# Imagerie holographique rétinienne hyperspectrale en temps réel sur GPU

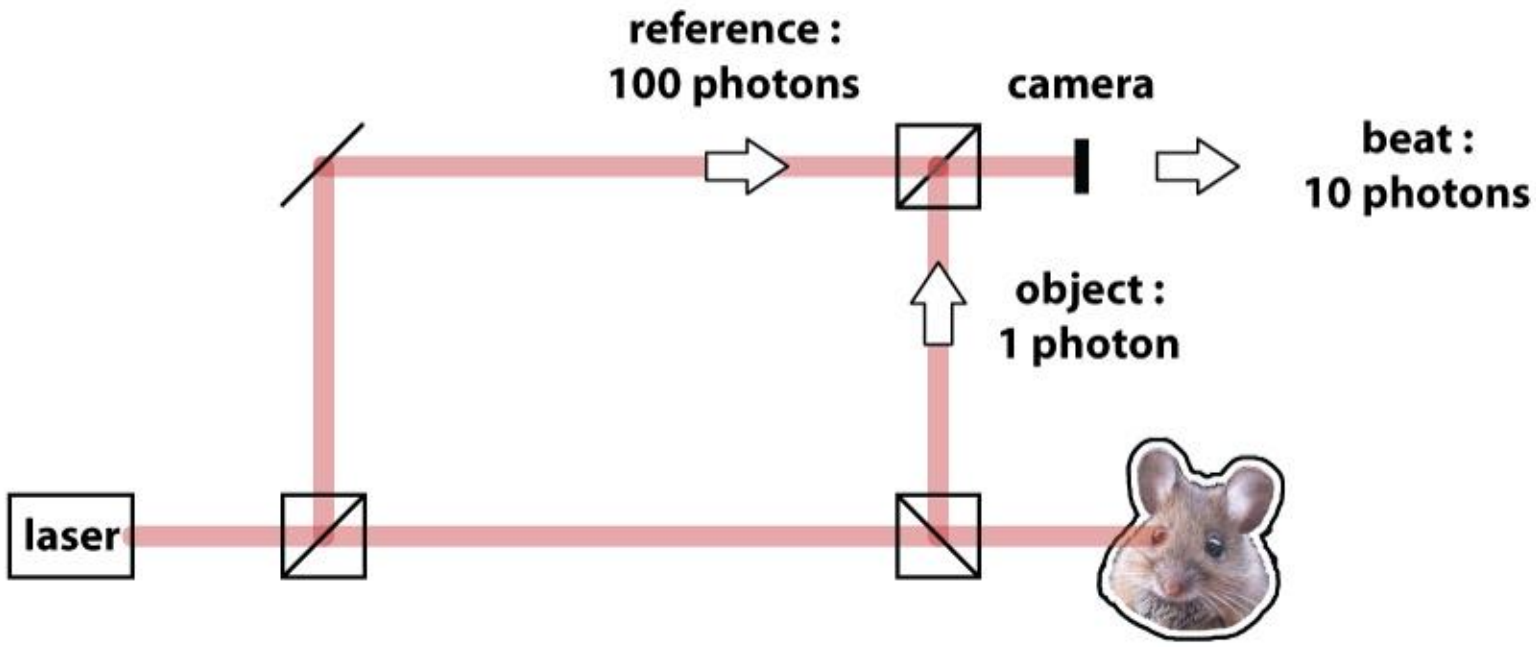

Institut **Langevin**
ONDES ET IMAGES


# Why holography ?

# Because of its sensitivity

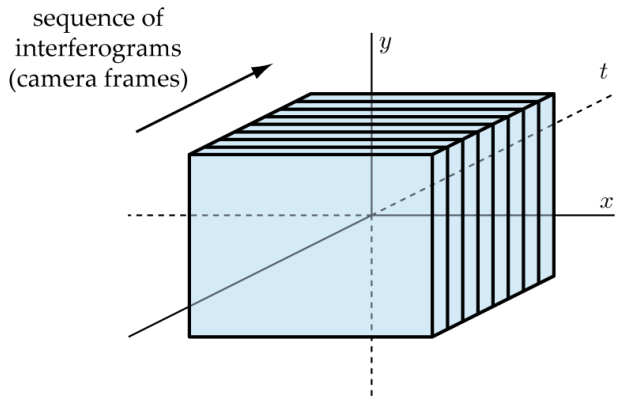
# Coherent detection in high heterodyne gain regime

The weak object wave beats against the reference wave.
Signal modulation depth is enhanced by coherent detection

