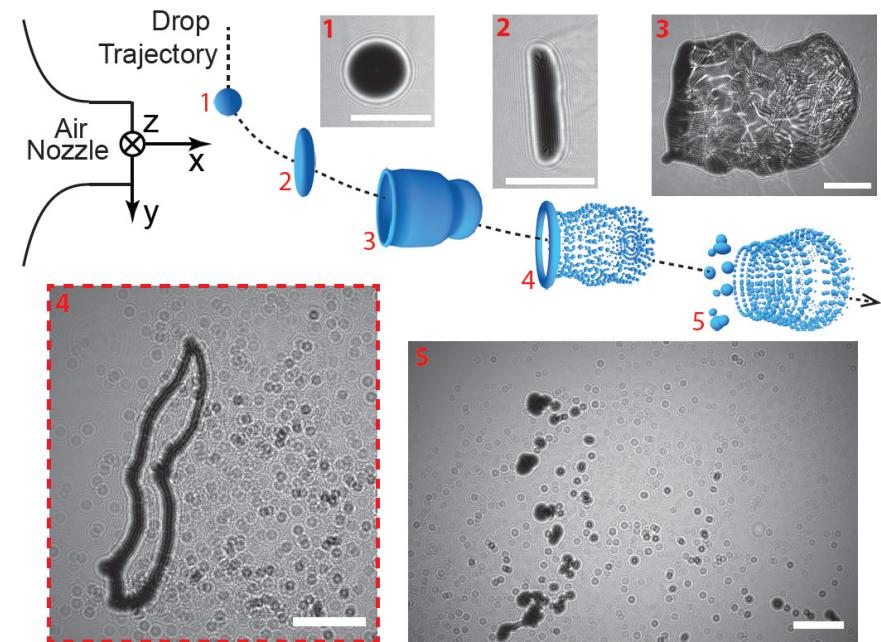
- $\lambda = 532 \text{ nm}$ , 5 ns pulselength
- Interline transfer CCD ( $4008 \times 2672$ , 9  $\mu\text{m}$  pixel pitch)
- Temporal separation,  $\Delta t = 62 \mu\text{s}$ , determined by laser timing

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

- Expensive injection seeders are not always needed
- Faster lasers (ps or fs) can be used with some advantages (e.g. Nicolas et al 2007, *Opt. Express*)



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

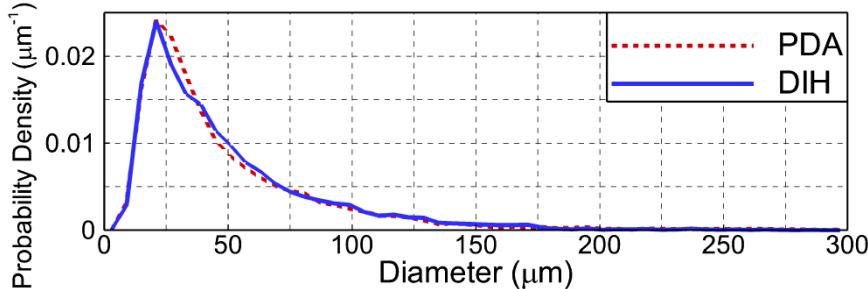


digital holograms of the breakup of an ethanol drop in an air-stream (Gao, Guildenbecher et al 2013, *Opt. Lett.*)

# Aerodynamic drop fragmentation

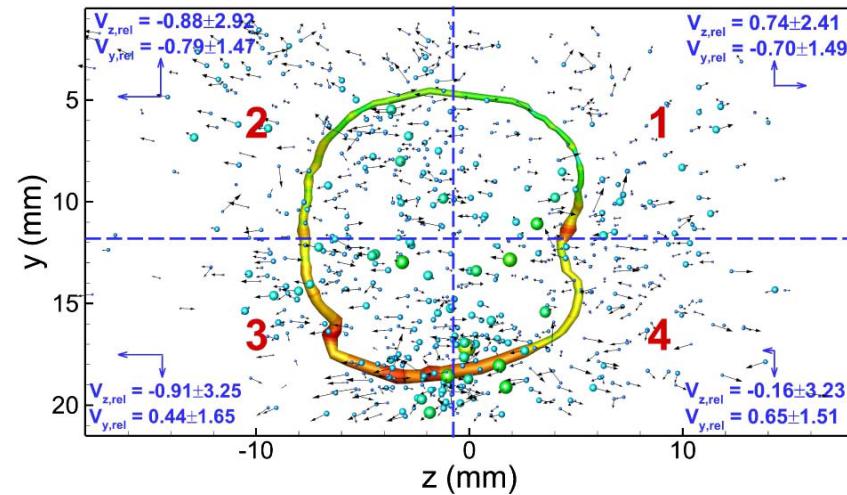
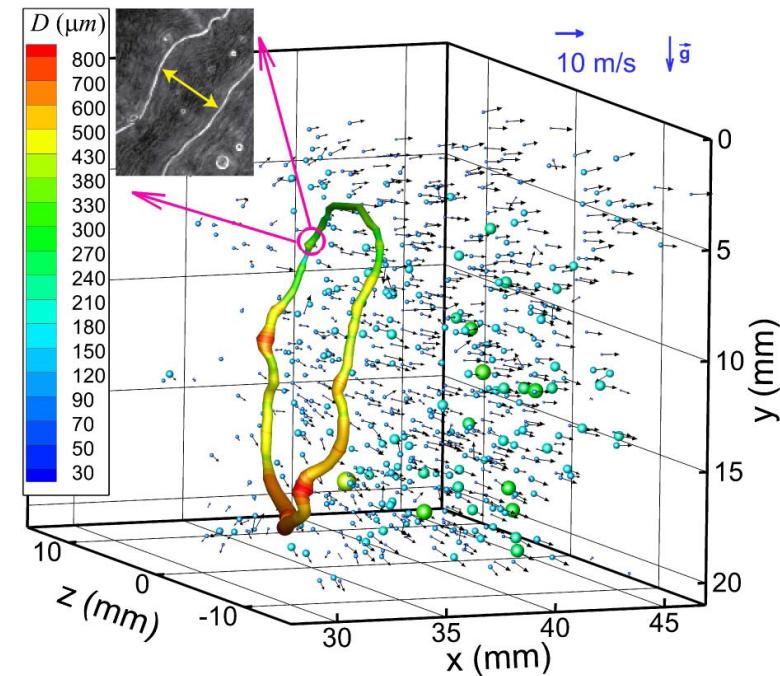
Secondary drop sizes/positions extracted by the hybrid method

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



Ring measured from z-location of maximum image gradient

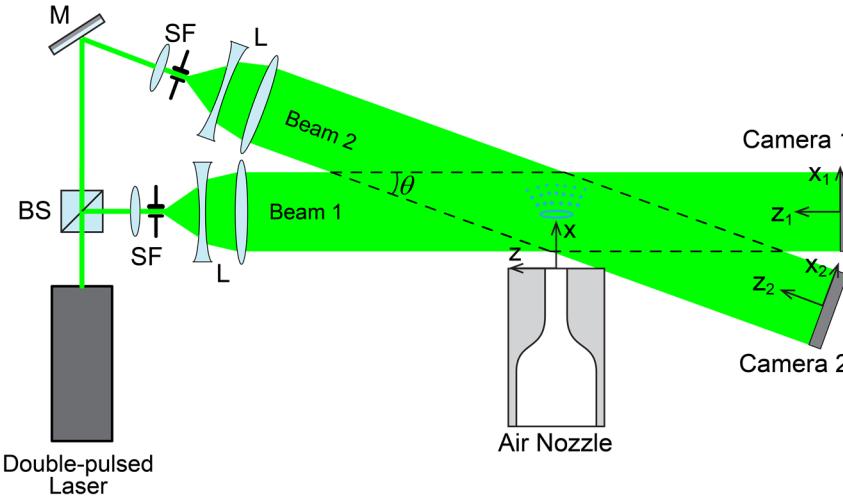
- Total volume of ring + secondary drops is within 2.2% of the initial volume



# Aerodynamic drop fragmentation

Velocimetry suffers from uncertainty in the out-of-plane (z) position

- A stereo-view configuration is one solution

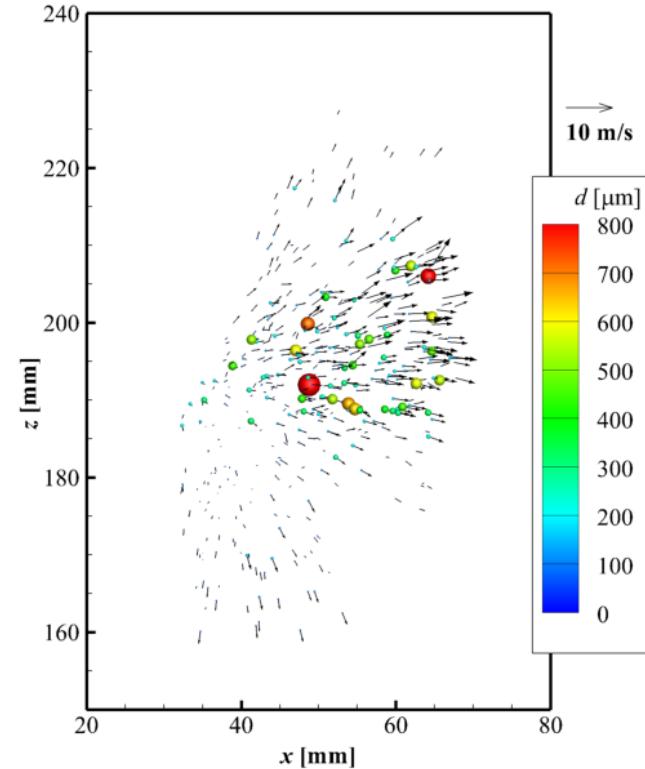
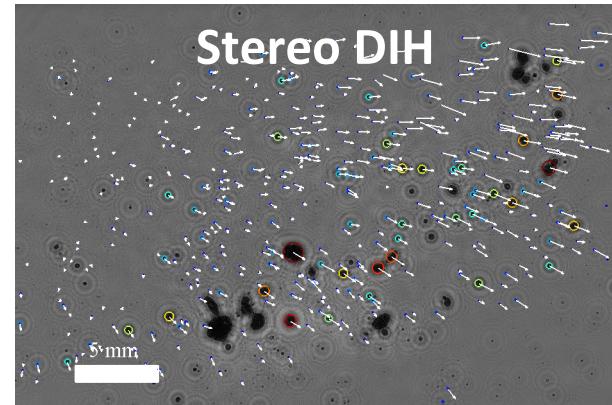


## Advantages:

- Improved z-uncertainty
- Eliminates false particle size and position measurements

## Challenges:

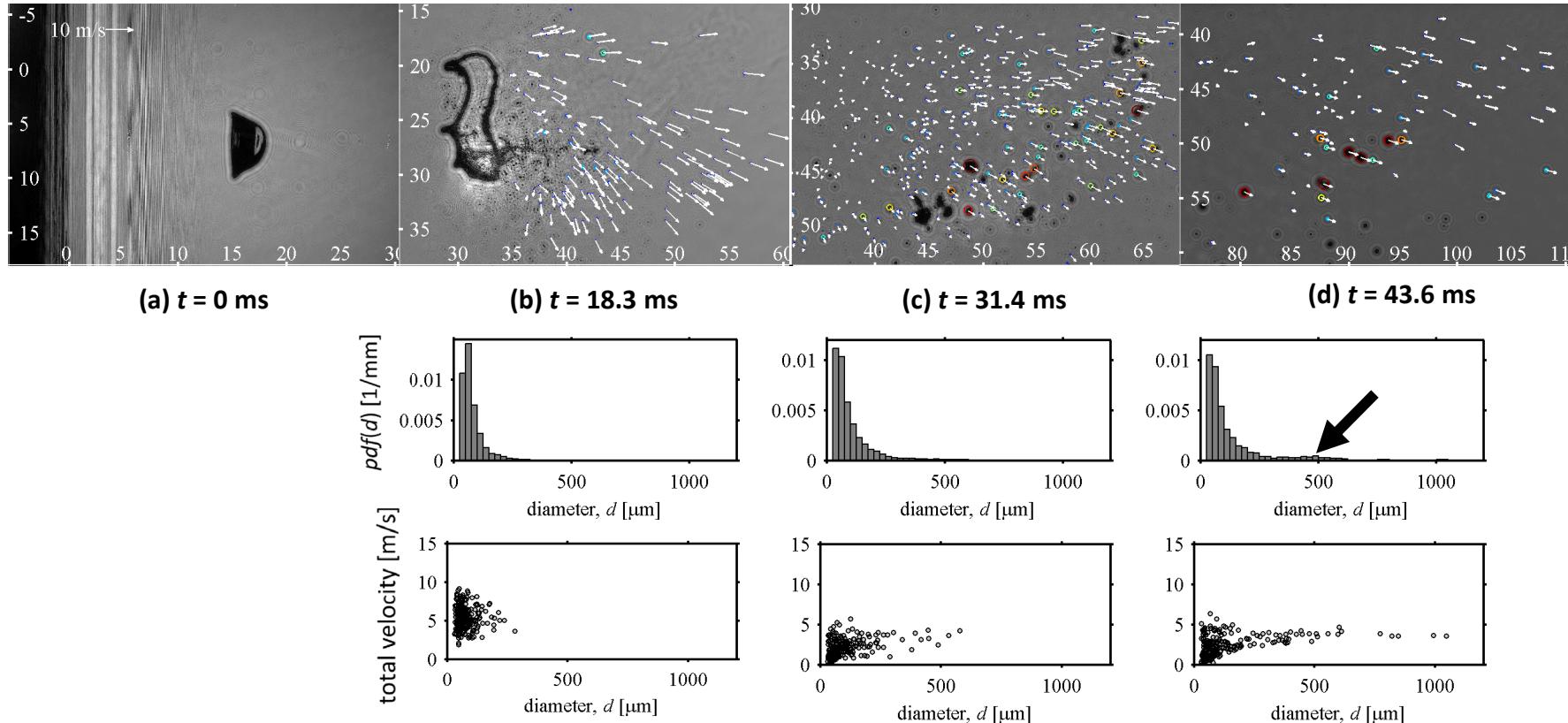
- Increased experimental complexity
- Careful calibration required



