Holographic Particle Image Velocimetry

Michael Barry, Alisha Schor, Anna Shih

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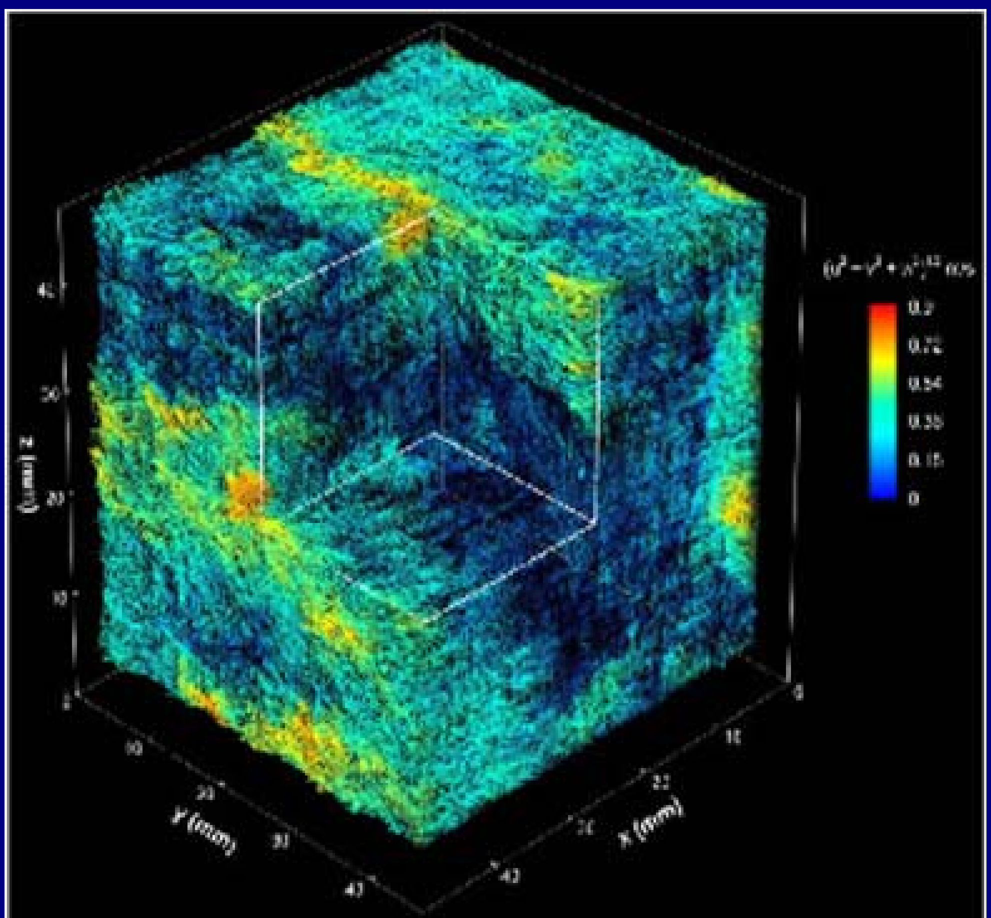
Motivation

Image removed due to copyright restrictions. Please see Fig. 7 in Meng, Hui, et al. "Holographic Particle Image Velocimetry." *Measurement Science and Technology* 15 (2004): 673-685.

Near field of a laminar je

image from Meng et. al, 2000



Turbulent flow in a square duc

Image from http://www.me.jhu.edu/meneveau/gallery.html

Holography - Basic Principles

Recording

Reconstruction

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

3d information to 2d representation

$$RI = R + RR^*O + R^2O^*$$

Reconstruct at discrete z depths

image from Meng et. al, 2000

Basic Illumination Types

In-Line

- ‘in-line’ reference beam
- simpler set up
- small diameter particles

Image removed due to copyright restrictions. Please see Fig. 6a,b in Meng, Hui, et al. "Holographic Particle Image Velocimetry." *Measurement Science and Technology* 15 (2004): 673-685.