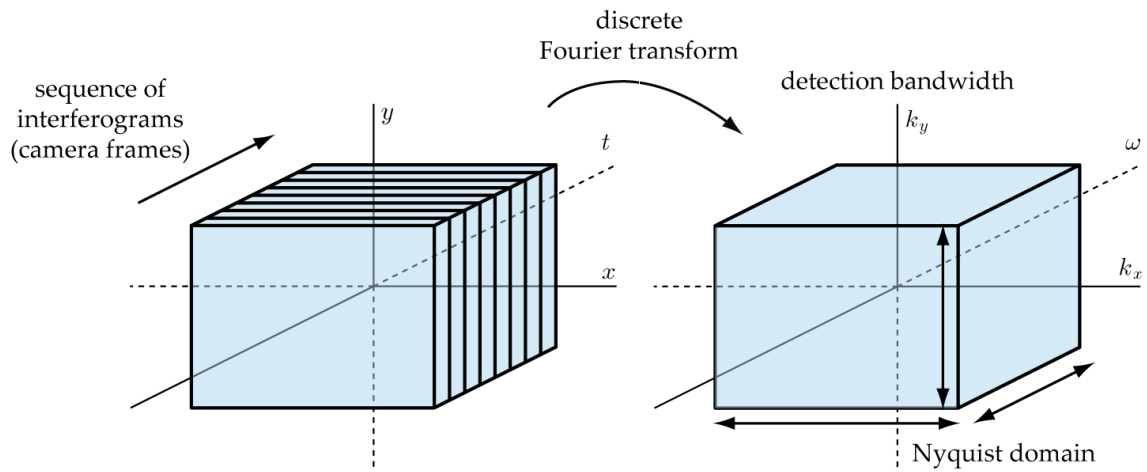



Purpose : assess weak signals

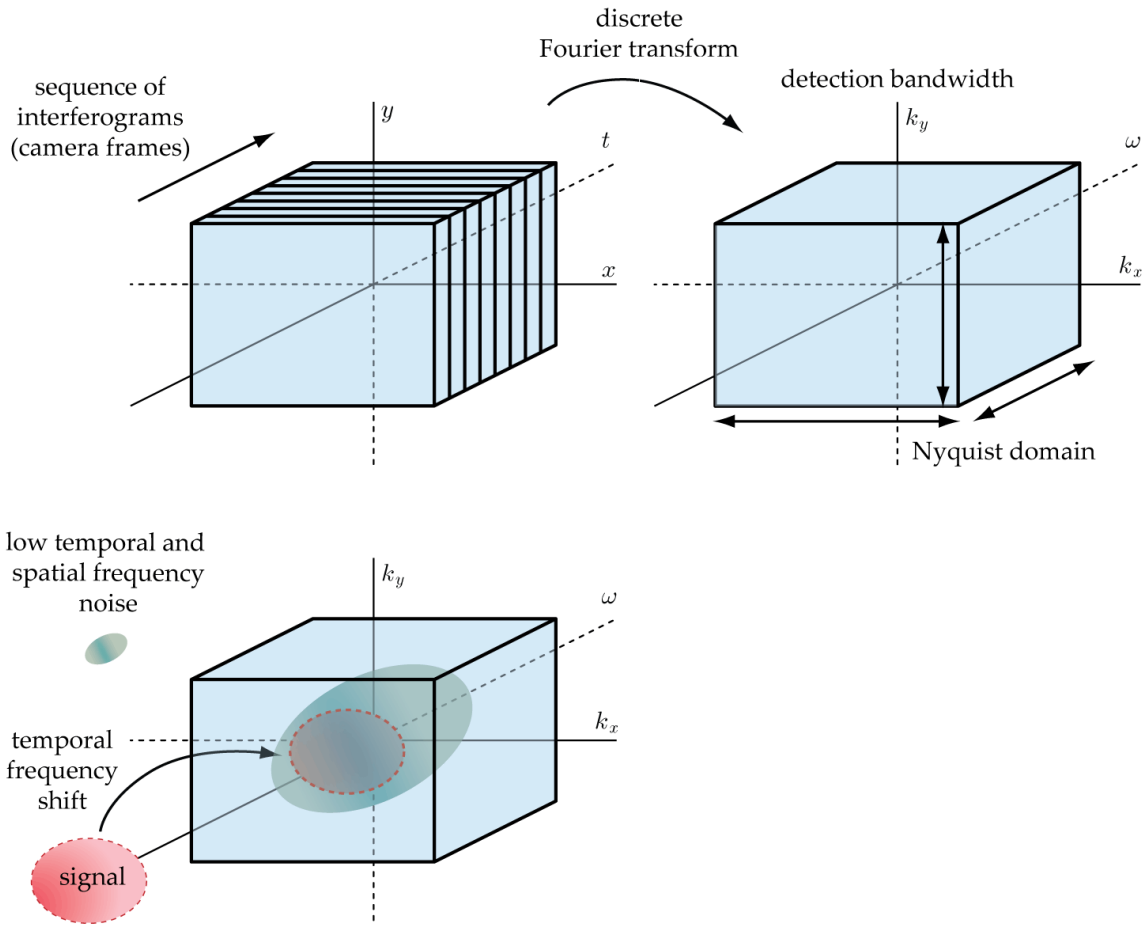
# Image recording. Direct domain



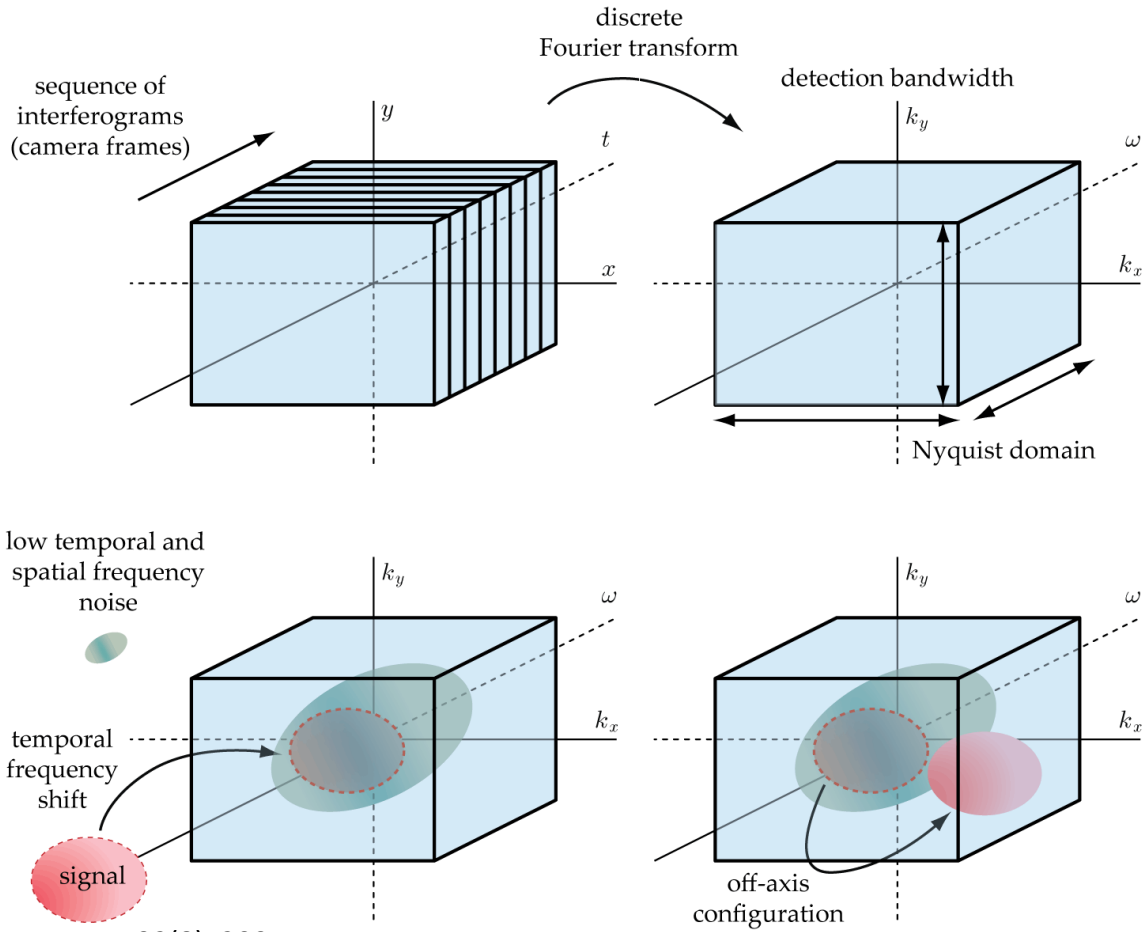
# Fourier domain



# Temporal modulation



# Spatial modulation : off-axis configuration

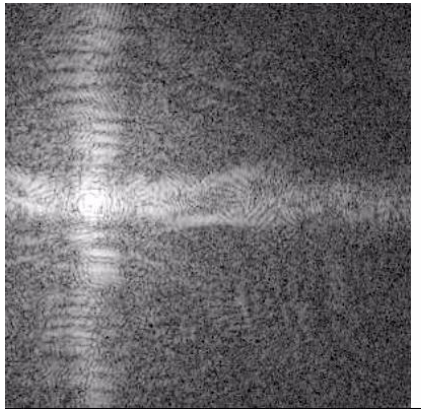


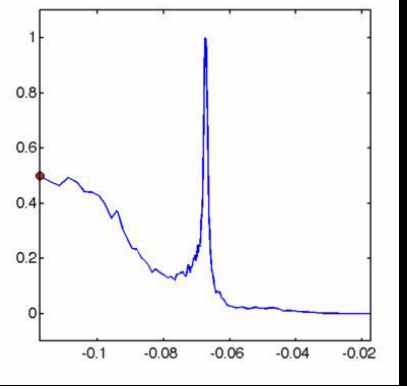

M. Gross;, M. Atlan. Optics Letters, 32(8), 2007
M. Atlan, M. Gross. JOSAA, 24(9), 2007

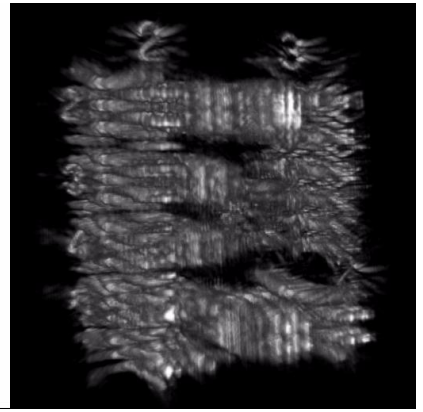
# Optical acquisition and numerical image rendering

$$E(x,y,z) \approx \iint \hat{E}(k_x,k_y,0) \times \exp\left(ik_z z\right)\exp\left(ik_x x + ik_y y\right)\mathrm{d}k_x\mathrm{d}k_y$$

$$E(x,y,z) \approx \frac{e^{ikz}}{i\lambda z}\iint E(x',y',0) \times \exp\left[\frac{ik}{2z}\left((x-x')^2+(y-y')^2\right)\right]\mathrm{d}x'\mathrm{d}y'$$