# Aerodynamic drop fragmentation

Ensemble averaging of 44 realizations at each condition

- Roughly 10,000 individual drops measured per condition



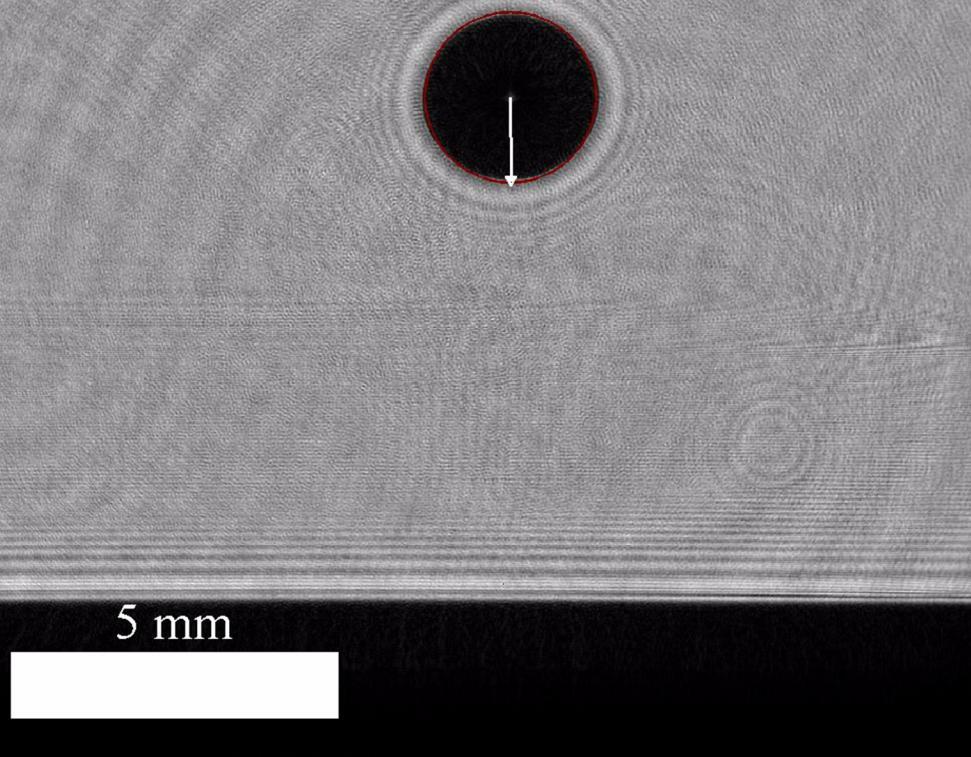
DIH is particularly advantageous for rapid quantification of particle statistics

# New concepts and opportunities

# High-speed (kHz) DIH

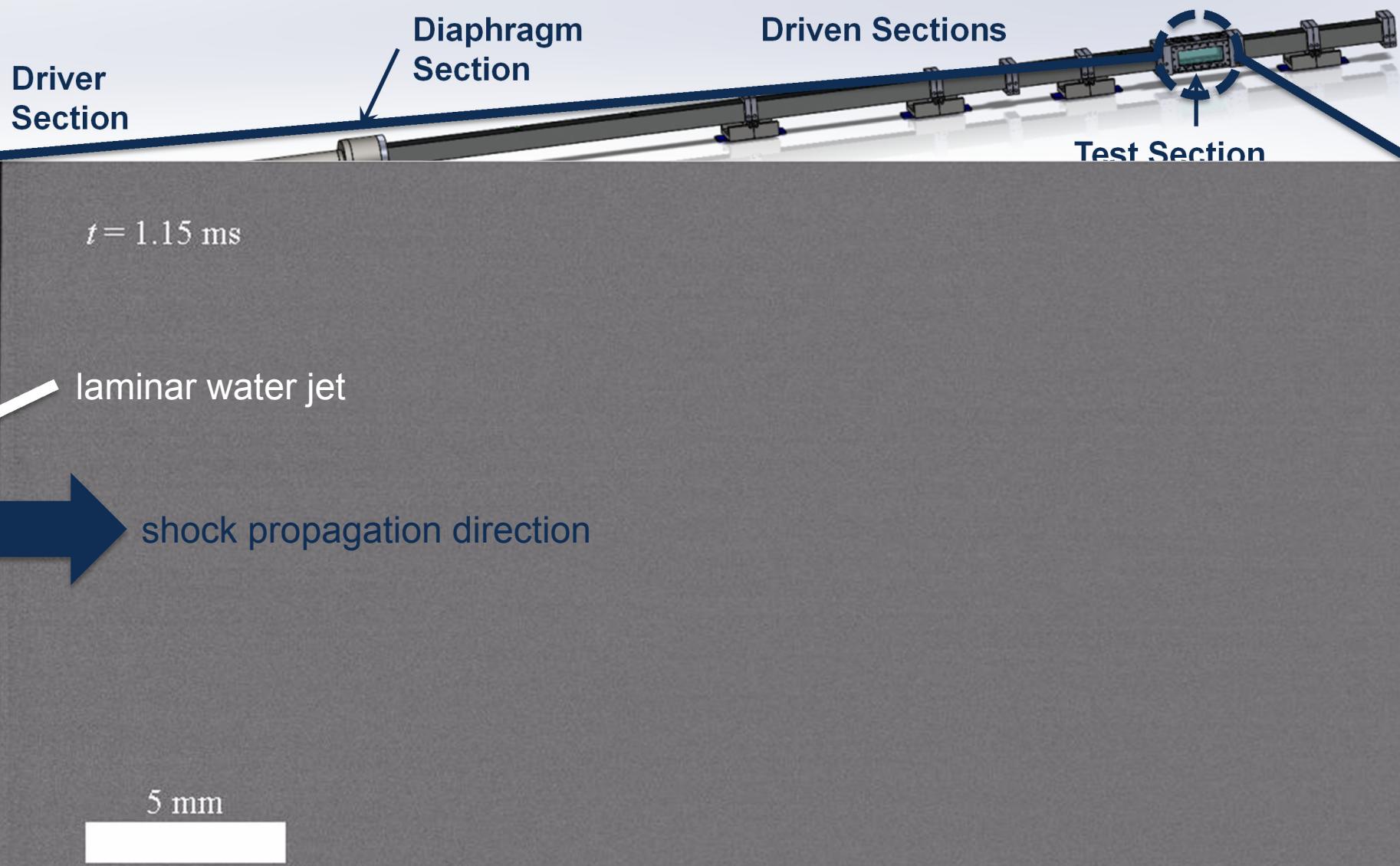
$$t - t_0 = -1.65 \text{ ms}$$

5 m/s →

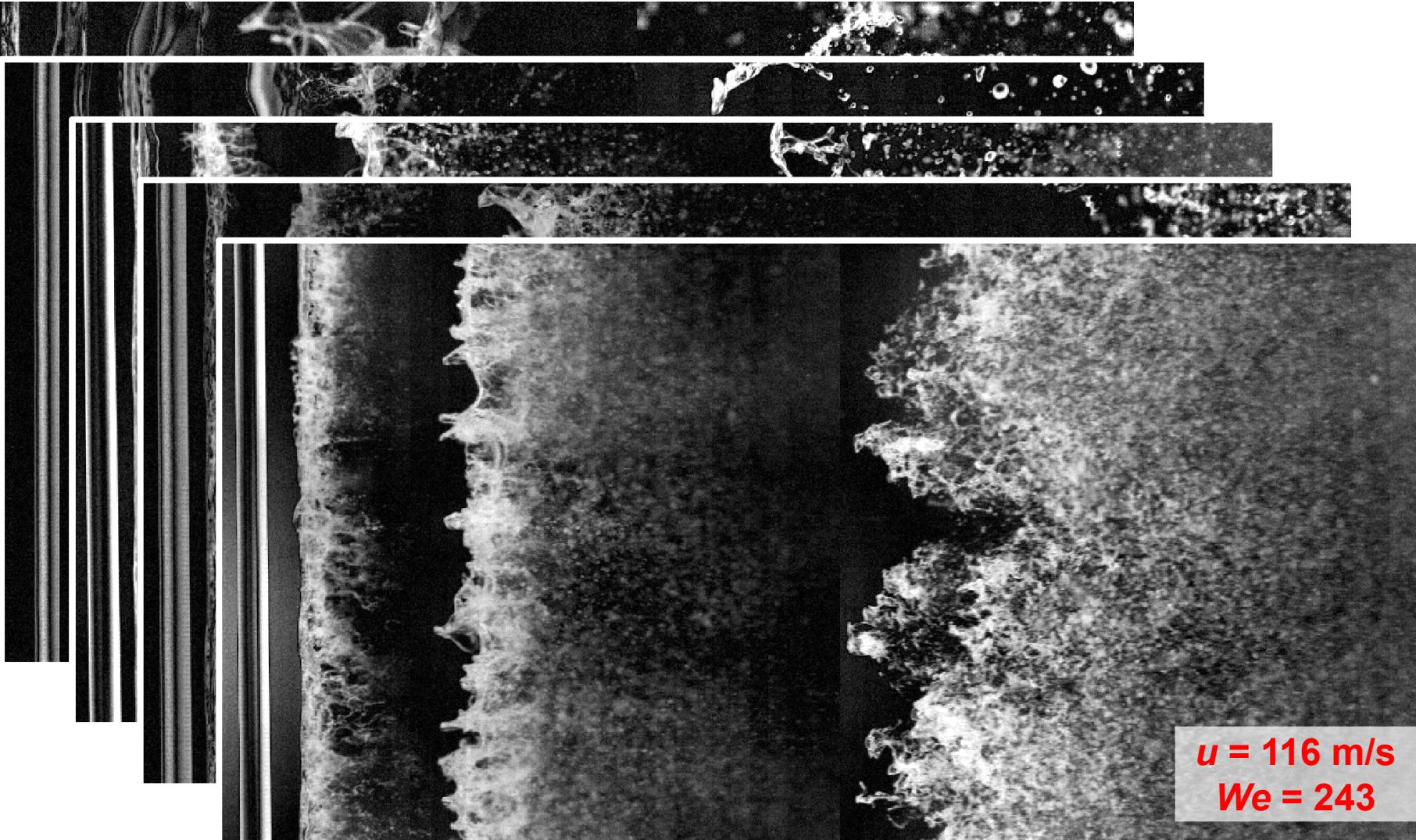


Regression based Multi-frame Tracking (RMT) allows for 3D-3C temporal measurements (Gildenbecher *et al.*, 2016, *Appl. Opt.*)

# Breakup of a water jet in a shock-tube

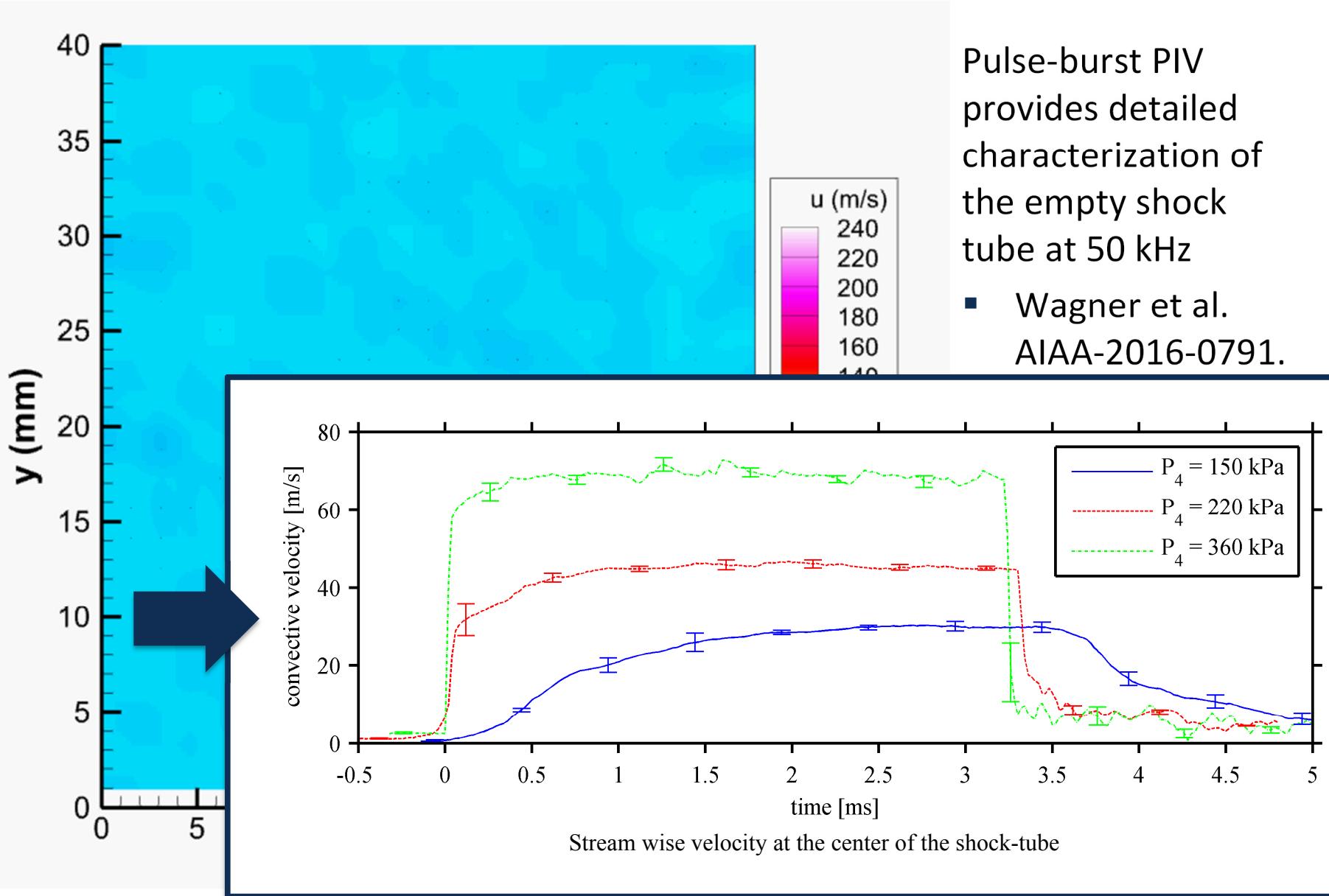


# Observed breakup morphologies



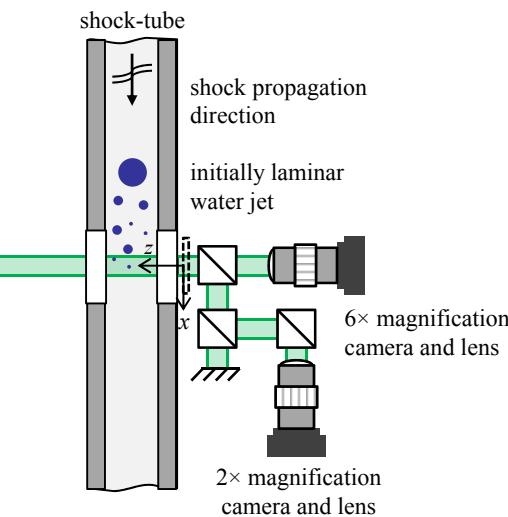
Breakup morphologies similar to those observed for isolated drops