Off-Axis

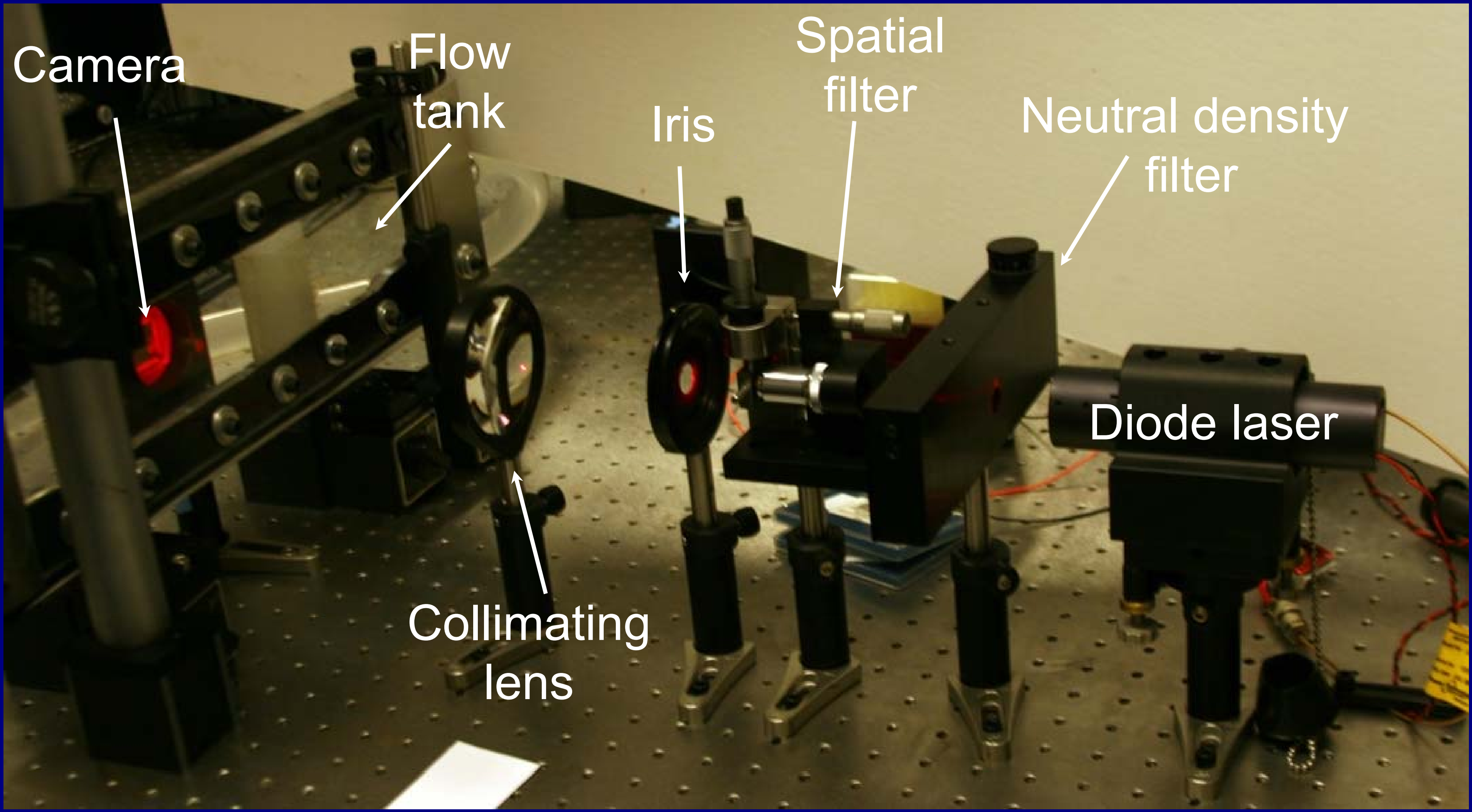
- obliquely incident reference beam
- real and virtual images separate during reconstructio..
- higher seeding densities
- for digital holography: incident angle < 2