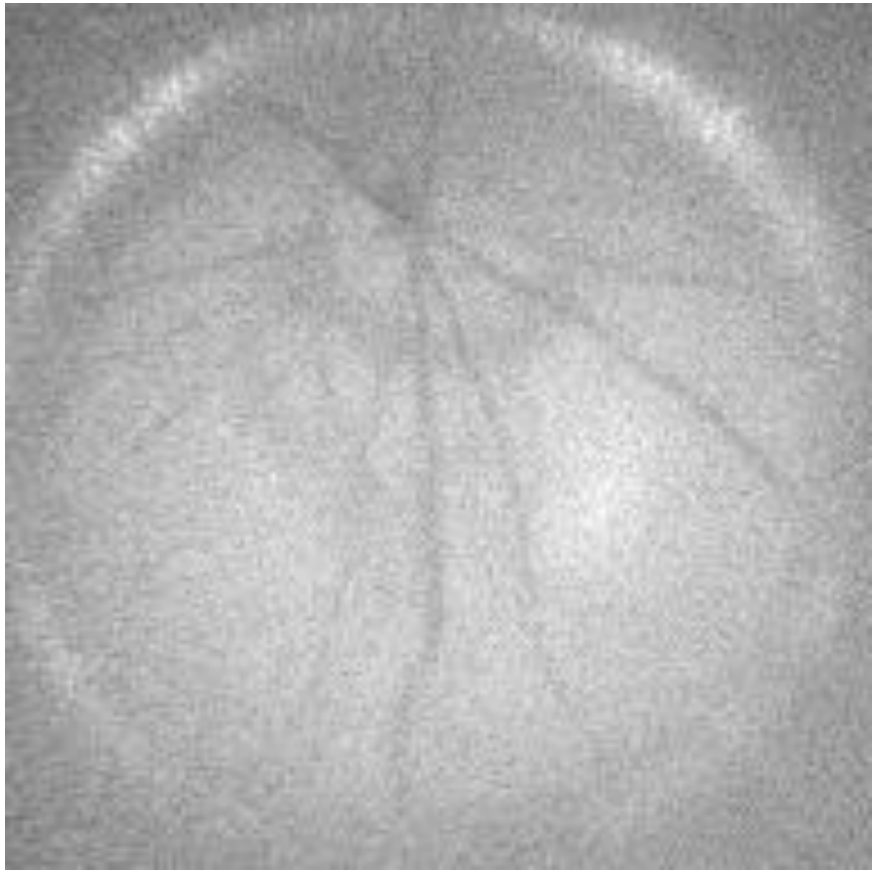


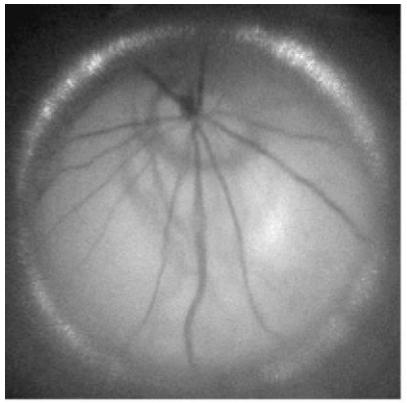



**Magnain et al. "Holographic laser Doppler imaging of microvascular blood flow." *JOSA A* 31.12 (2014): 2723-2735.**

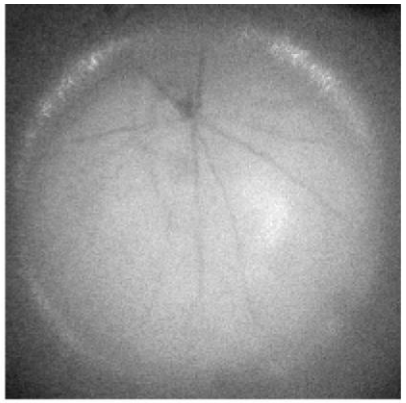
# Retinal blood flow

1Hz – 25 kHz

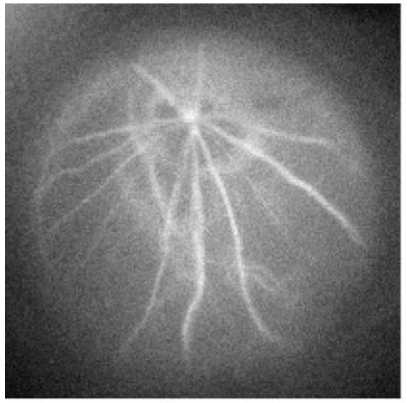




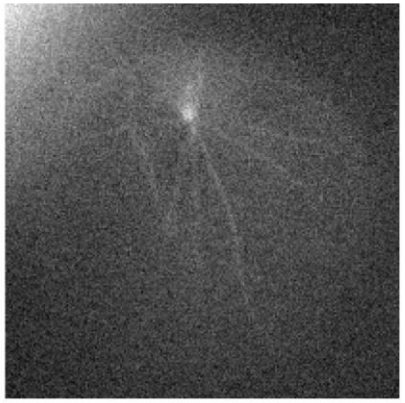
10 Hz



1 kHz



3 kHz

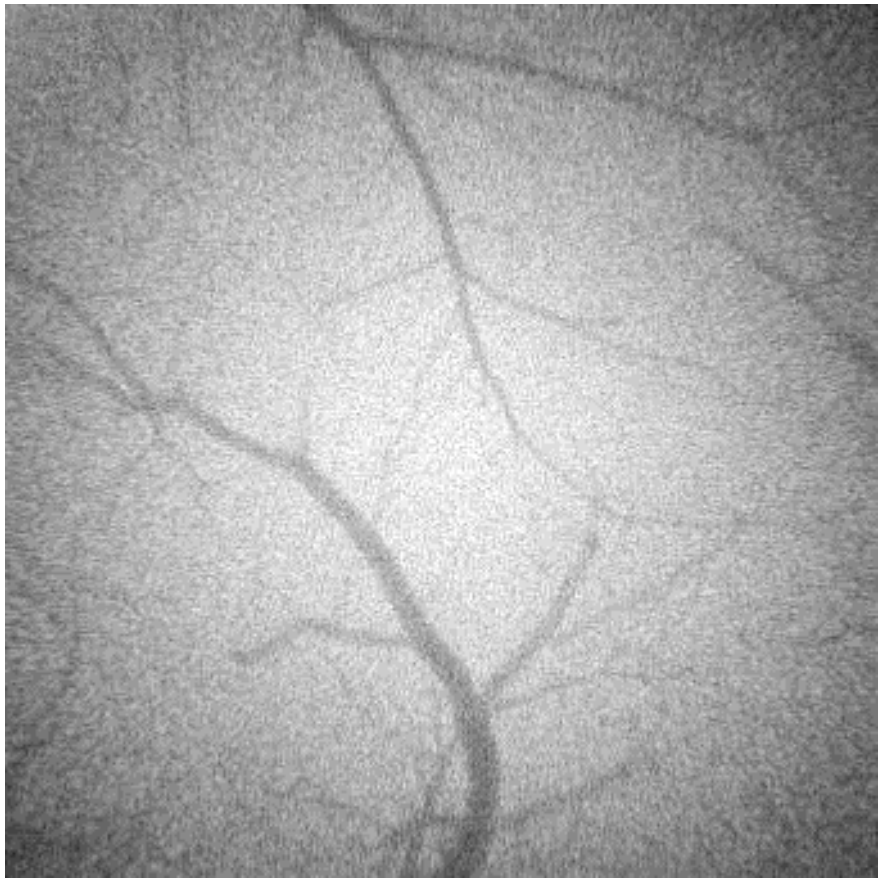


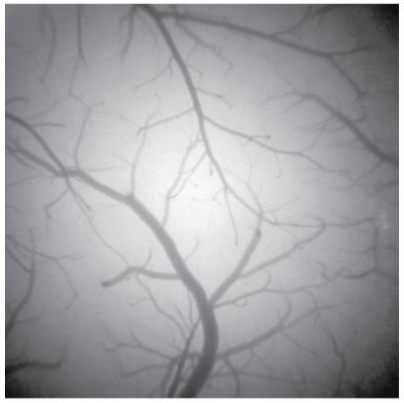