# Well characterized boundary conditions



# DIH recorded at 100,000 fps

recorded hologram at  $t = 1.16$  ms



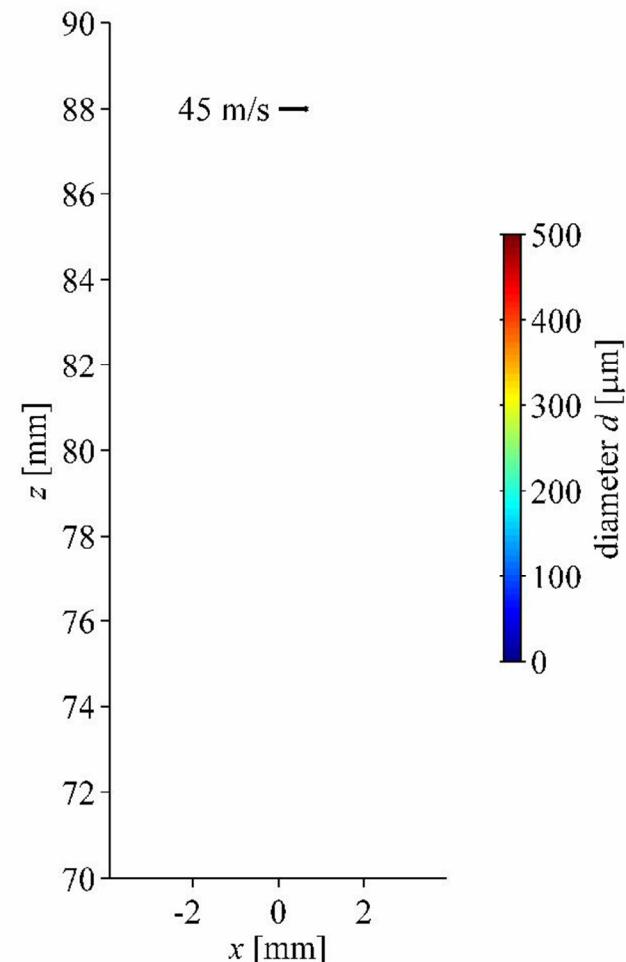
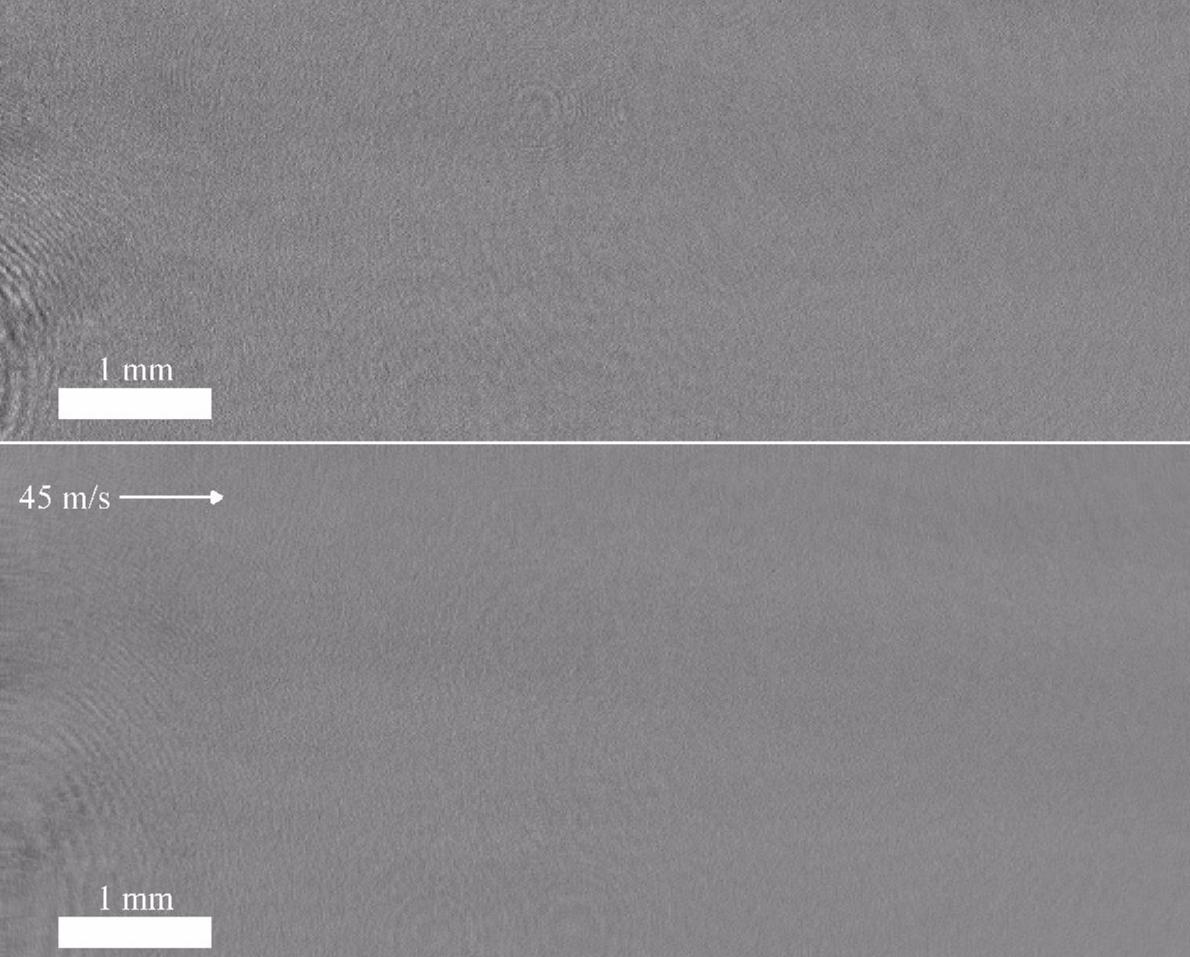
refocused to  $z = 80$  mm

1 mm

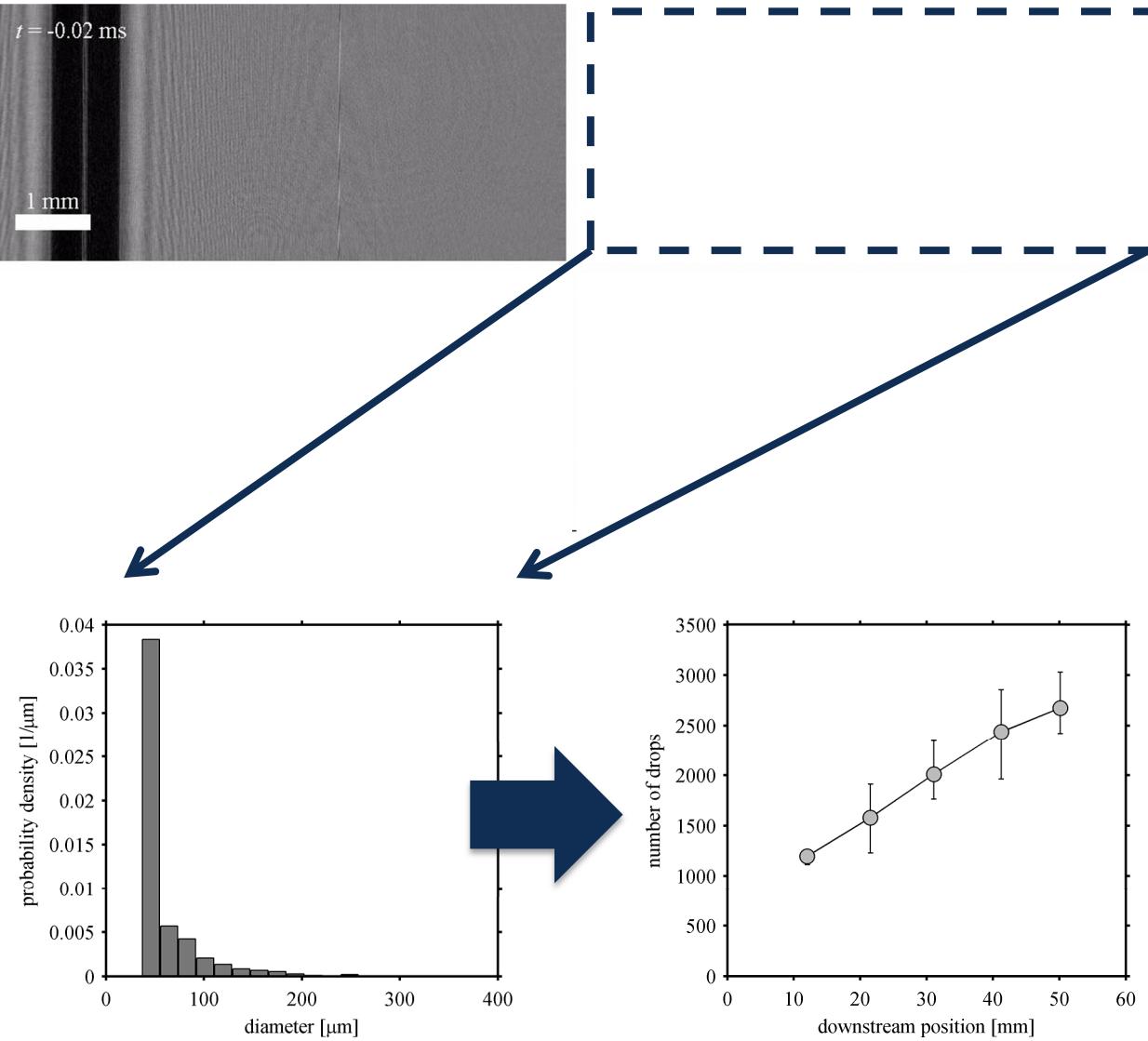
# Temporally resolved, 3D particle field

Data processing similar to drop impact experiment

recorded hologram at  $t = 1.29$  ms



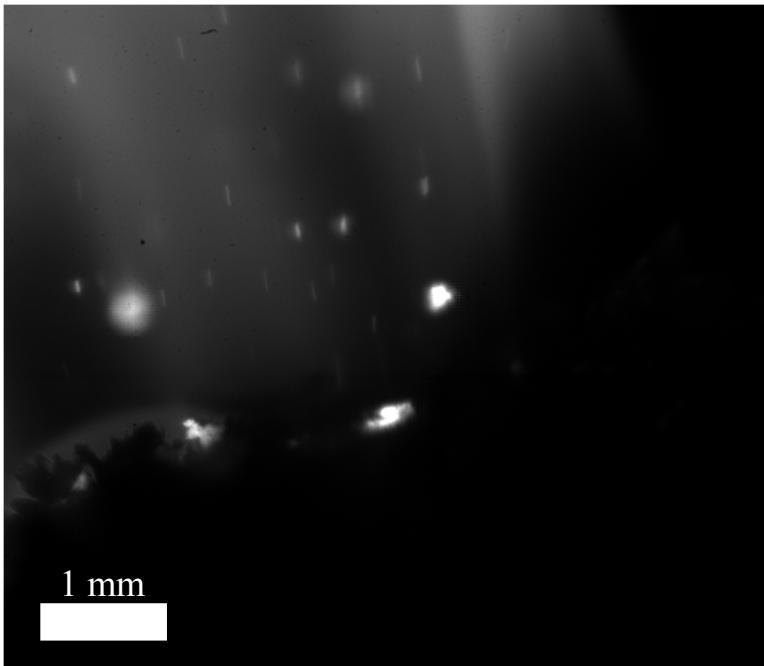
# Multiple downstream fields of view



# Aluminum drop combustion in propellants

Motivation: rocket failures can lead to propellant fires

- Sandia Laboratories is interested in predicting the response of objects in this environment



high-speed video of a burning propellant

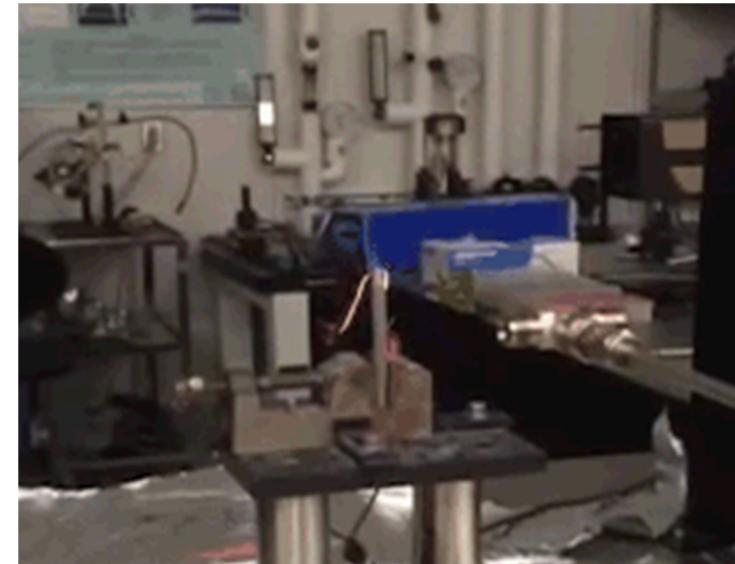
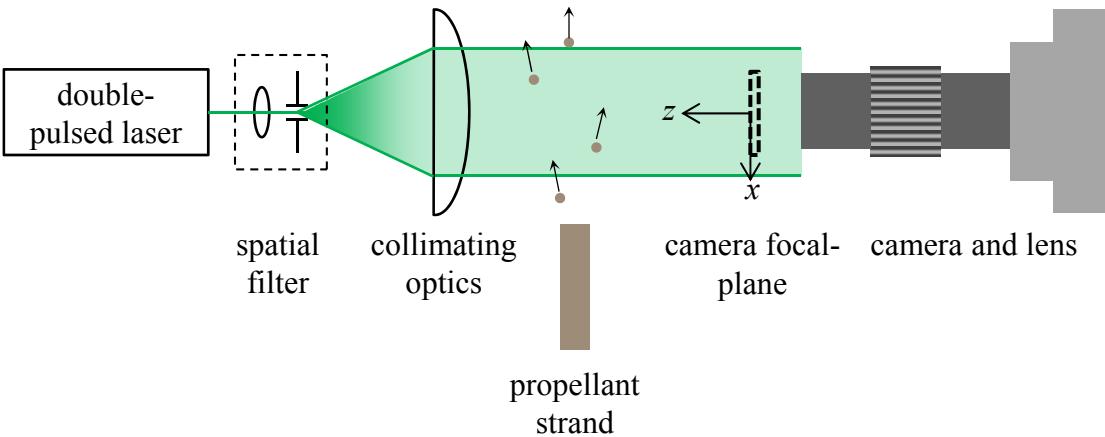


<http://www.cbsnews.com/news/rocket-crash-no-immediate-threat-to-station-but-cause-is-unknown/>

Aluminum agglomeration at the surface yields large reacting drops with high damage potential

- Prediction requires knowledge of particle *size, velocity, and temperature*

# Aluminum drop combustion in propellants



propellant in the test fixture

Propellant: solid-rocket propellant pressed into a pencil size strand

- Combusts from the top surface down, ejecting molten aluminum particles traveling a few m/s