image from Meng et. al, 2000

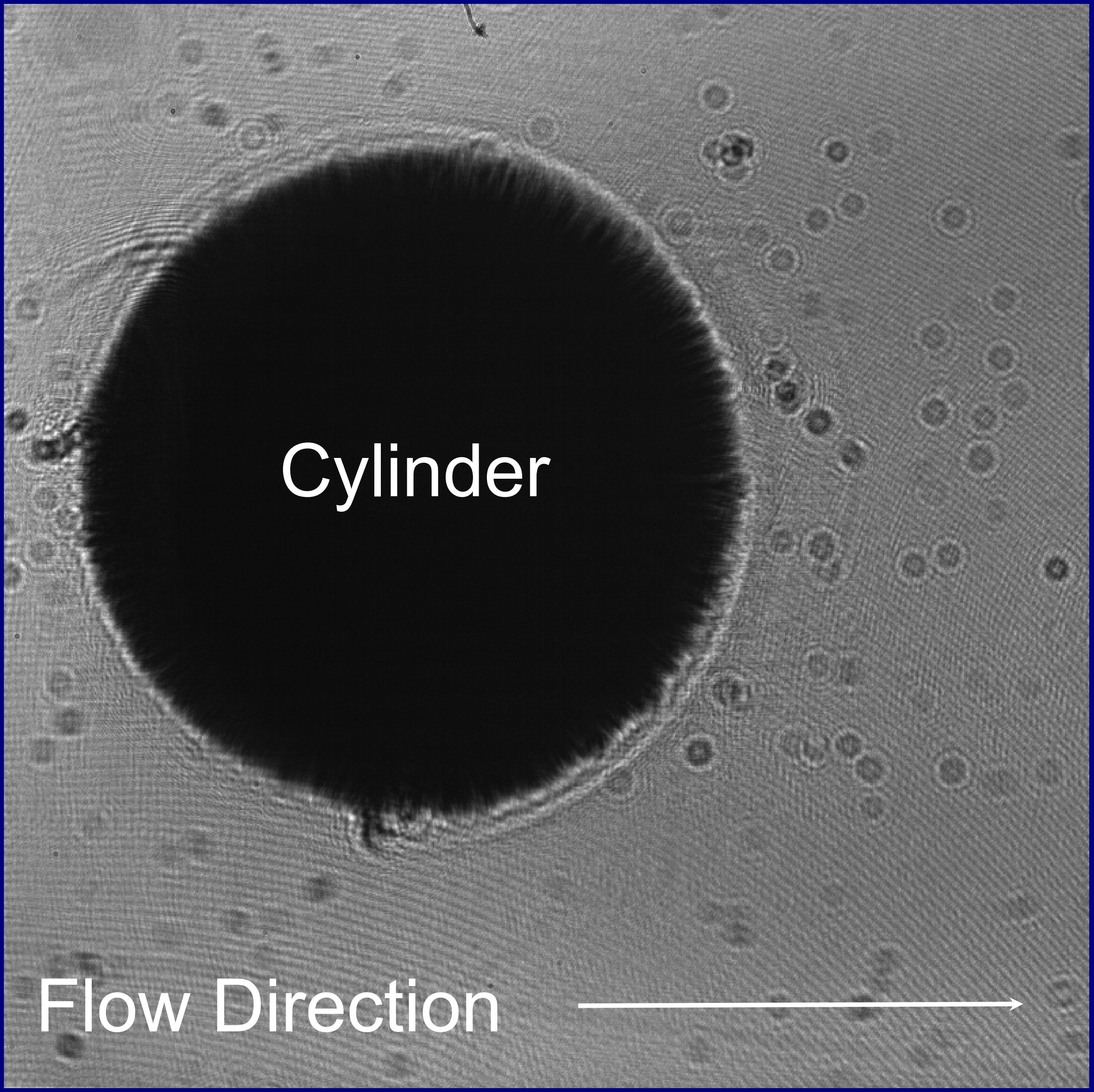
Experimental Design Considerations

- Recording distance (Zhang 2006)
  - If large z: low pass filter
  - If small z: limited FOV, aliasing
- Particle concentration (Kim, 2008)
  - Speckle noise vs. flow information recovery
- CCD: size, pixel size

Experimental Setup



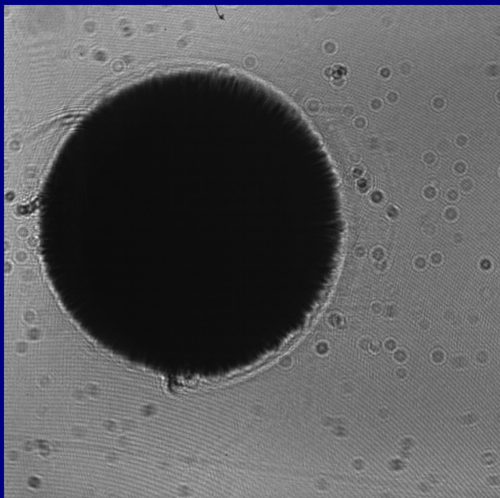
Raw Image



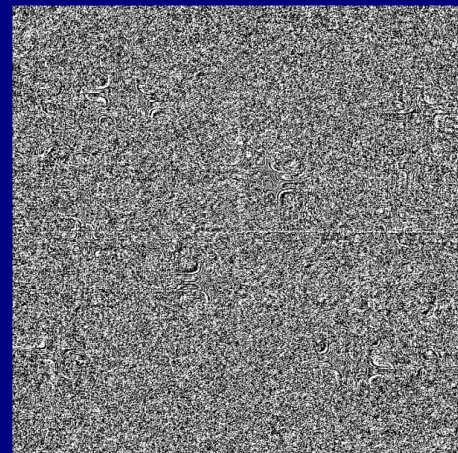
Reconstruction Code

(Convolution Method)