8 kHz

**Acquisition time : 2.7 s per image. Frame rate : 12 Hz**

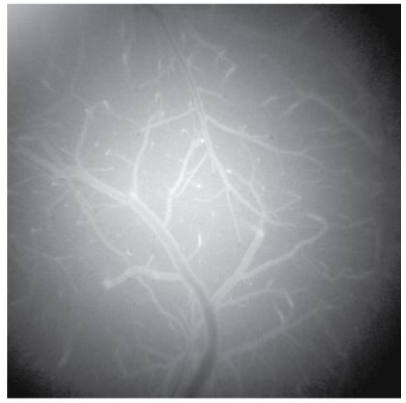
# Cerebral blood flow

1Hz – 100 kHz

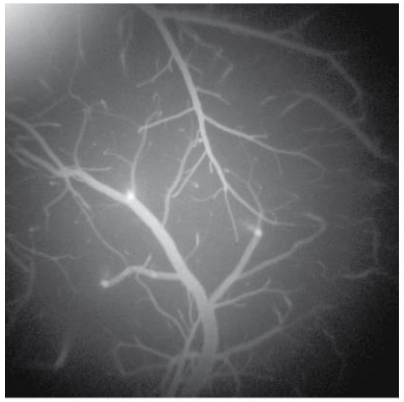




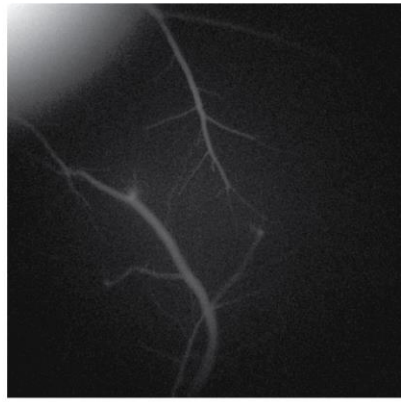
15 Hz



1.2 kHz



3 kHz

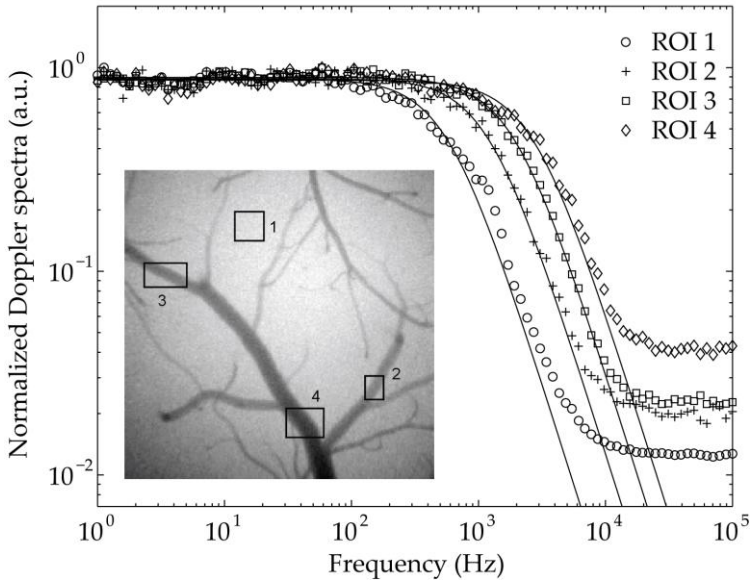


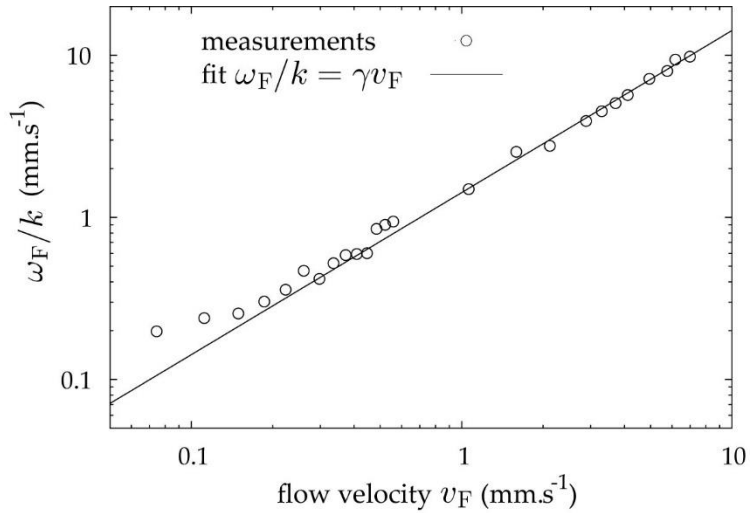
7 kHz

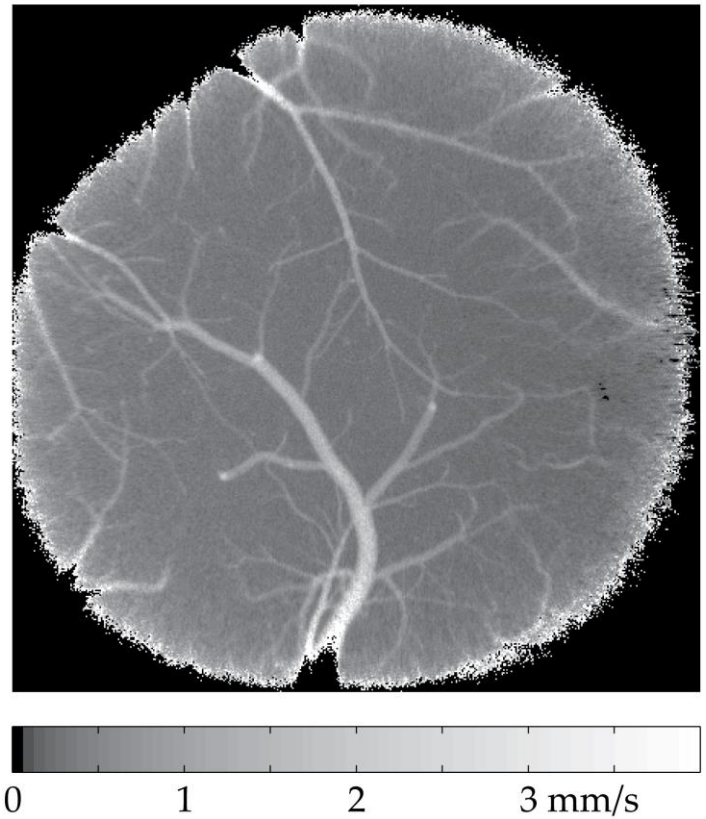
**Acquisition time : 2.7 s per image. Frame rate : 12 Hz**