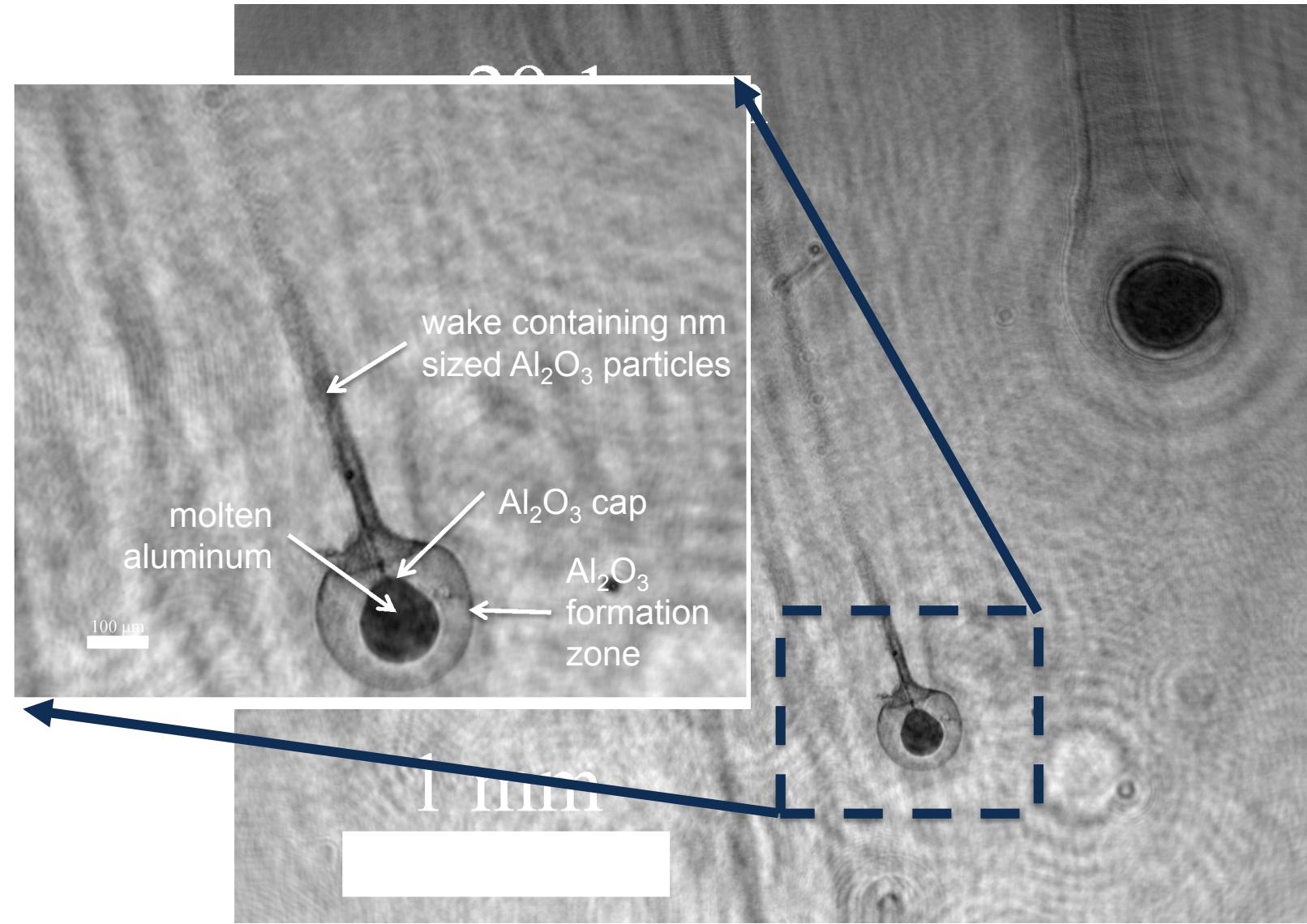
Laser: Continuum Minilite Nd:YAG, 532 nm wavelength, 5 ns pulse duration

Camera: sCMOS from LaVision at 15Hz

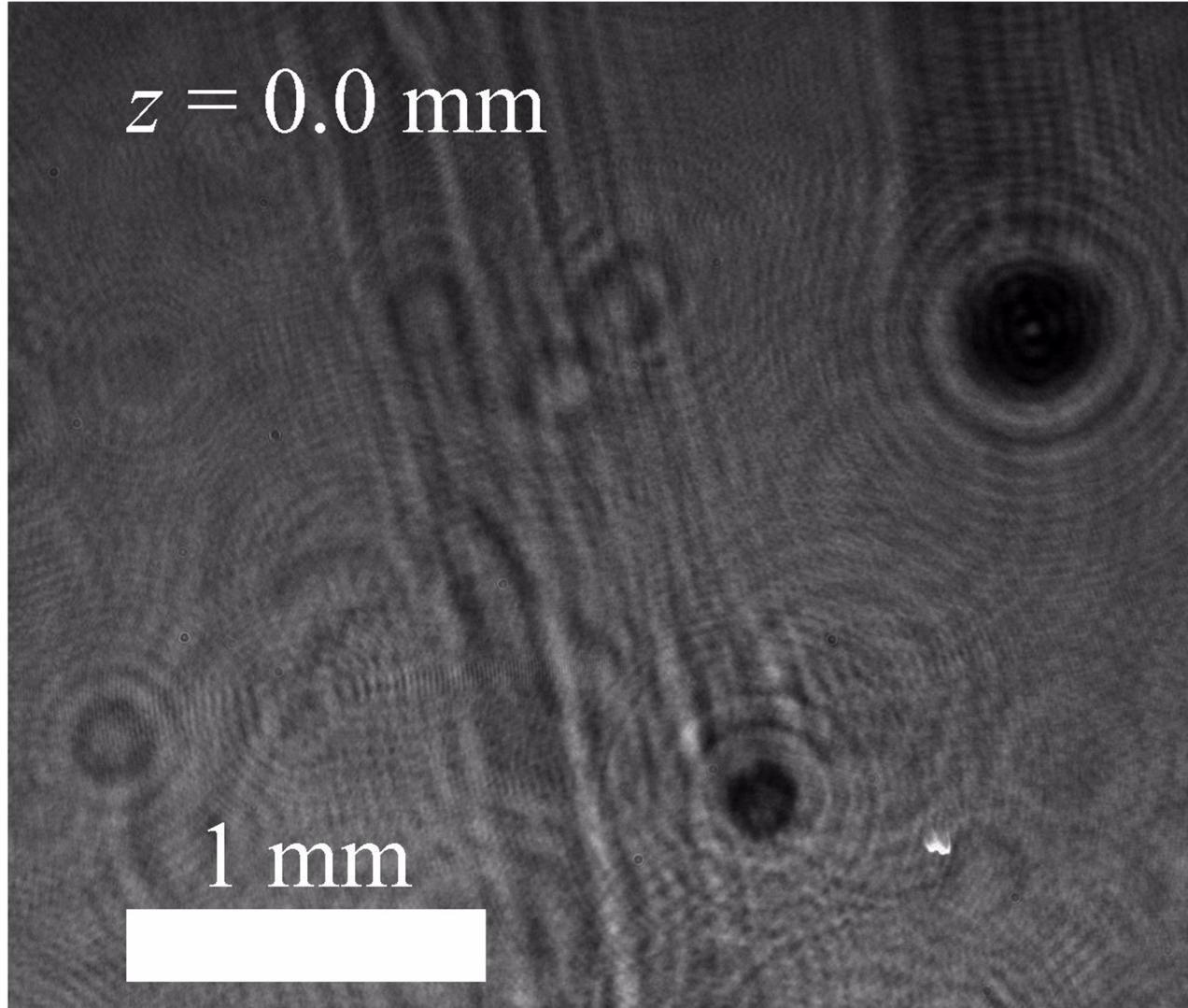
Lens: Infinity K2 long distance microscope with CF-4 objective

- ~ 6X magnification

# Aluminum drop combustion in propellants



# Aluminum drop combustion in propellants



Algorithms automatically measure unique features of burning aluminum

# Aluminum drop combustion in propellants

Three strand burns  $\rightarrow$  5594 images and 17496 measured drops

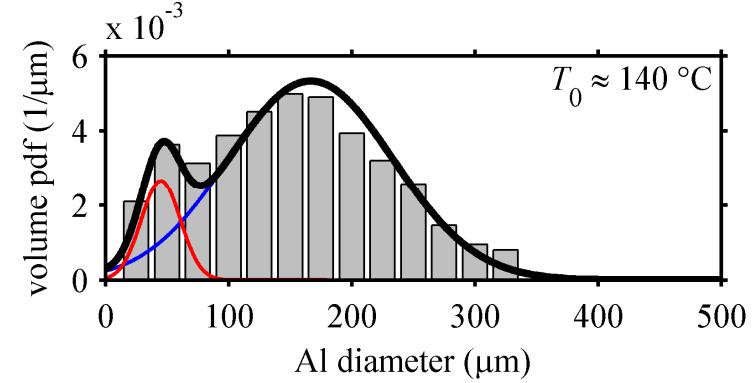
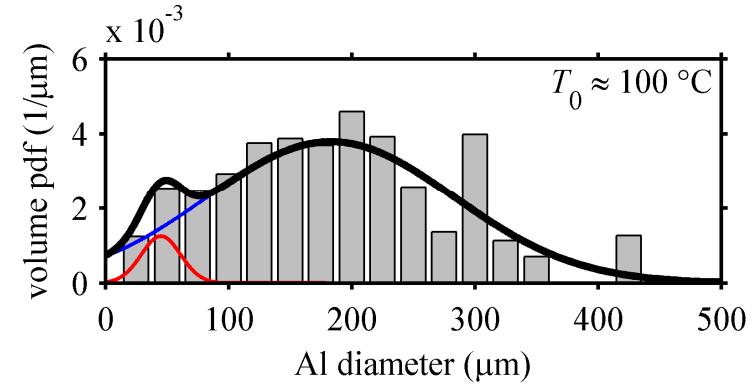
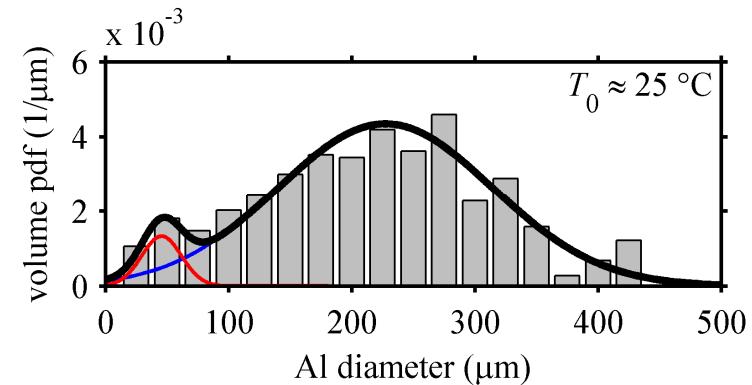
- Main peak due to agglomerated particulates
- Peak at 50  $\mu\text{m}$  due to non-agglomerated particulate

Experiments repeated at higher initial temperature (faster burn rate)

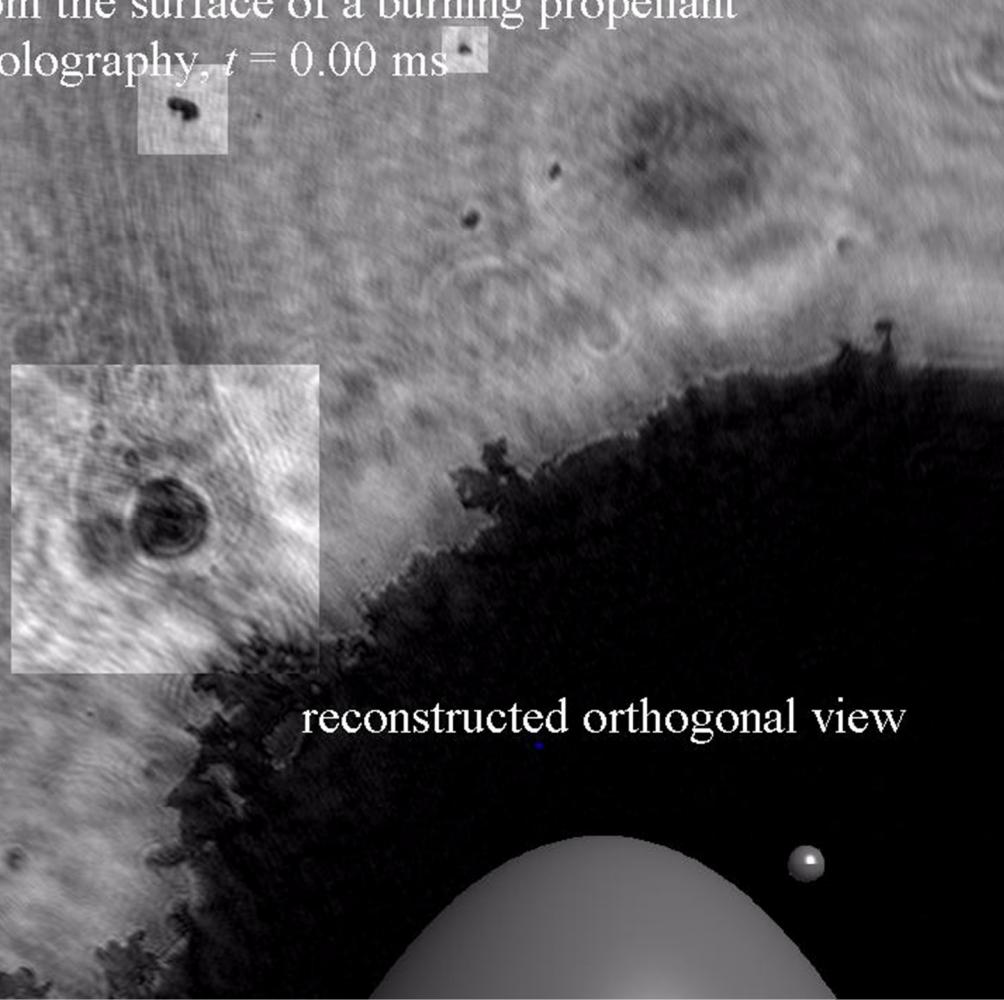
- Main peak is reduced due to decreased residence time for agglomeration
- Peak at 50  $\mu\text{m}$  remains

Trend is consistent at still higher initial temperatures

- Main peak reduced further
- Peak at 50  $\mu\text{m}$  remains



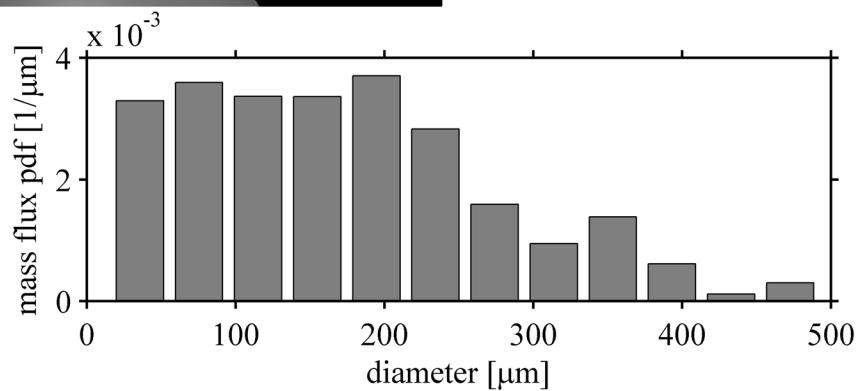
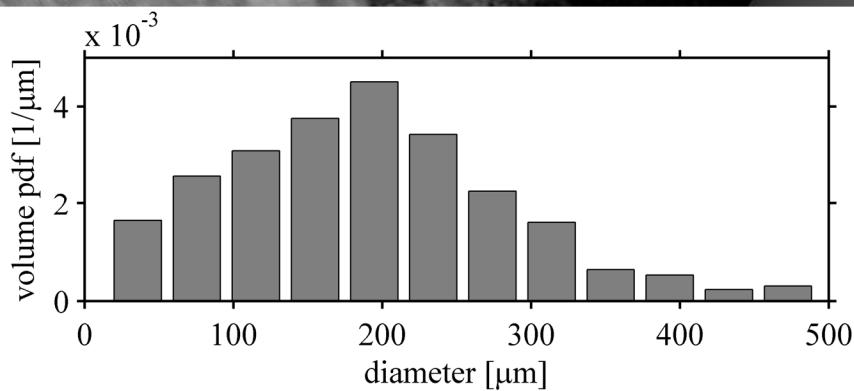
particles ejected from the surface of a burning propellant  
captured with 3D holography,  $t = 0.00$  ms