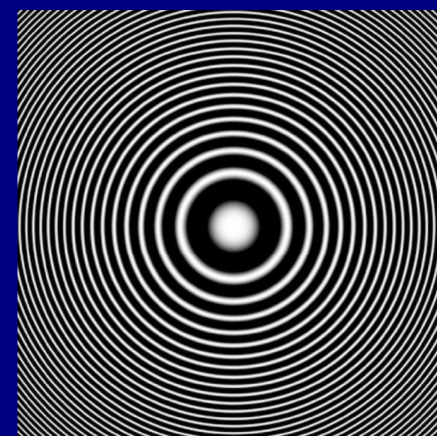
Crop initial image to square



Take the Fourier Transform



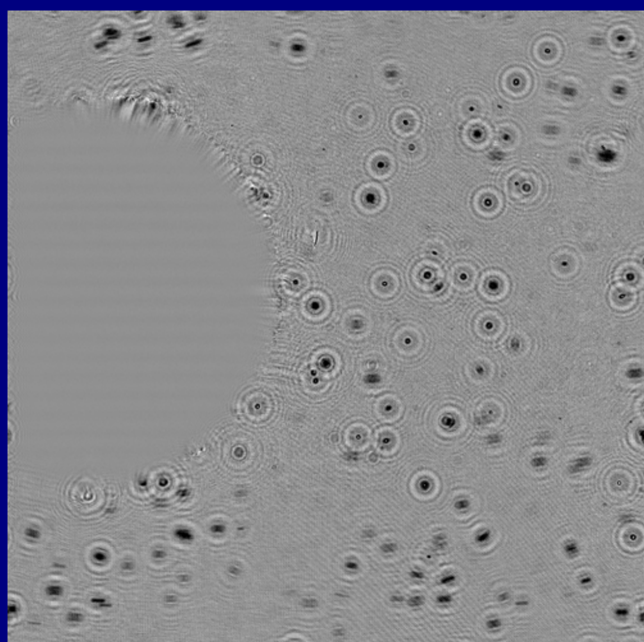
Multiply this by the Fresnel “diffraction kernel”