# Derivation of flow maps

## Local RMS flow velocity scales as local Doppler broadening

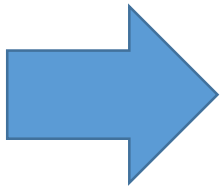



**Magnain et al. "Holographic laser Doppler imaging of microvascular blood flow."** ***JOSA A*** **31.12 (2014): 2723-2735.**

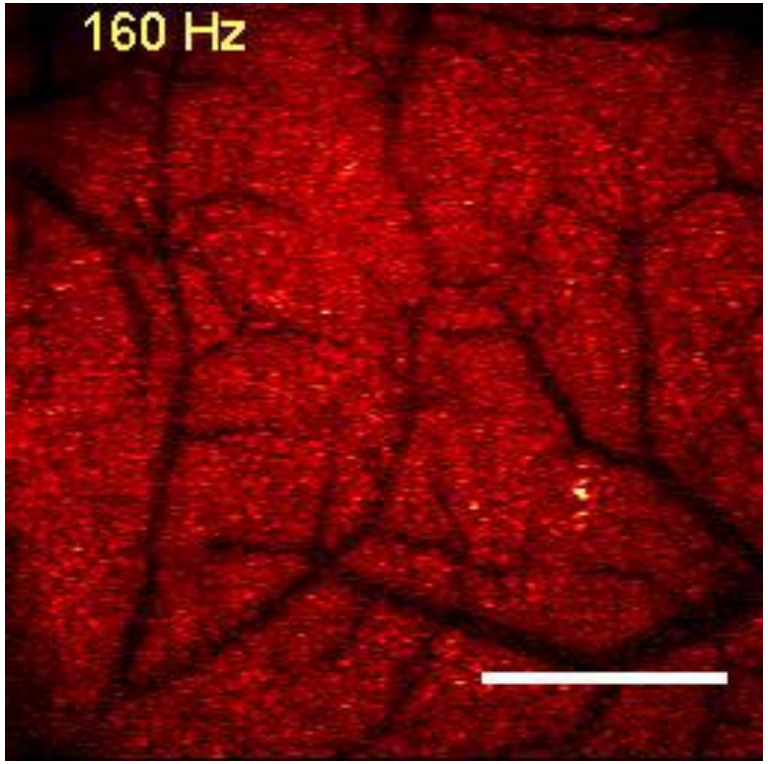
# Increasing temporal resolution

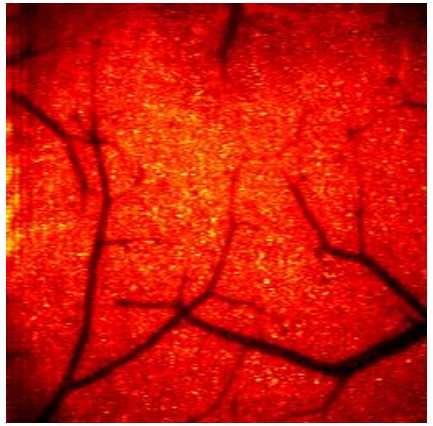



Readout rate:
~15 000 000
pixels/s
(1 Megapixel @ 15 Hz)

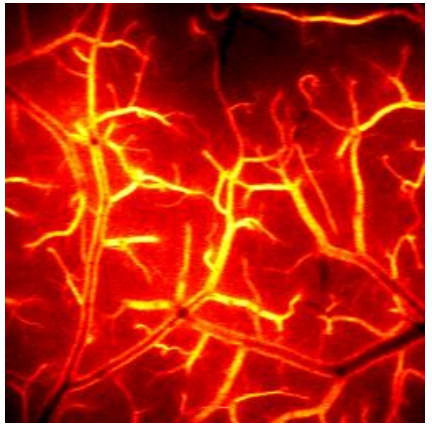
Readout rate:
~12 000 000 000
pixels/s
(1 Megapixel @ 12 kHz)