Recorded at  
20,000 fps  
Camera: Photron SA-  
Z  
Laser: Coherent  
Verdi V6

43,684 frames →  
▪ 15,991 drops  
▪ mass flux =  
0.24 mg/s·mm<sup>2</sup>

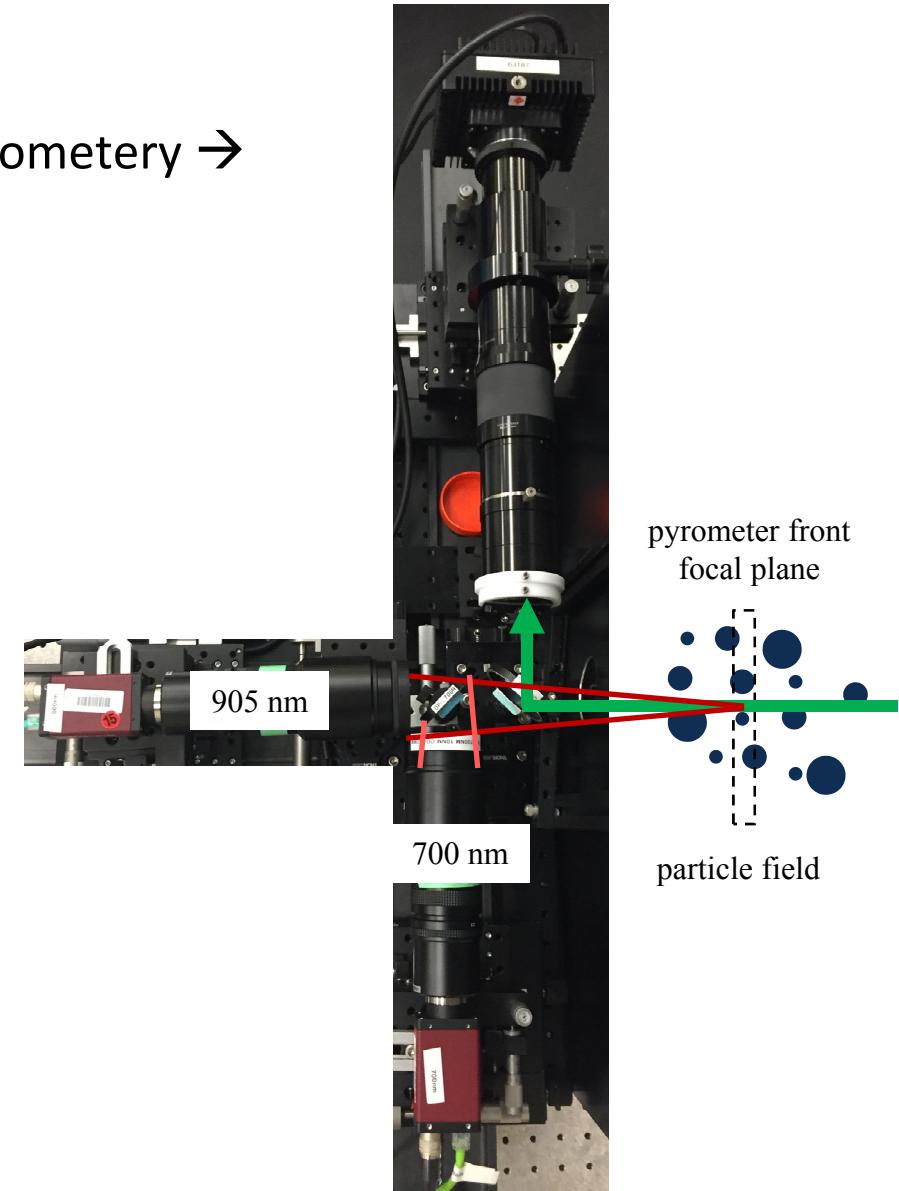
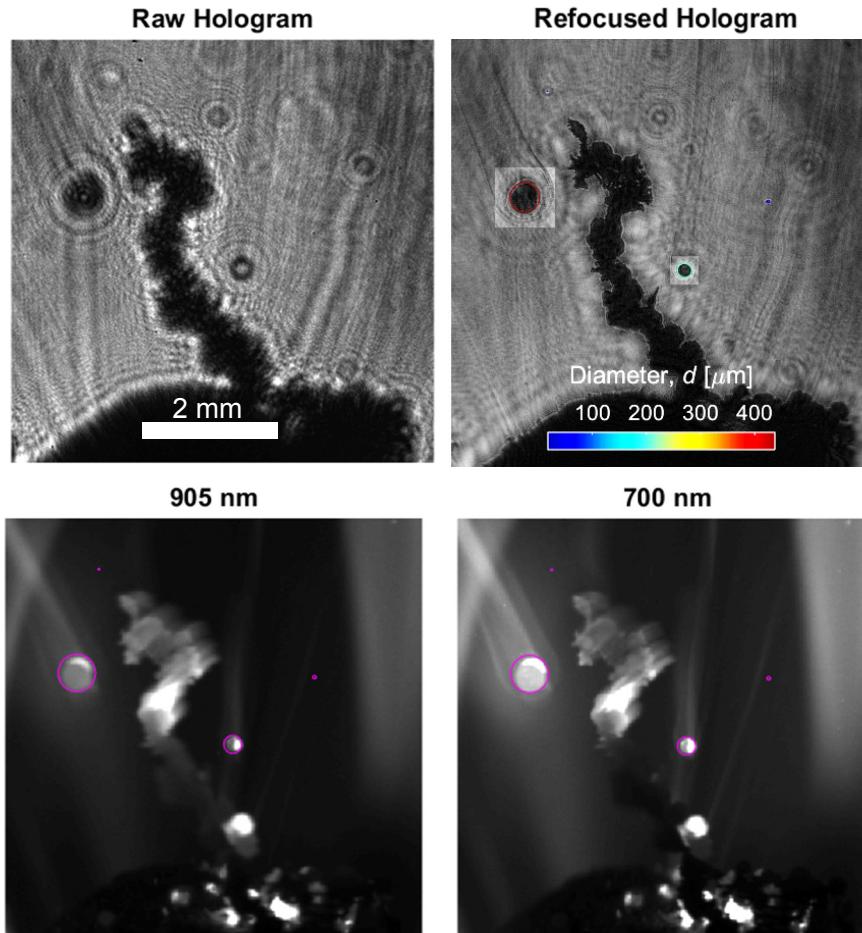
From burn rate and  
known composition,  
expected mass flux is



# Particle temperature measurements

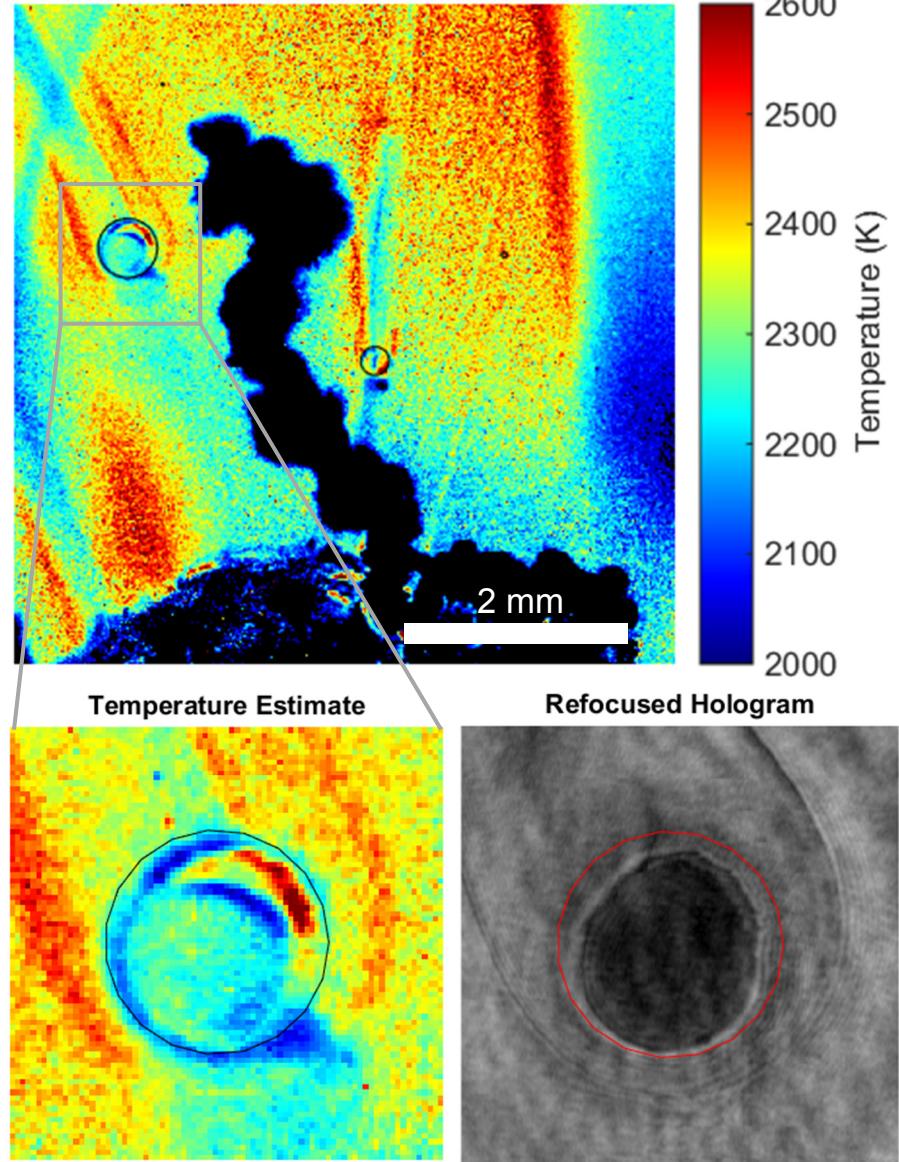
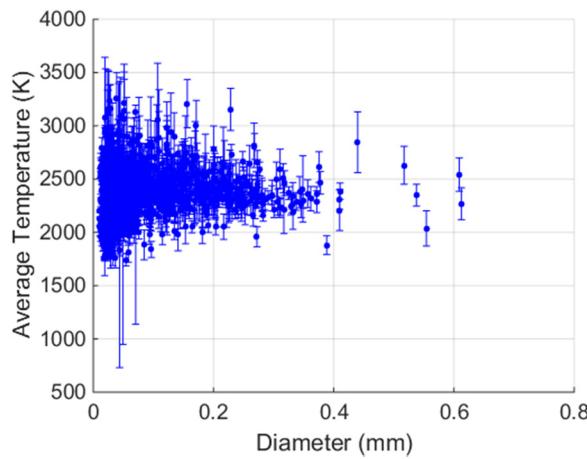
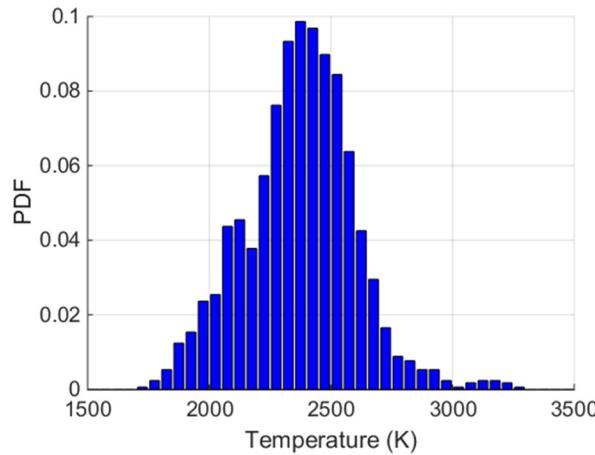
We also need to quantify heat transfer

- Combination of DIH and two-color pyrometry →  
particle size + velocity + *temperature*



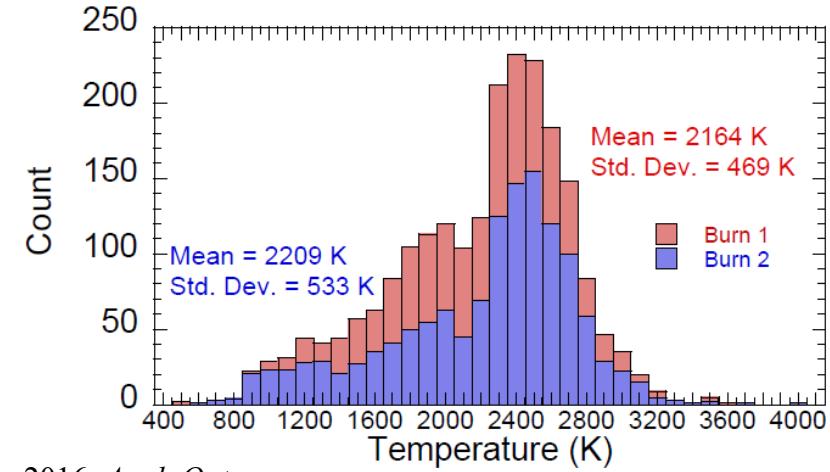
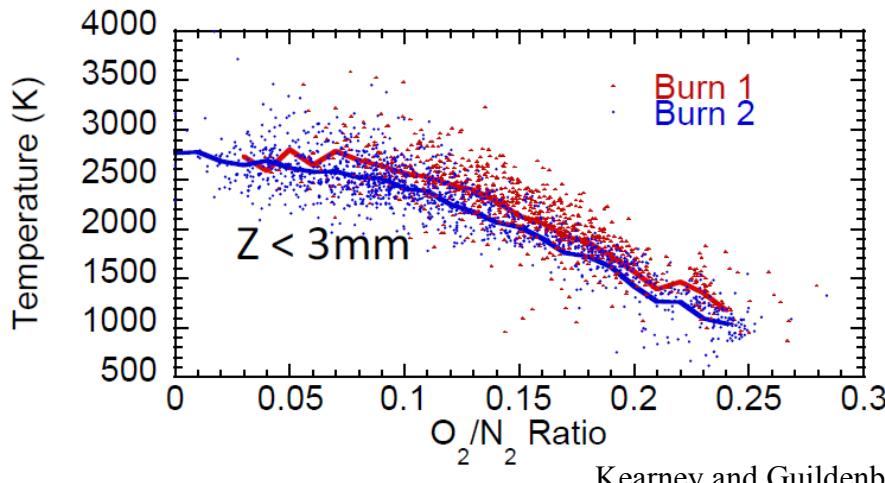
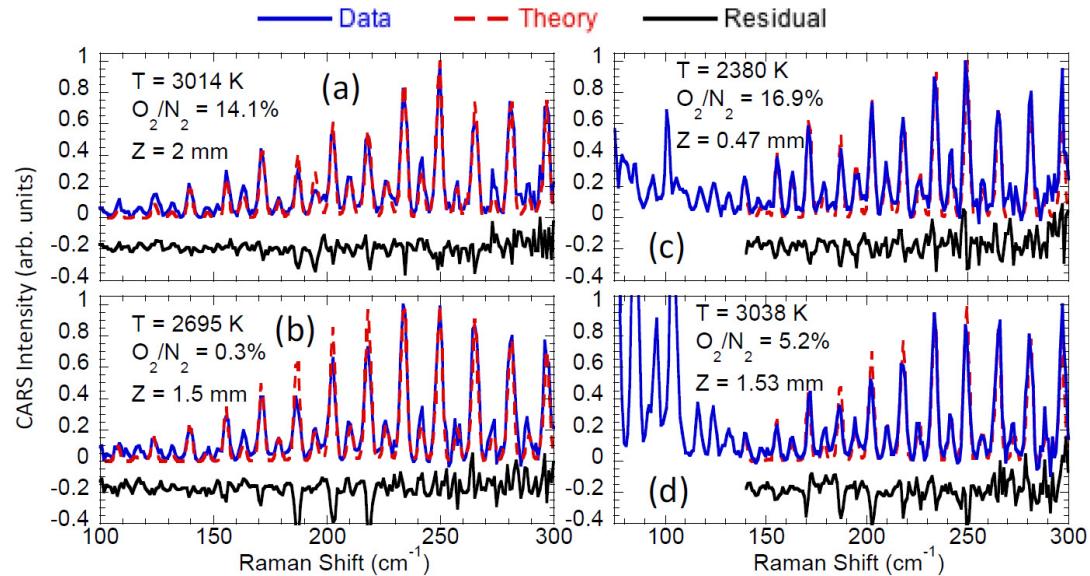
# Particle temperature measurements