$\exp\{-i\pi\lambda z\,(u^2+v^2)\}$

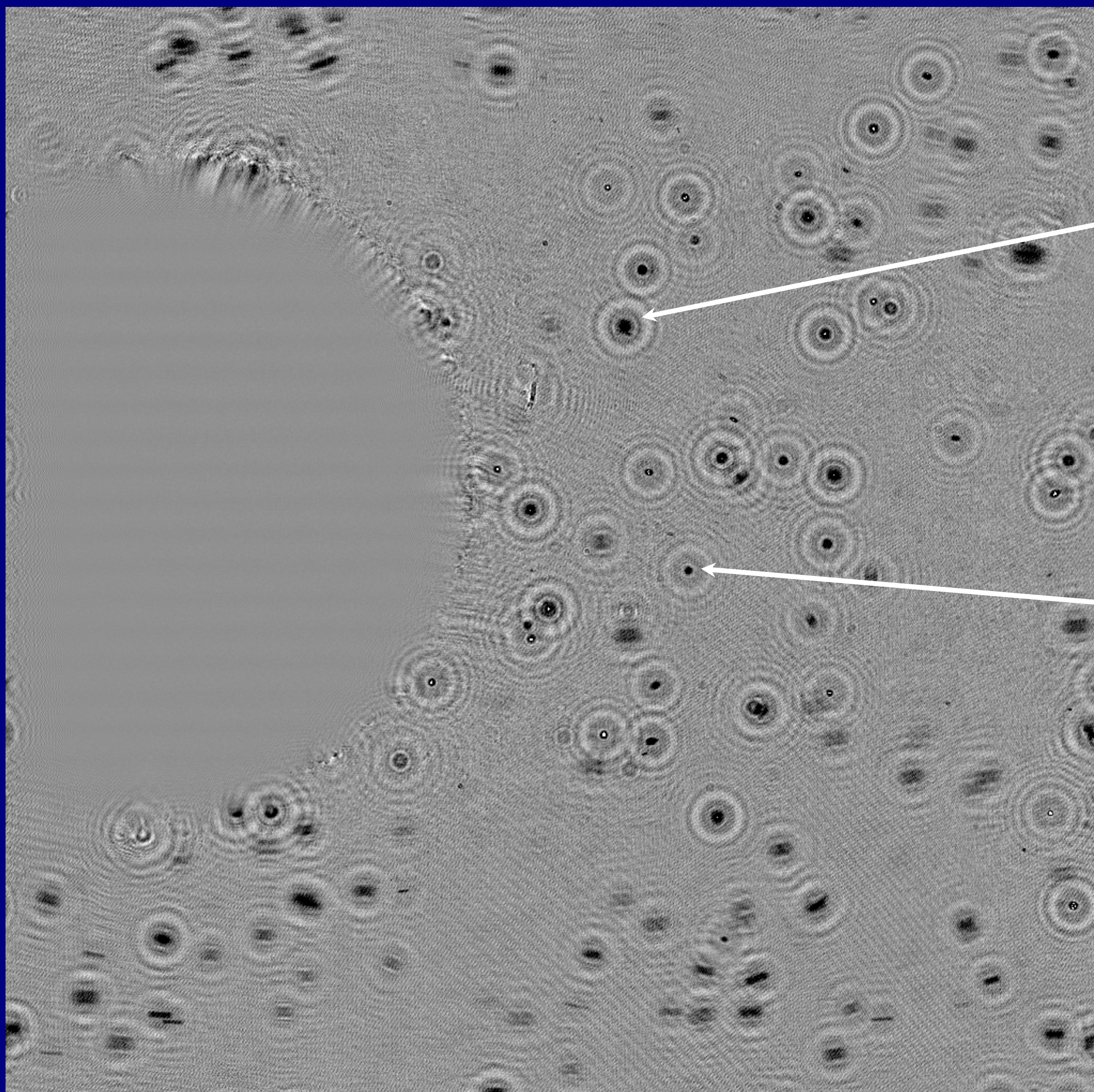
note the dependence on z depth

Take the inverse Fourier Transform



Reconstructed image

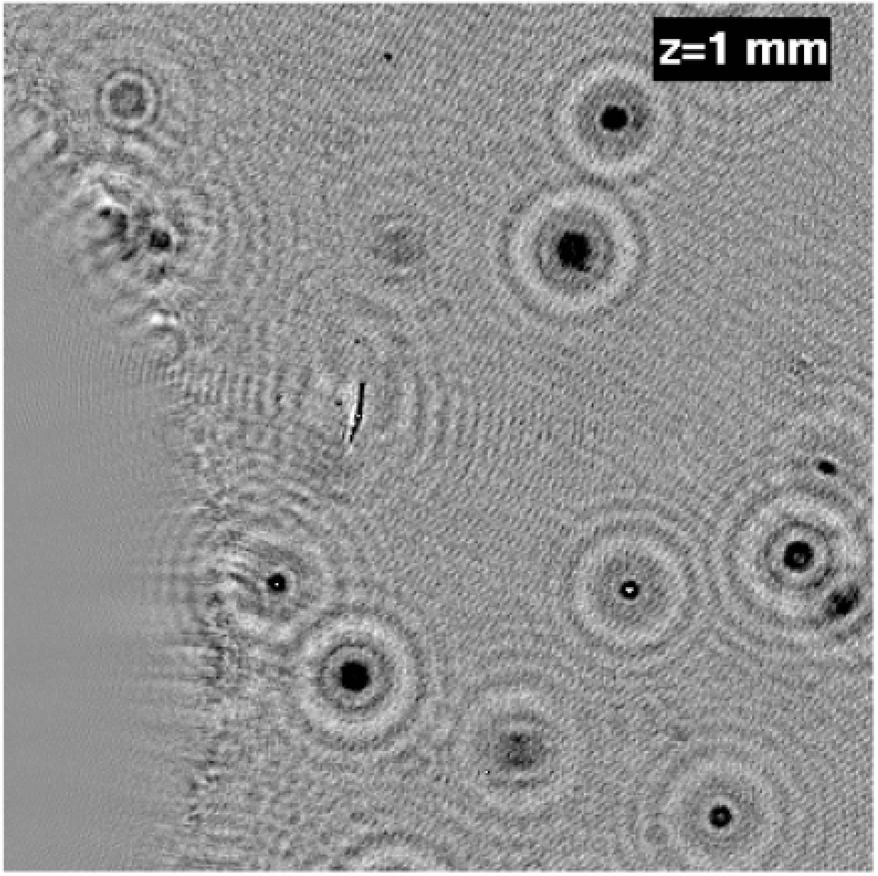
Reconstructed Image



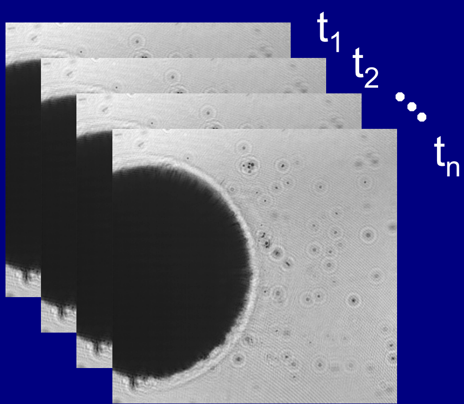
Out of focus particle

In focu particle

Reconstruction In Depth



Particle Detection



Input: Time series of raw holograms

1. Image Preprocessing and Reconstruction:
- Subtract background
- Reconstruction
- Threshold
- Convert to B&W

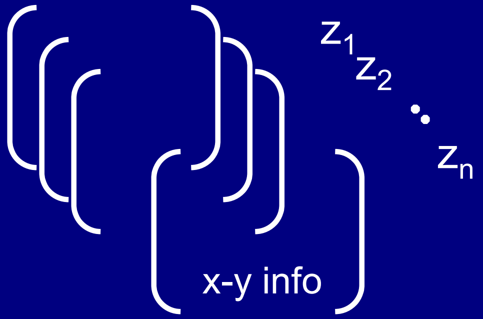
2. Locate Particles in x-y:
- `bwlabel` (MATLAB)
- Bounding box and centroid of contiguous white zones