# Cerebral blood flow. High speed Doppler spectra

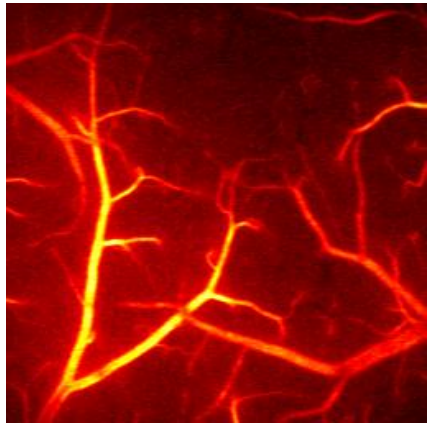


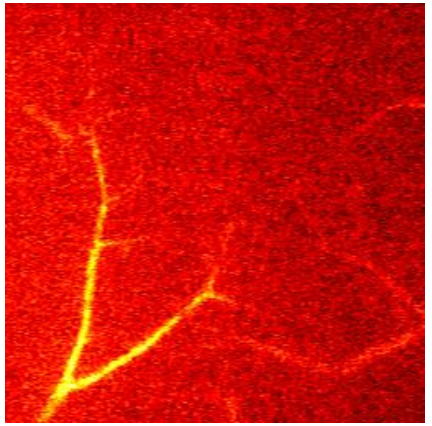
960 Hz



3400 Hz



11 kHz

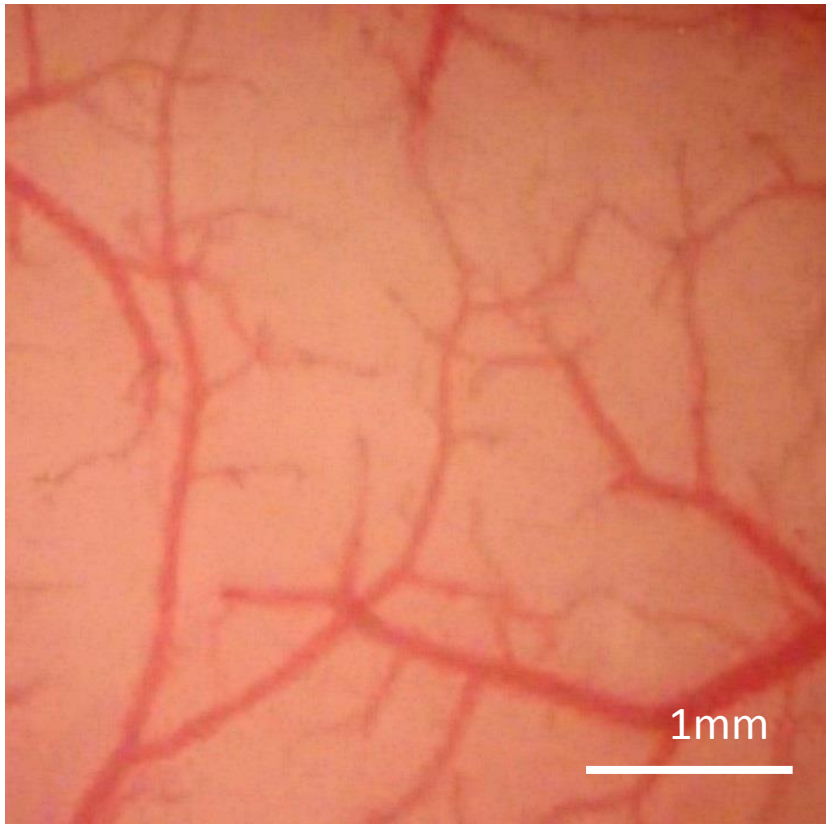


24 kHz

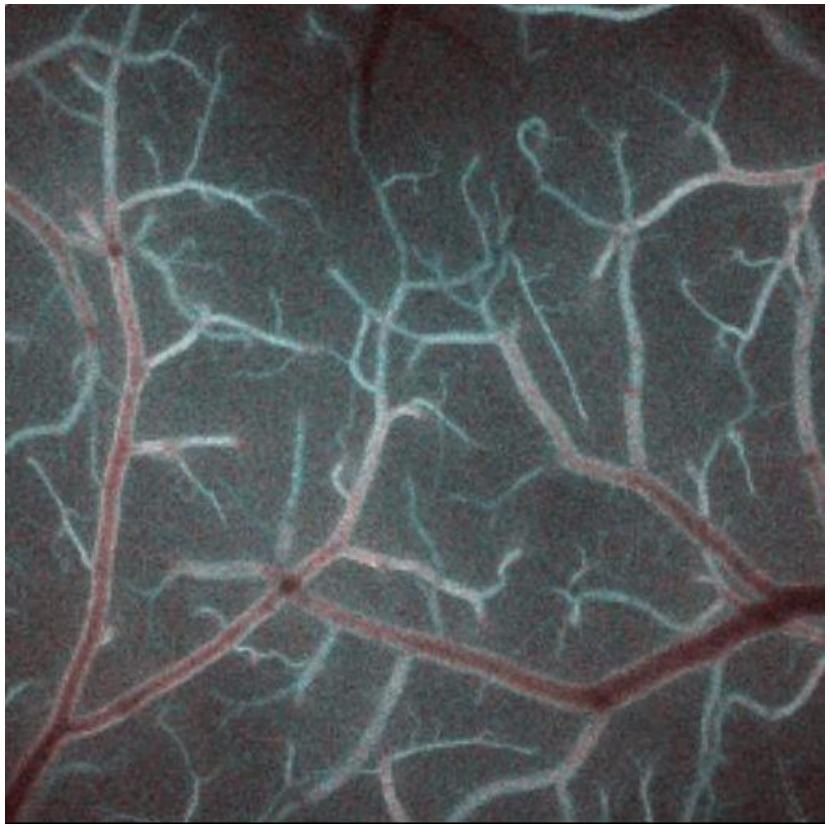
**FFT window : 160 ms. Frame rate : 50 kHz.**

# Pulsatile cerebral blood flow

White-light microscopy



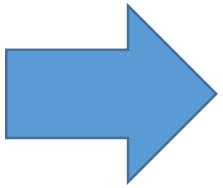

holography



**Puyo et al. “Pulsatile microvascular blood flow imaging by short-time Fourier transform analysis of ultrafast laser holographic interferometry”, arXiv. 2015.**

**FFT window : 20 ms. Frame rate : 50 kHz.**

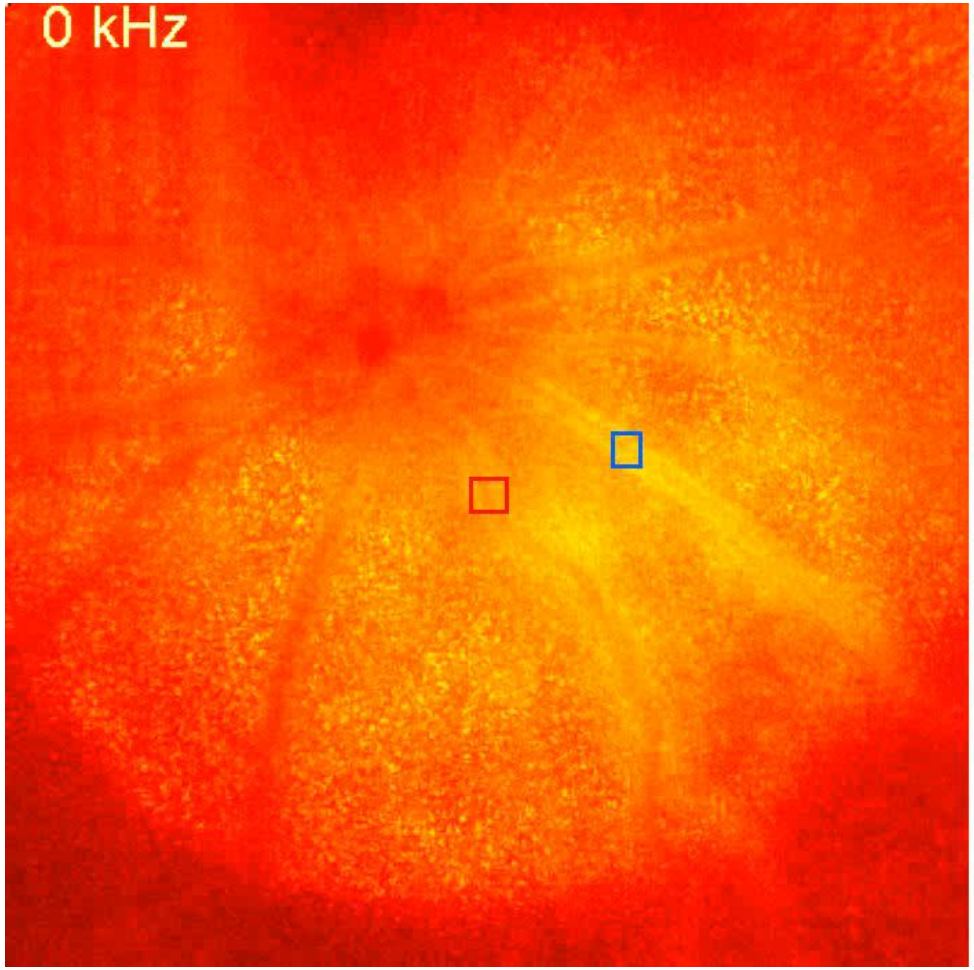
# Increasing temporal resolution (again)

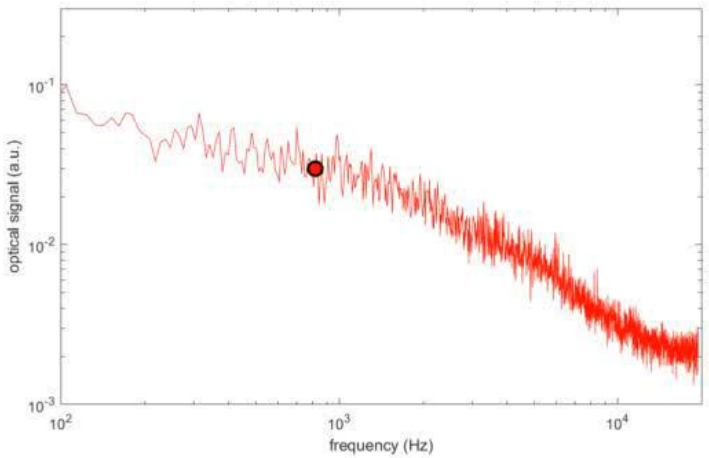


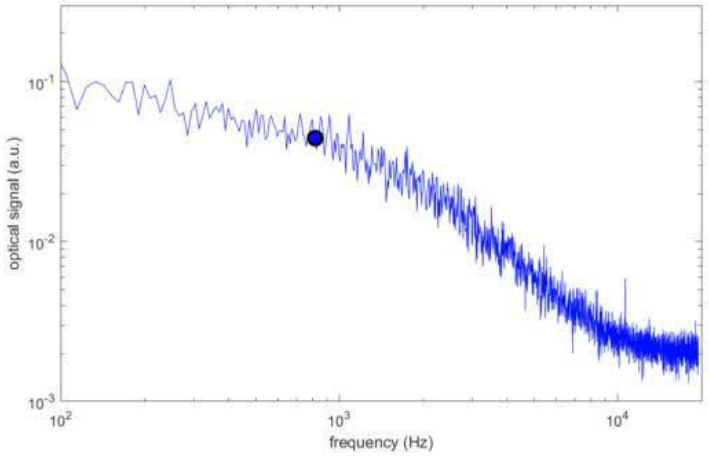
Readout rate:
~12 000 000 000
pixels/s
(1 Megapixel @ 12 kHz)