Assuming graybody emission,  
calibrated ratio imaging gives an  
estimate of particle temperatures



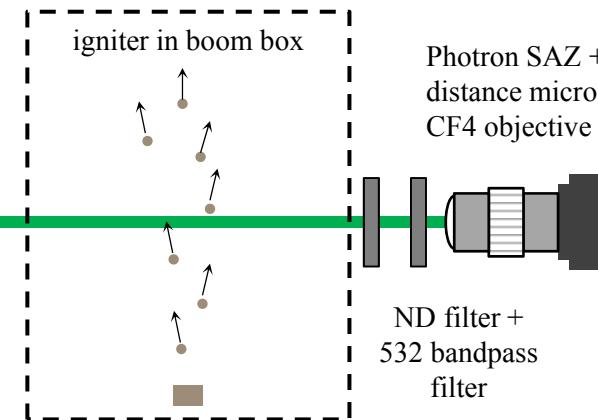
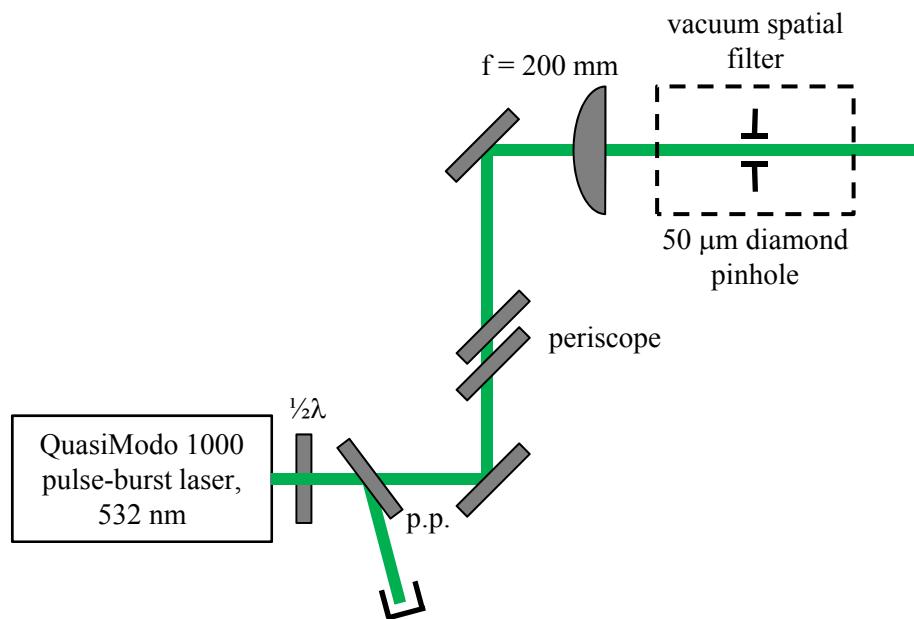
# Gas-phase temperatures with CARS

S. Kearney is measuring gas-phase temperatures using fs/ps CARS



Kearney and Guildenbecher, 2016, *Appl. Opt.*

# Pulse-burst DIH



# Pulse-burst DIH

$t = 0.00 \text{ ms}$

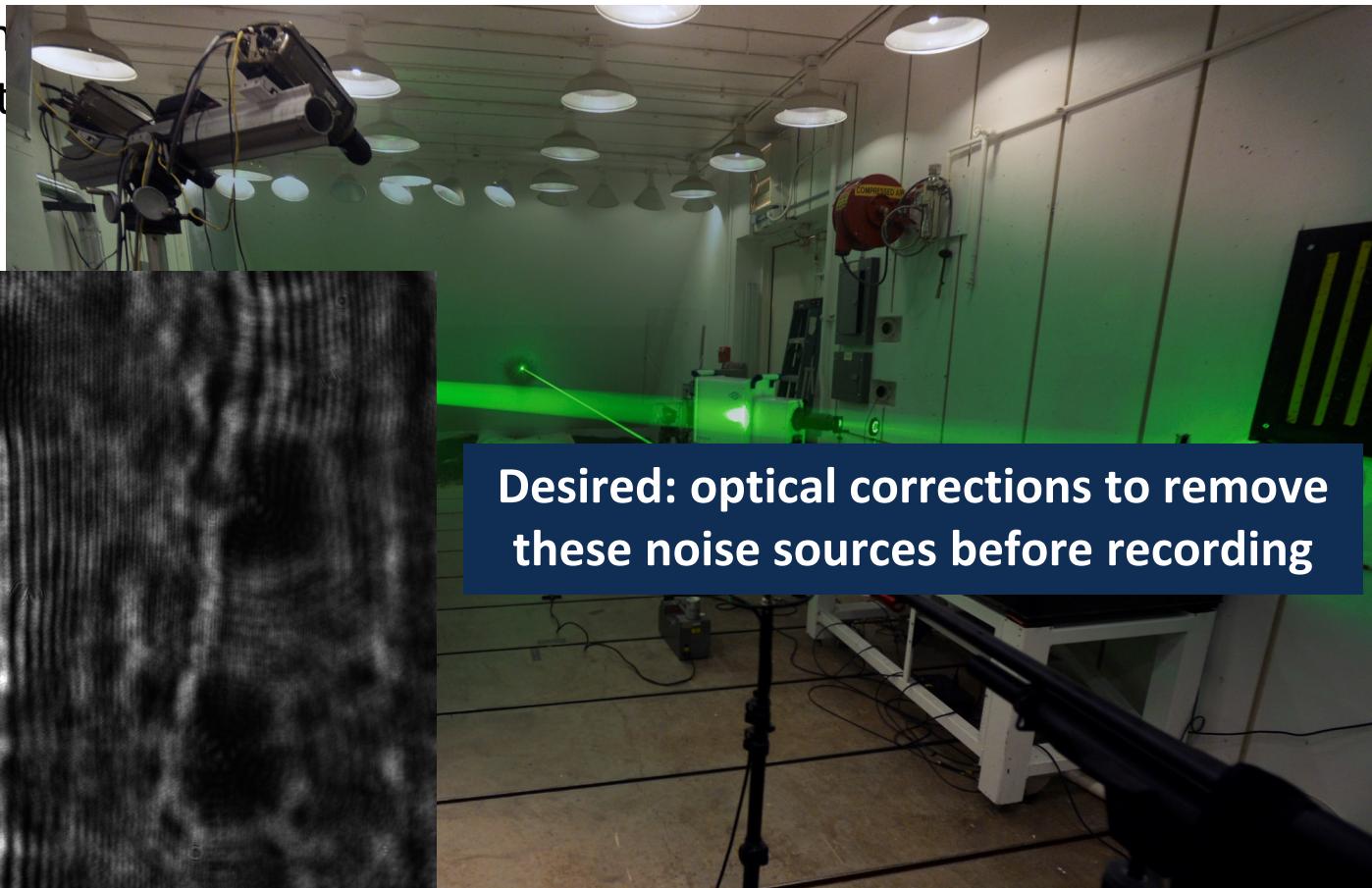
1 mm

- Beam quality is sufficient for DIH
- Freezes high-speed particles and penetrates through flash and smoke
- Noise due to soot and index-of-refraction gradients

# Optical challenges in DIH

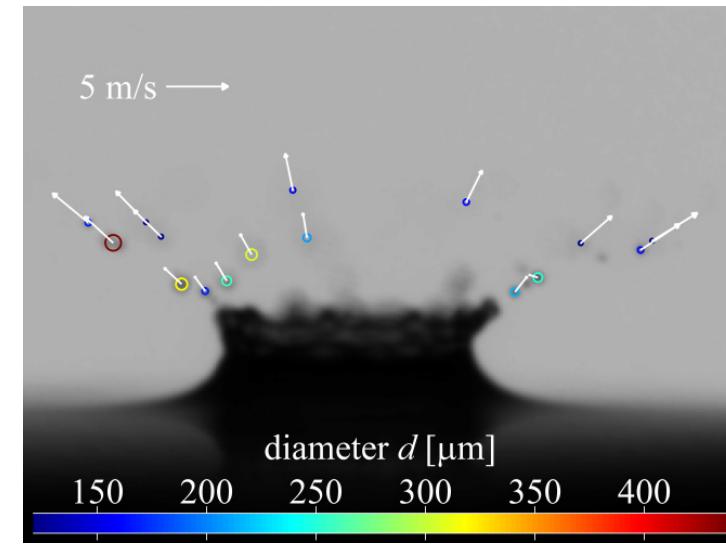
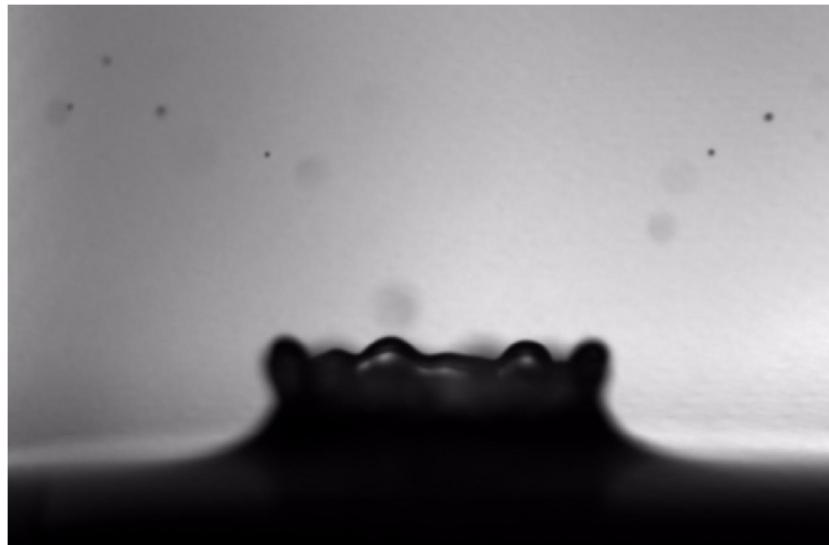
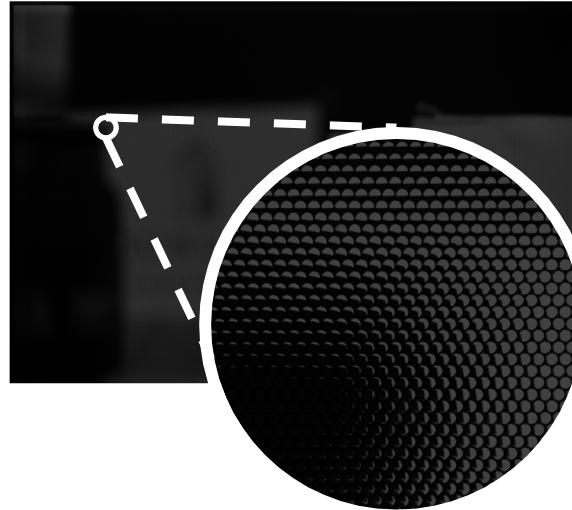
Coherent imaging is susceptible to:

- Image distortion through index of refraction gradients
- Loss of phase information due to multiple-scattering