3. Eliminate invalid particles
- Outside of expected size
- Double-counting a single particle

Output: matrix of labeled particles with x-y position of centers and area for each z-plane

Label	x	y	area
1			
2			
…			
n			

Particle Detection (cont'd)

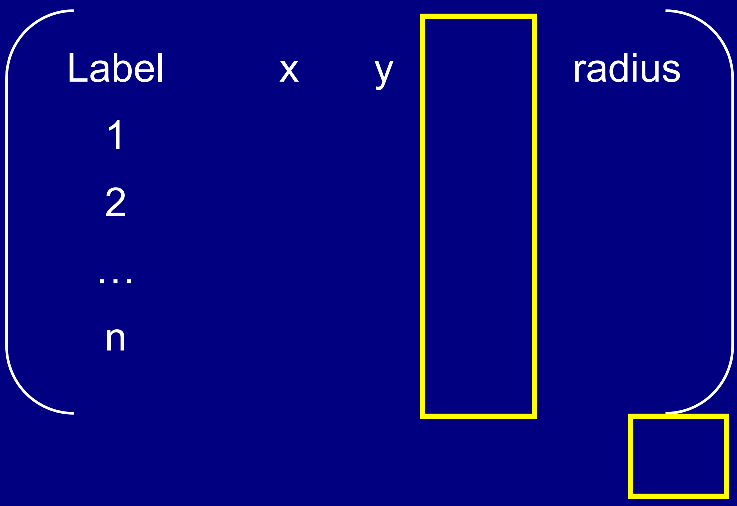


Input: x-y coordinate matrices at each z-plane

1. Load output of previous step
- z-plane is determined by step size

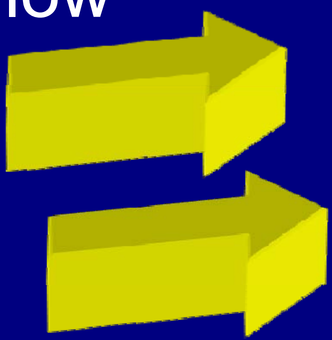
2. Eliminate doubles:
- Particles may appear in focus in multiple planes
- Choose based on minimum radius

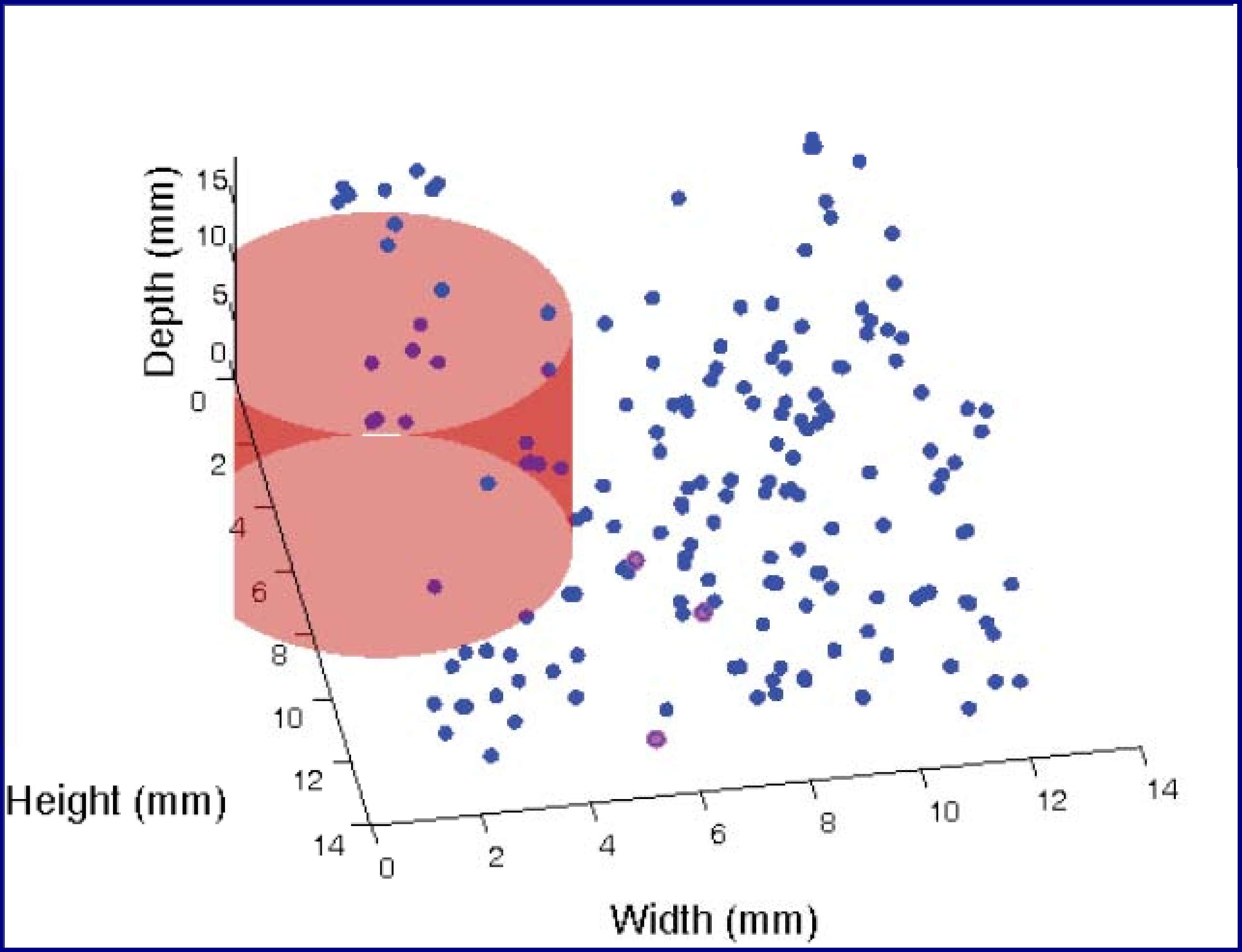
Output: matrix of labeled particles with **x-y-z** position of centers and **radius** for each **time step**