Readout rate:
~25 000 000 000
pixels/s
(1 Megapixel @ 25 kHz)

# Retinal blood flow. High speed Doppler spectra

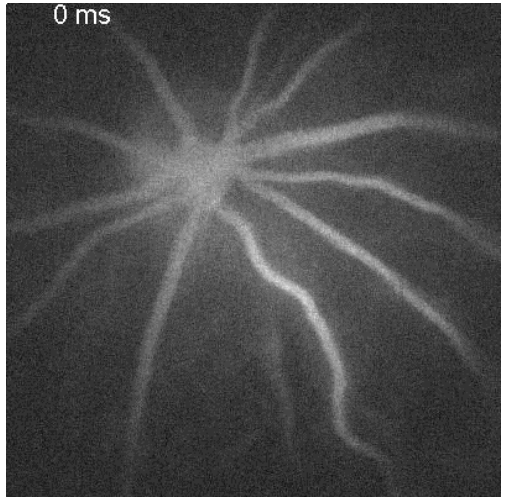


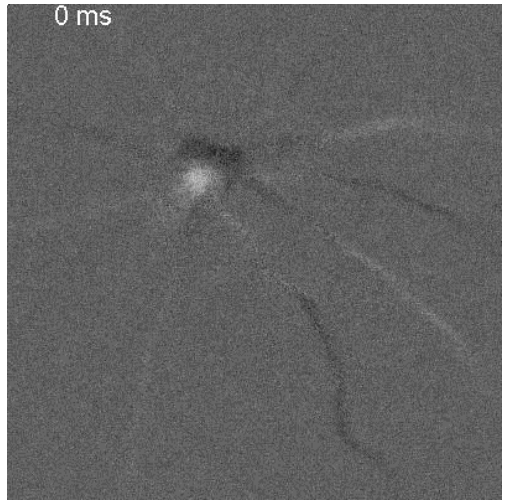



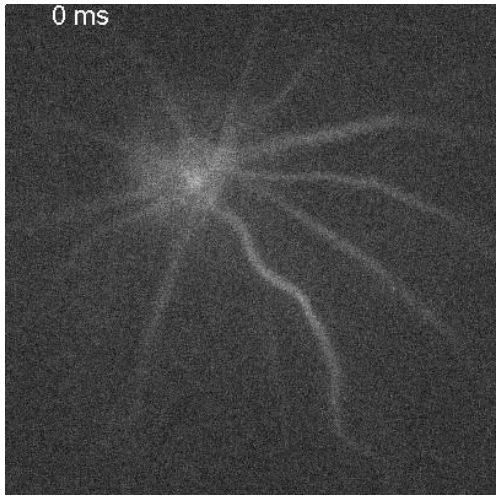




**Frame rate : 39 kHz. FFT window : 25 ms.**

# First moments of the spectrum



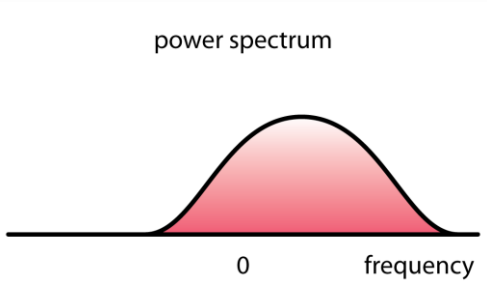



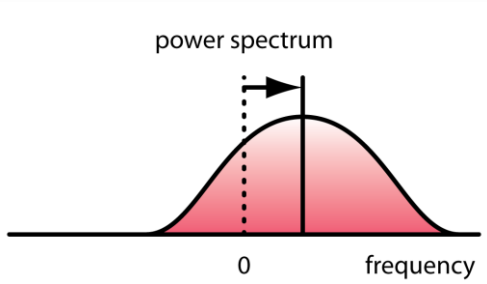



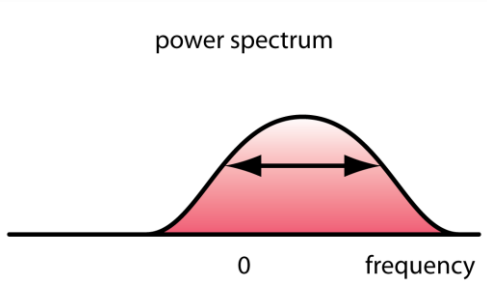

M0

M1

M2



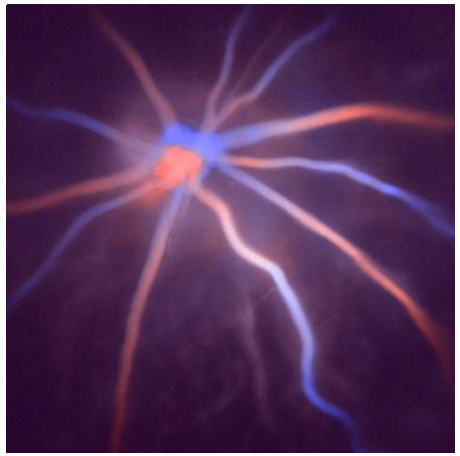



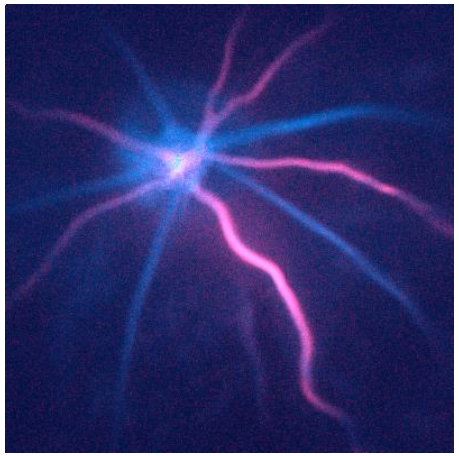




Pellizzari et al. “High speed optical holography of retinal blood flow”, arXiv. 2016.