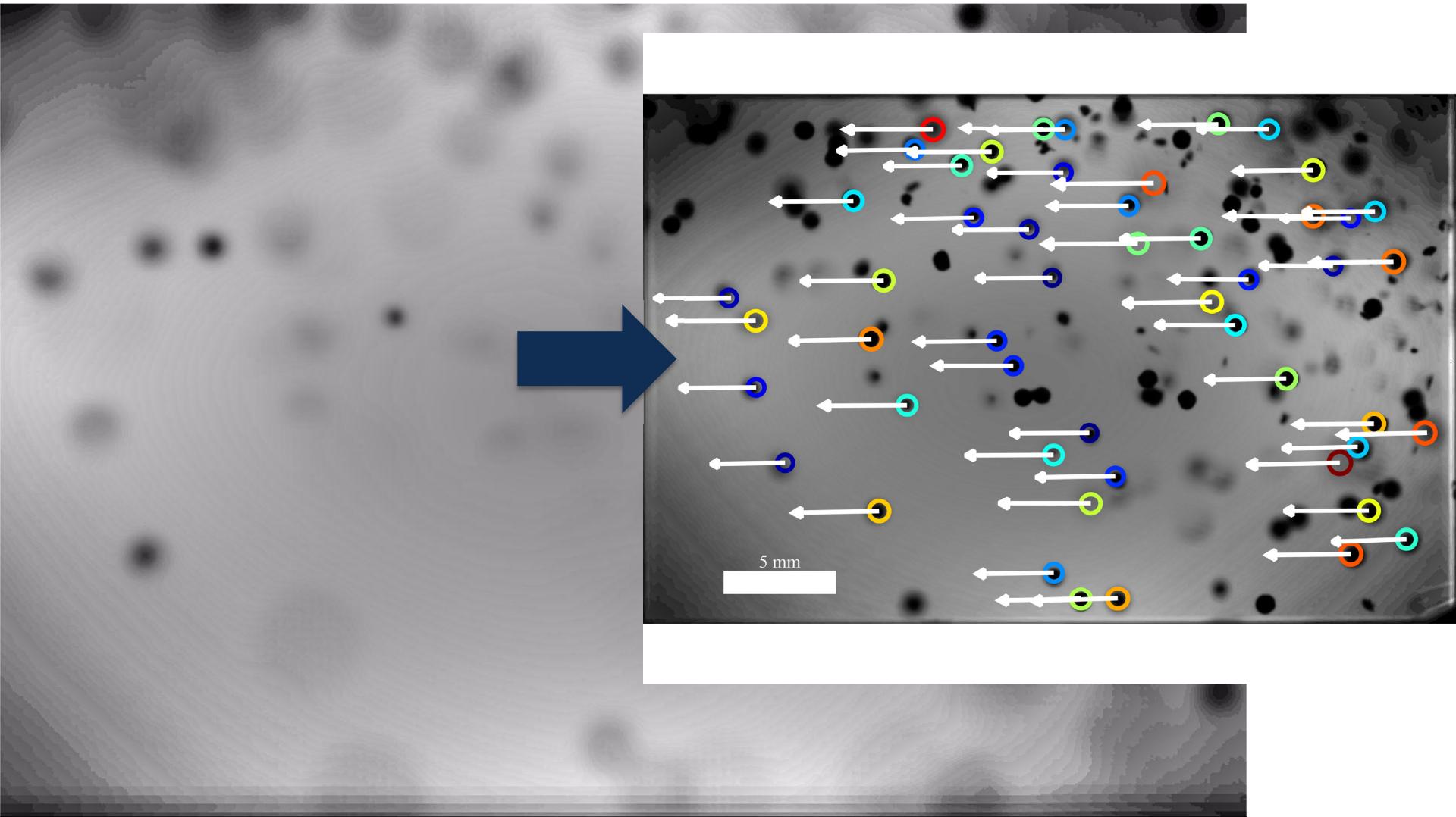
# Alternative 3D measurements

Plenoptic cameras use micro-lens arrays and white light to create a 3D image



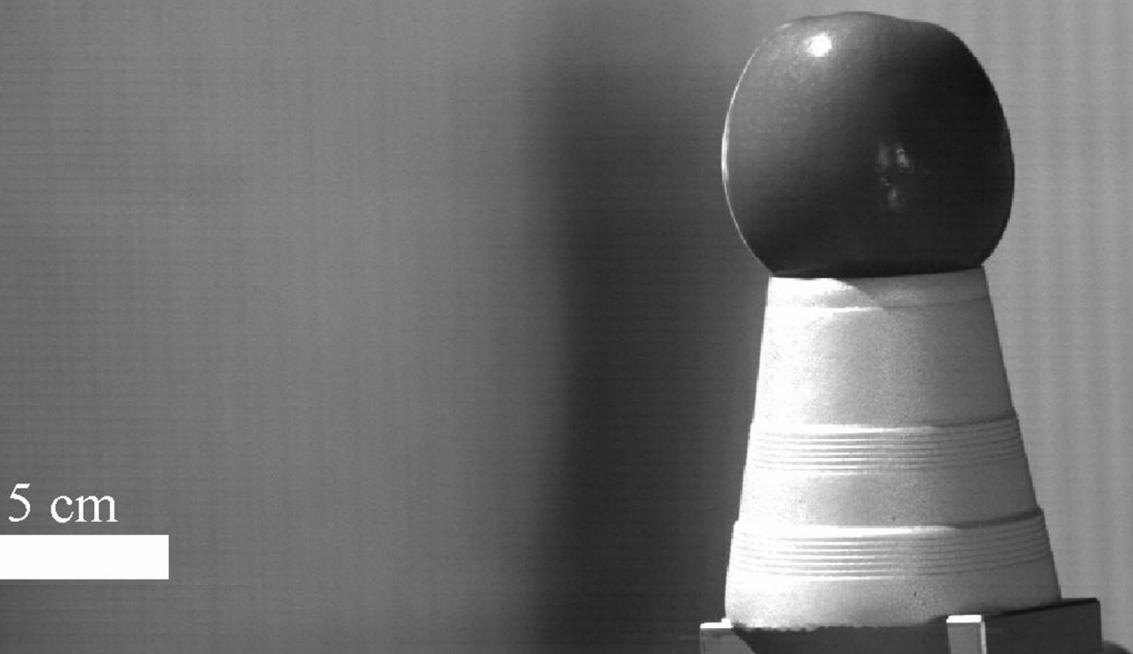
# Alternative 3D measurements

Plenoptic imaging of a shotgun



# Particle tracking methods are versatile...

$t = 3.00 \text{ ms}$   
 $350 \text{ m/s} \rightarrow$

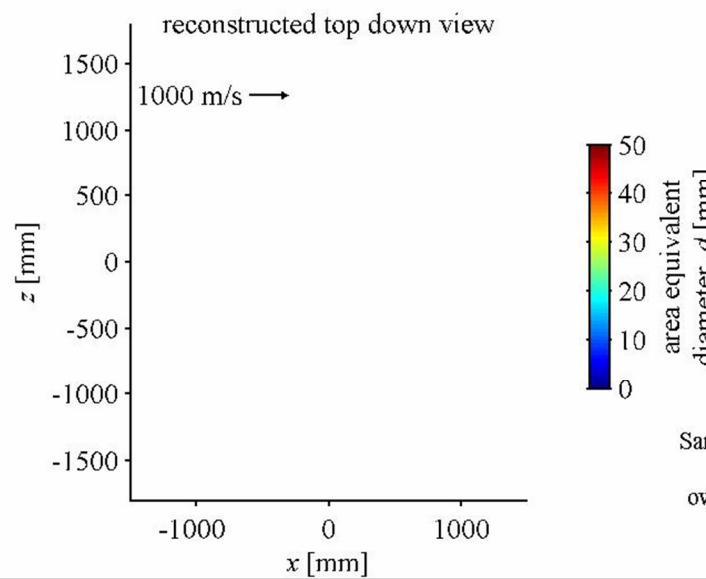


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# ... including large-scale munitions testing

$t = 14.40$  ms  
1000 m/s →

left view



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# Conclusions

## DIH has many advantages:

- 3D-3C measurement
- Rapid quantification of statistics
- Simple optical configuration

## ... and opportunities for research:

- Depth-of-focus problem
- Data processing
- Optical improvements

## Acknowledgements:

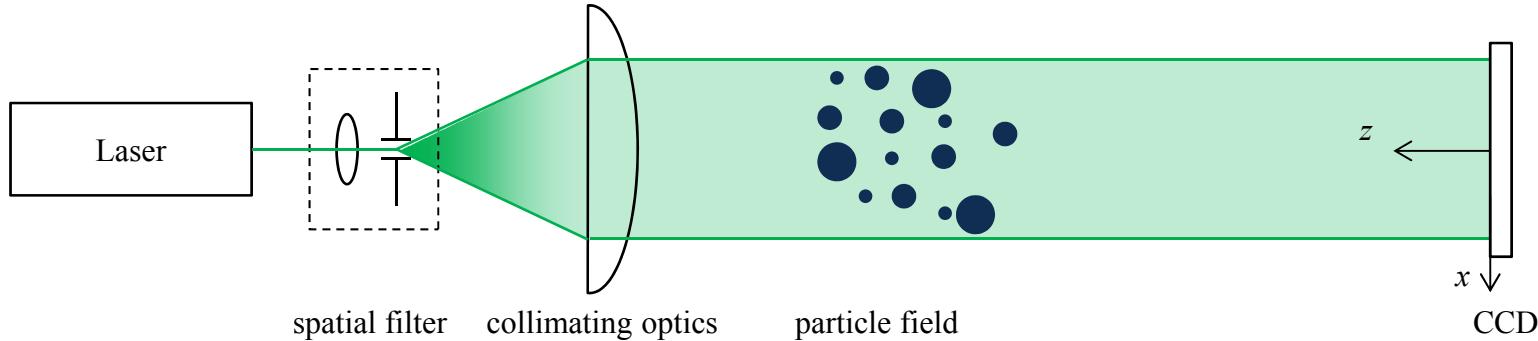
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## Questions

# Backup slides

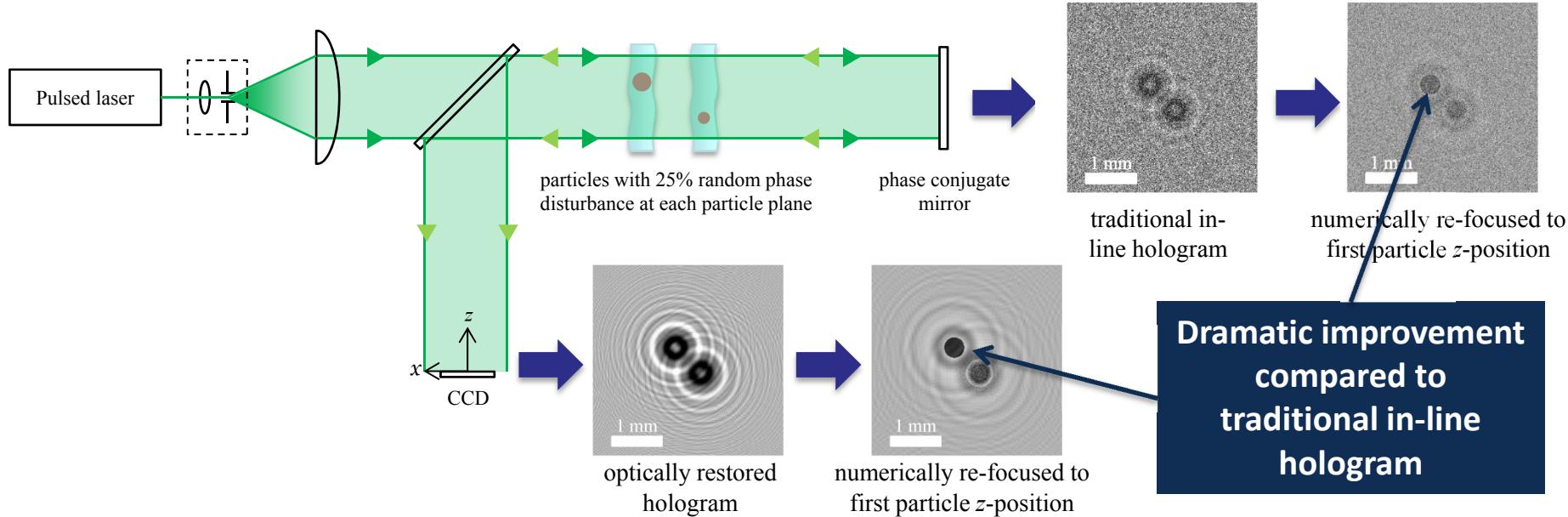
# Where is the reference wave?



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

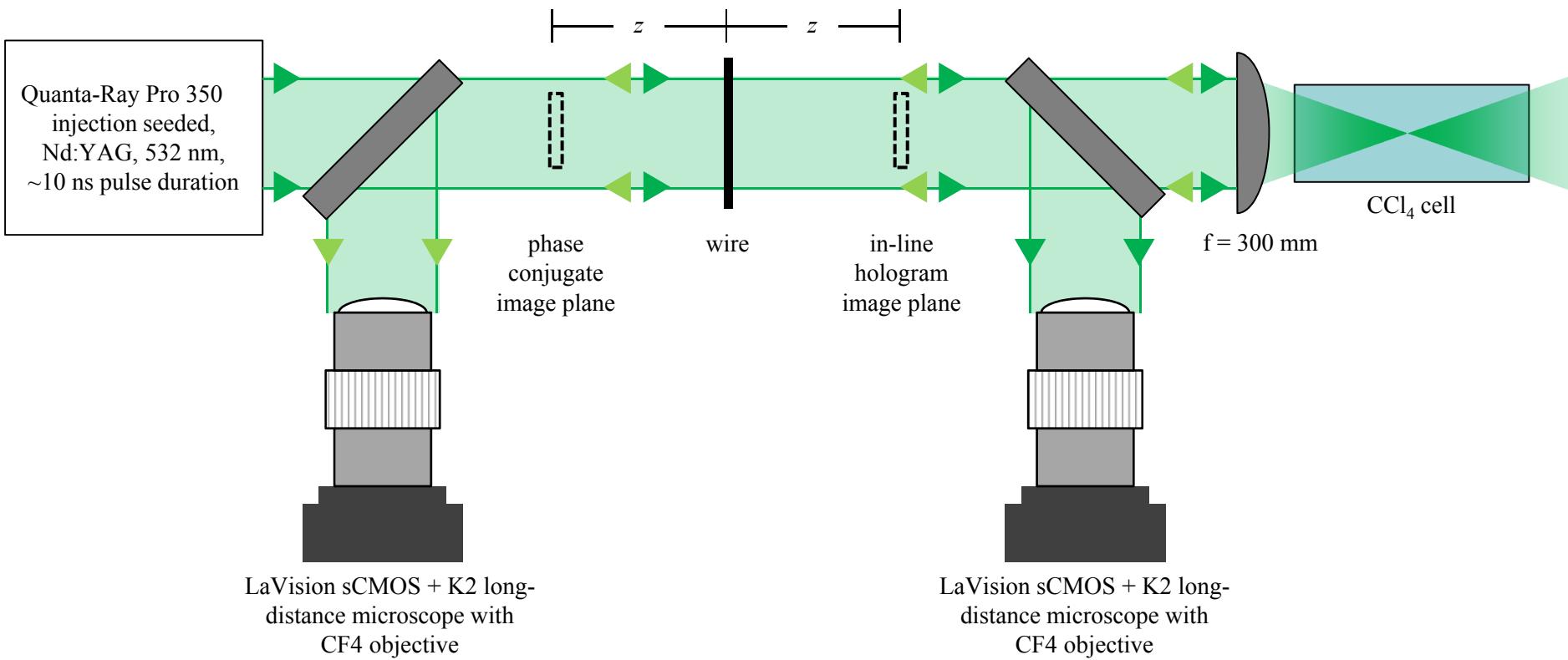
# Phase-conjugate DIH theory



- Phase-conjugate mirror reflects the incoming wave with opposite phase
  - Non-linear optical effect achieved through passive means (stimulated Brillouin scattering) or active means (degenerate four-wave mixing)
- After double passing, the phase disturbance is canceled