Result: 3D Flow

Flow



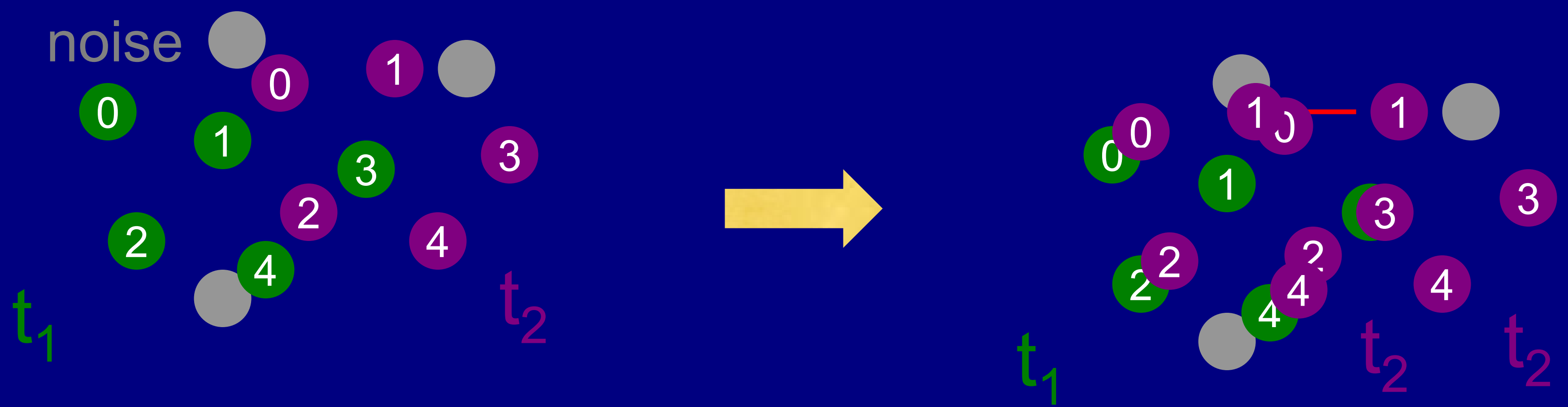


Calculating Velocity Maps

- HPIV typically uses 3D coordinates as data
  - Computing cost of images is high (96 GB)
- Tradeoffs depending on complexity of flow, mean velocity
  - Correlation: complex flows, dense particle seeding
  - Particle tracking: low velocity flows, sparse seeding (reduces speckle noise)

Velocity Maps by Correlation

- Correlation (Pu & Meng, 2000)



Two spatially shifted images (time sequence)

Mean displacement vector

- Shift images according to mean velocity vector
- Within discrete interrogation windows, pair particles based on closest distance, group deformation threshold

Velocity Maps by Particle Tracking

- Pair particles by minimizing a cost function (Stellmacher & Obermayer 2000)