**Frame rate : 39 kHz. FFT window : 6.5 ms.**

# Axial flow and quadratic mean flow in rat. High speed camera

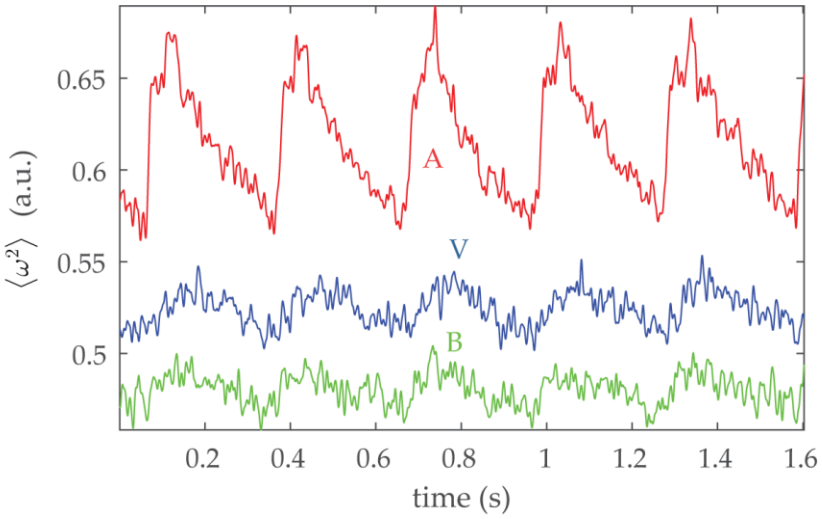


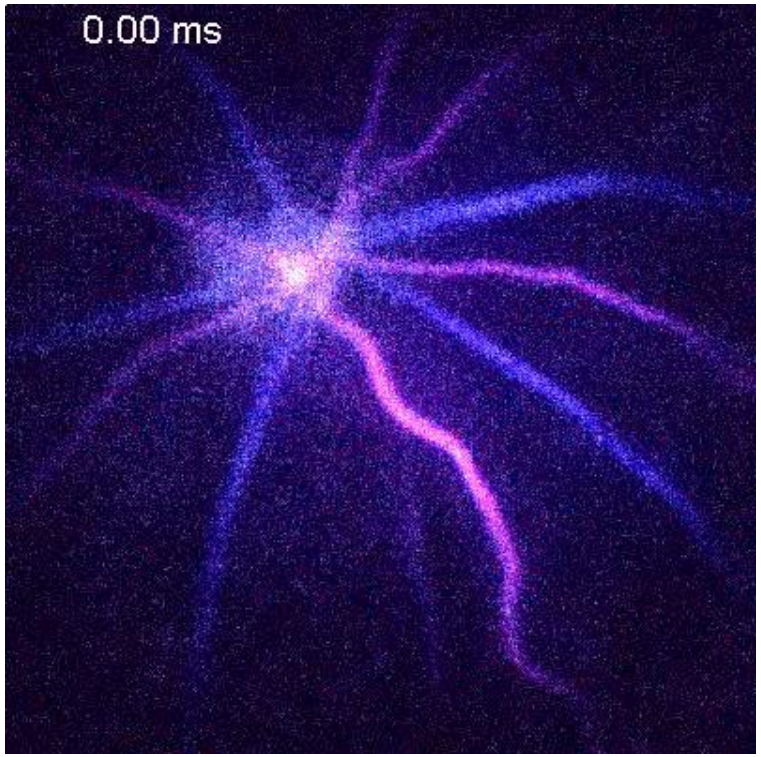


M0 + M1

M0 + M2

M2 versus time




quadratic mean flow.
Not quantitative yet

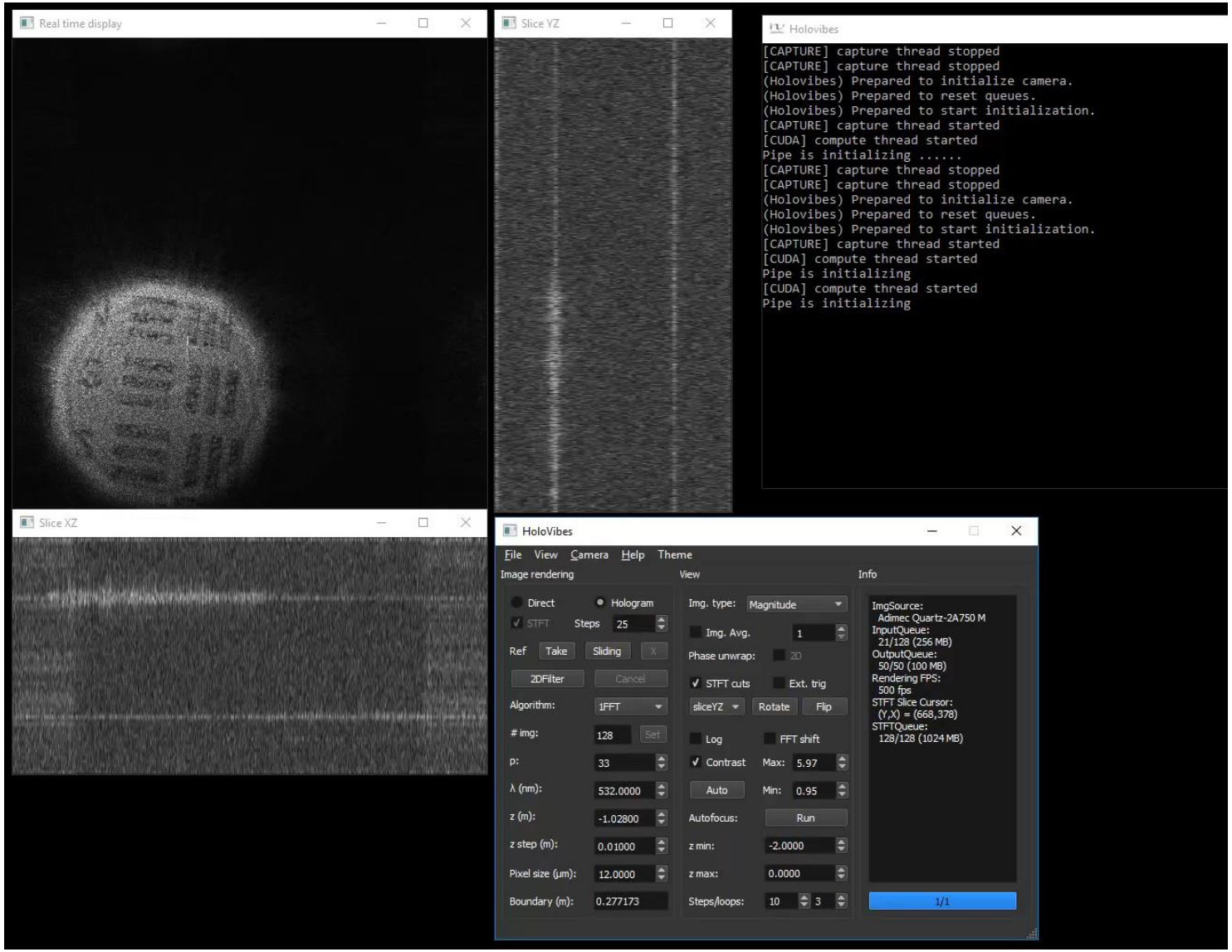
Frame rate : 39 kHz. Temporal resolution : 6,5 ms

# Real-time ultrahigh-speed hologram rendering


www.holovibes.com

**1024x1024x128 voxels @ 20Hz ~ 2.5 billion voxel/s**
**1024x1024x256 voxels @ 10Hz ~ 2.5 billion voxel/s**
**512x512x512 voxels @ 20Hz ~ 2.5 billion voxel/s**

# Real-time ultrahigh-speed hologram rendering + short-time Fourier transforms



Spoon drop: ~1 ml

Niagara falls : ~2,500 m^3/s

# = 2.5 billion 💧 /s

# Advantages

Quantitative narrowband and wideband laser Doppler imaging of the retina by holographic interferometry

- No exogenous contrast agent
- High throughput sampling @ 25 billion pixels/s
- **Low-light sensitivity : exposure to CW NIR (785 nm) radiation ~1.6 mW over 3 mm x 3 mm**
- Wide-field imaging ~ $10^6$ pixels (x ¼, off-axis config.)
- Temporal resolution of the Doppler maps ~ 6.5 ms
- Quantitative imaging of optical phase and fluctuation spectra