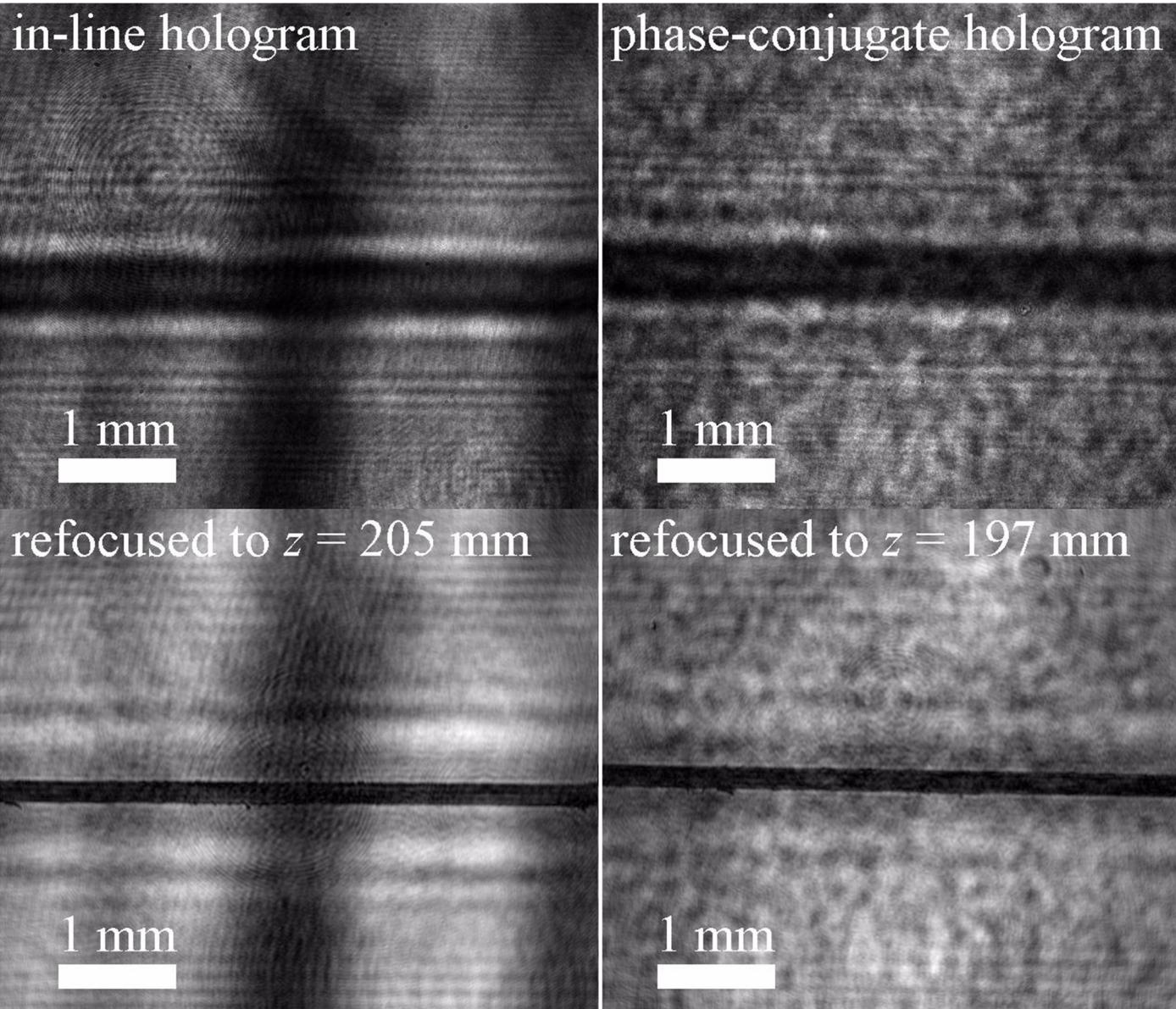
# SBS phase-conjugate DIH

A focused beam in a non-linear medium induces phase conjugation via stimulated Brillouin scattering (SBS)



# SBS phase-conjugate DIH

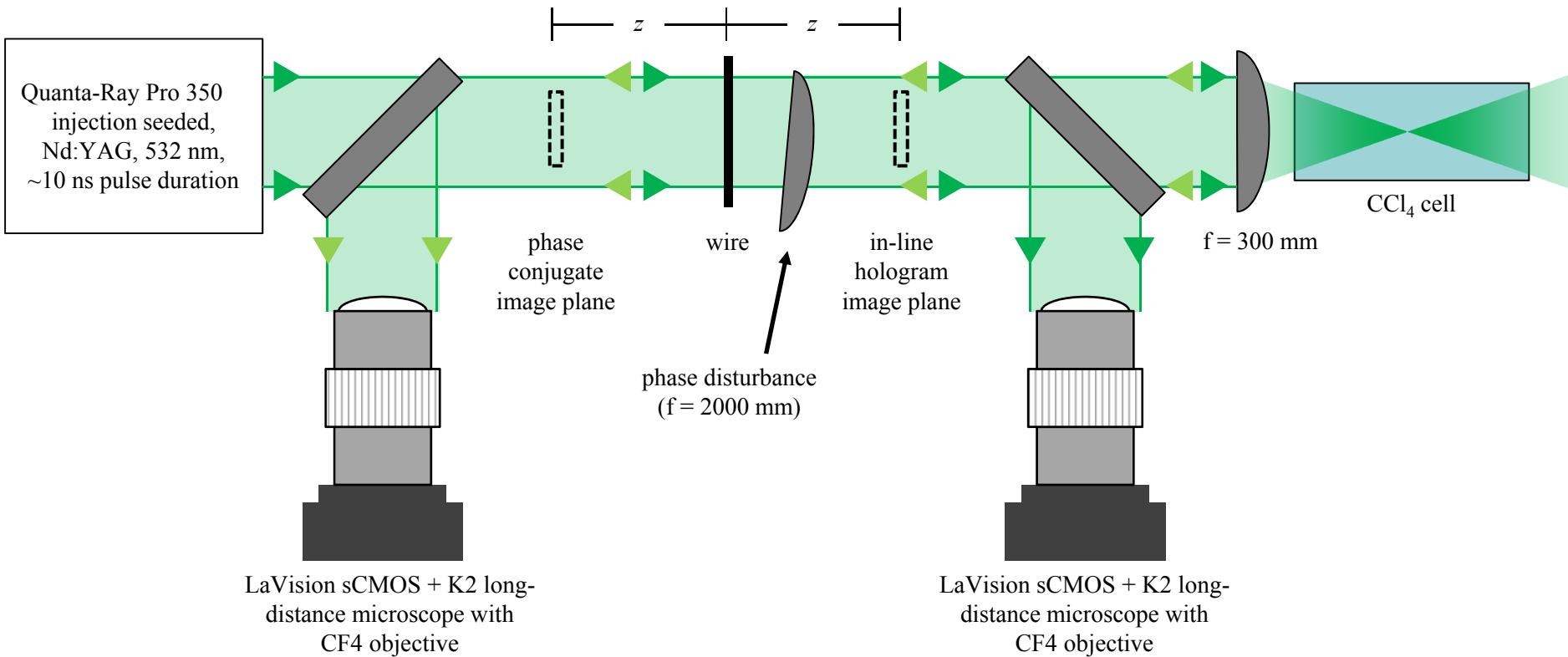
Without a  
disturbance  
both views give  
similar results



# SBS phase-conjugate DIH

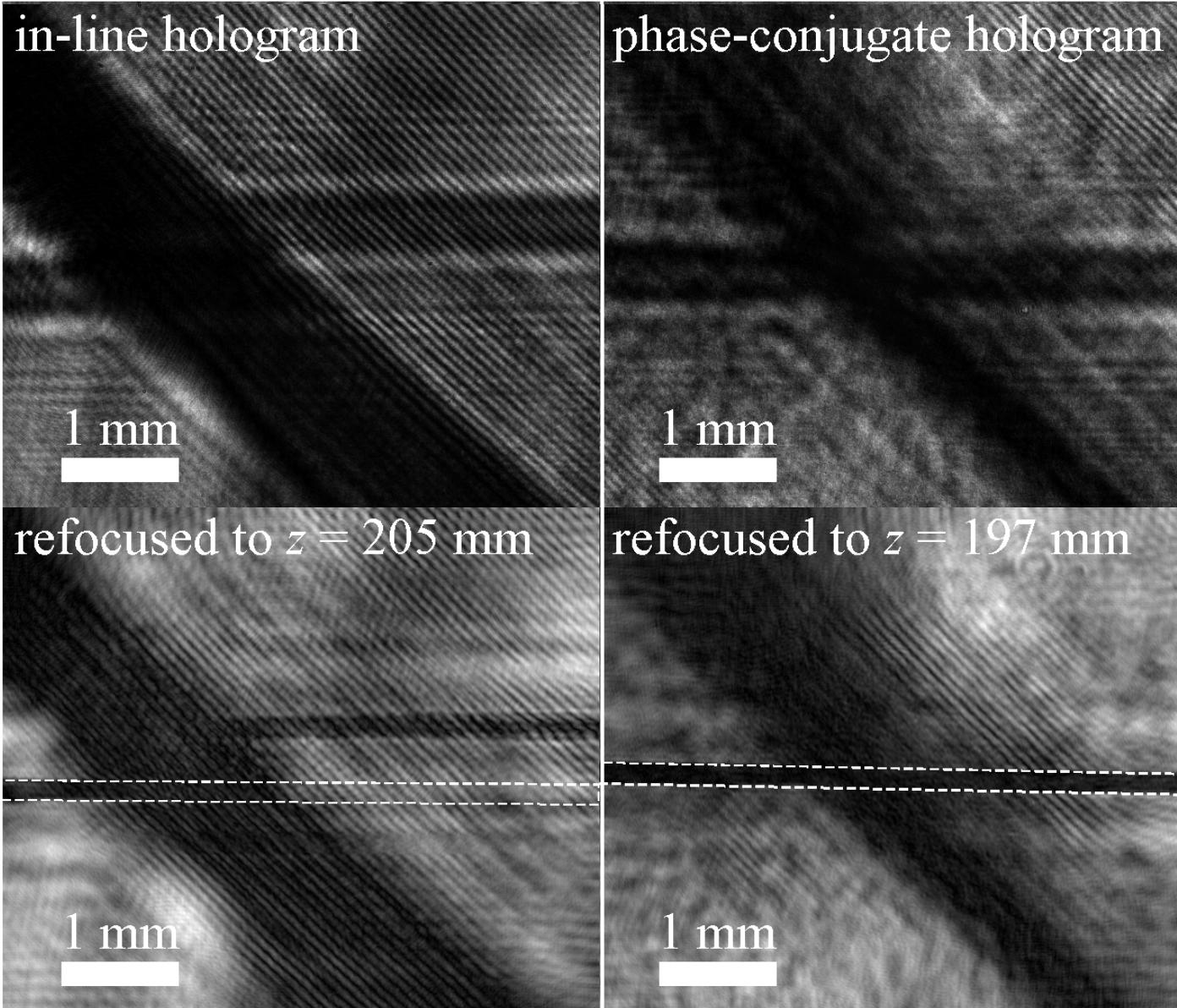
A focused beam in a non-linear medium induces phase conjugation via stimulated Brillouin scattering (SBS)

- A misaligned lens in the beam path causes a phase disturbance



# SBS phase-conjugate DIH

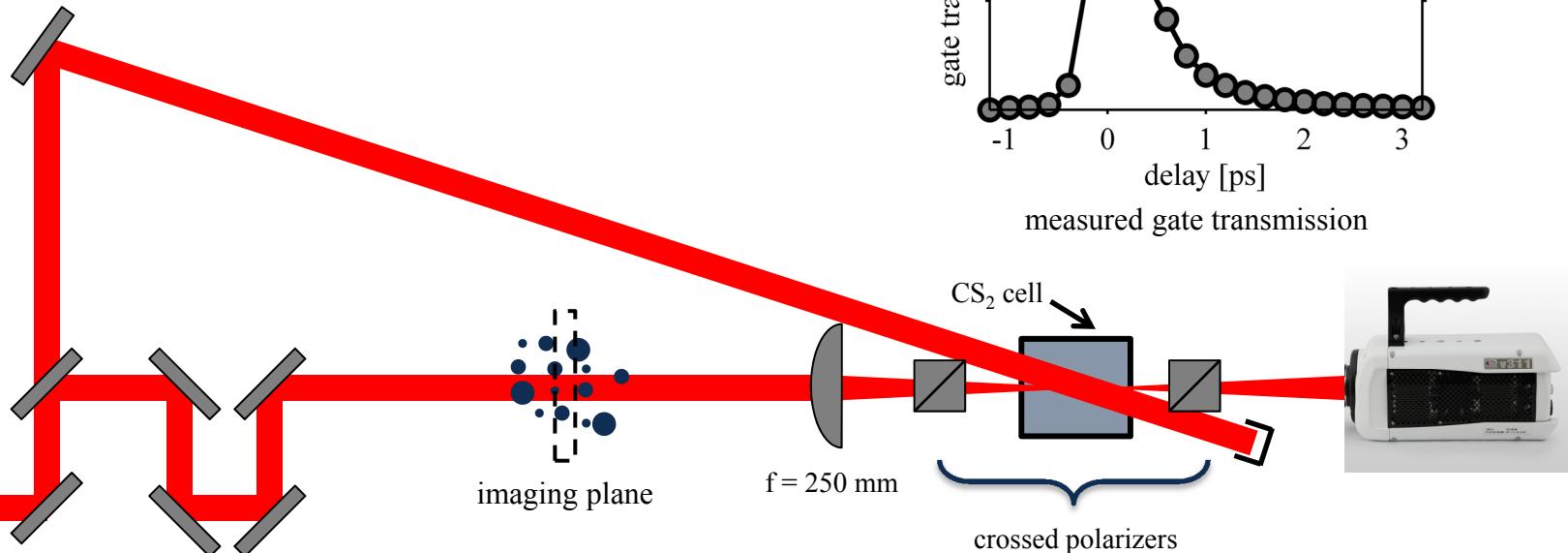
Phase  
conjugation  
corrects image  
distortion



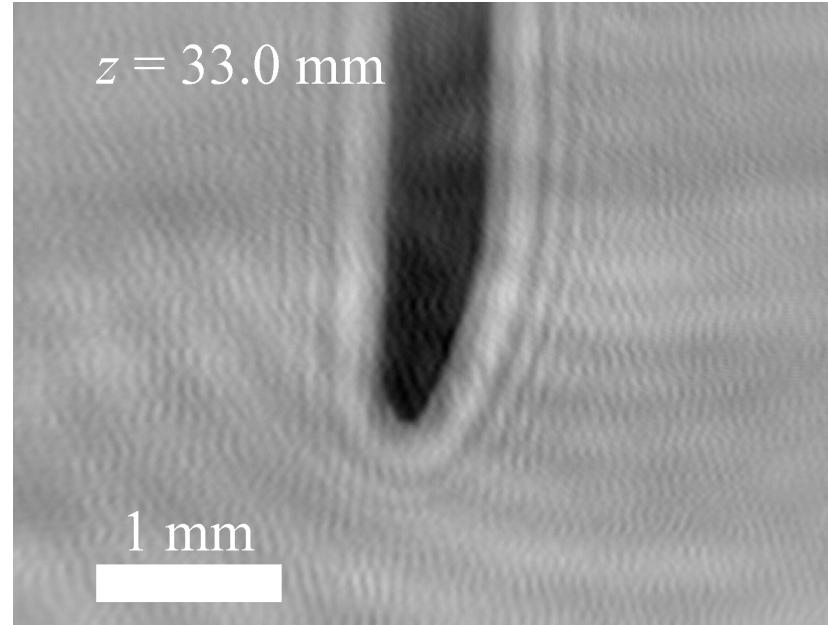
# Ballistic DIH

Multiple scattering can be reduced through ps time gating

- Combination with DIH might enable scatter free 3D imaging through optically dense media
  - First proposed by: Trolinger et al 2011, *International Journal of Spray and Combustion Dynamics*



DIH imaging through a Kerr gate (no scatter sources)



DIH image of a needle recorded with the ballistic configuration (1.6 ps switch delay)

Next step: Explore ballistic DIH through dense scattering sources

- Challenge: *Can we retain sufficient image fidelity and coherence to resolve 3D phenomena?*

# Two-color, in-line ballistic imaging