- Utilize knowledge about flow:

$$\vec{Y}_i - \vec{A}\vec{X}_i + \vec{t}$$

- Cost function

$$E(m,t,A) = \sum_{j=1}^{J}\sum_{k=1}^{K} m_{jk} \left\| Y_j - \underbrace{t - AX_k}_{Y_k} \right\|^2 + \underbrace{g(A)}_{\text{“regularizer”}} + \underbrace{\alpha \sum_{j=1}^{J} m_{j(K+1)} + \alpha \sum_{k=1}^{K} m_{(J+1)k}}_{\text{Cost for unmatched particles}}$$

- Maximize expectation

Velocity Maps - Others

- Genetic algorithm particle pairing (Sheng and Meng 1998)
  - Treat pairings like chromosomes
  - Choose "most fit" pairs to propogate
- Optical correlation (Coupland and Halliwell 1997)
  - Expand 2D autocorrelation to 3D
  - Can utilize FFT

Velocity Maps

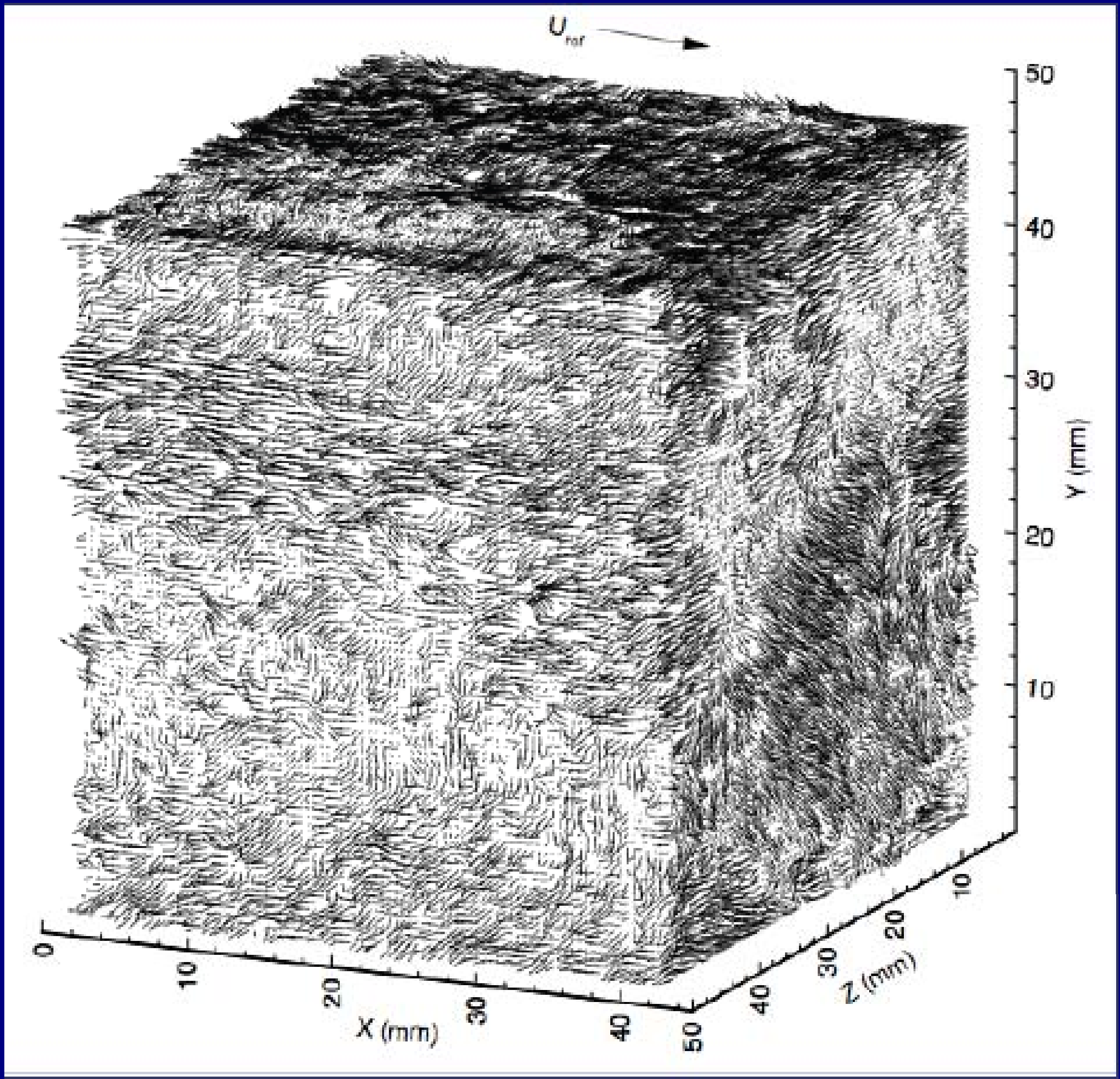


Image from http://www.me.jhu.edu/lefd/hpiv/3d_vec.pdf
Courtesy of Bo Tao. Used with permission.

- Questions?

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