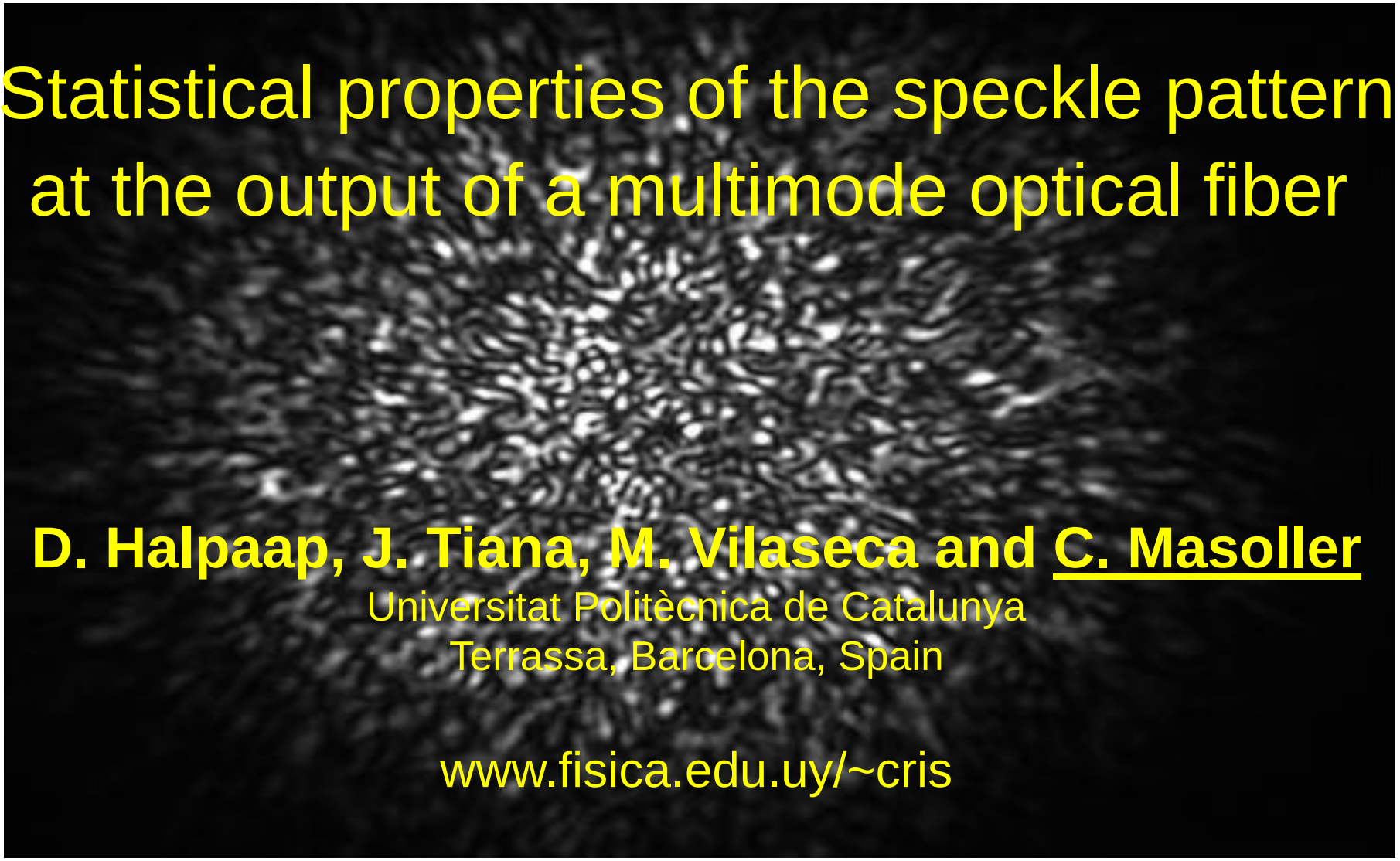
Statistical properties of the speckle pattern at the output of a multimode optical fiber



D. Halpaap, J. Tiana, M. Vilaseca and C. Masoller

Universitat Politècnica de Catalunya
Terrassa, Barcelona, Spain

www.fisica.edu.uy/~cris

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GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

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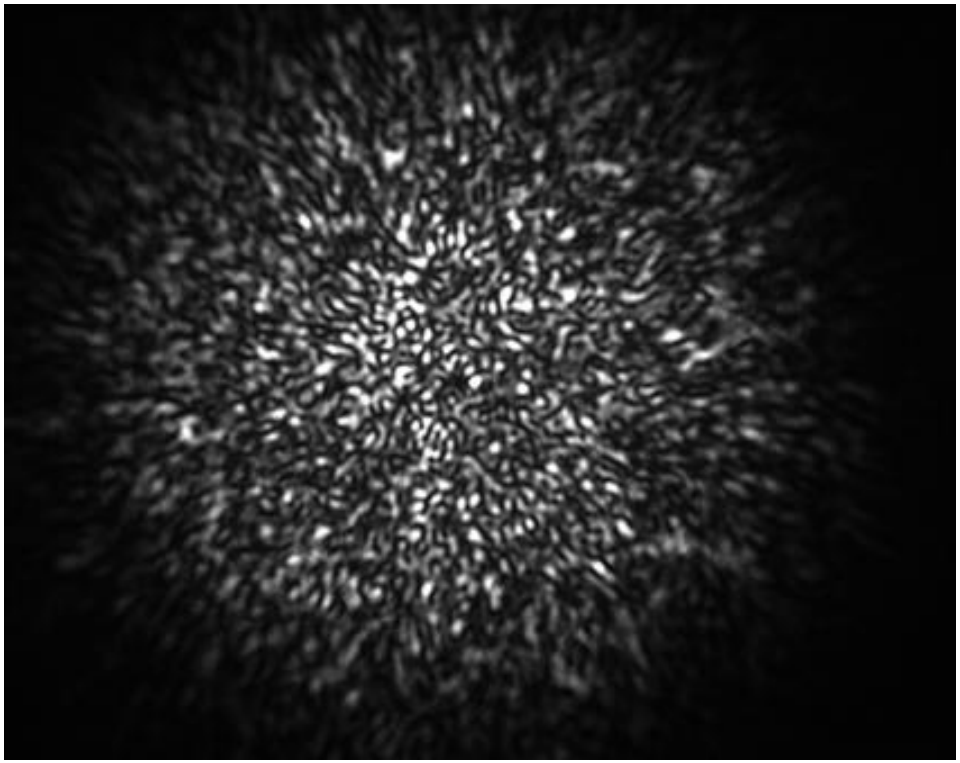
Advanced Biomedical Optical Imaging and Data Analysis

ICREA

What is speckle?

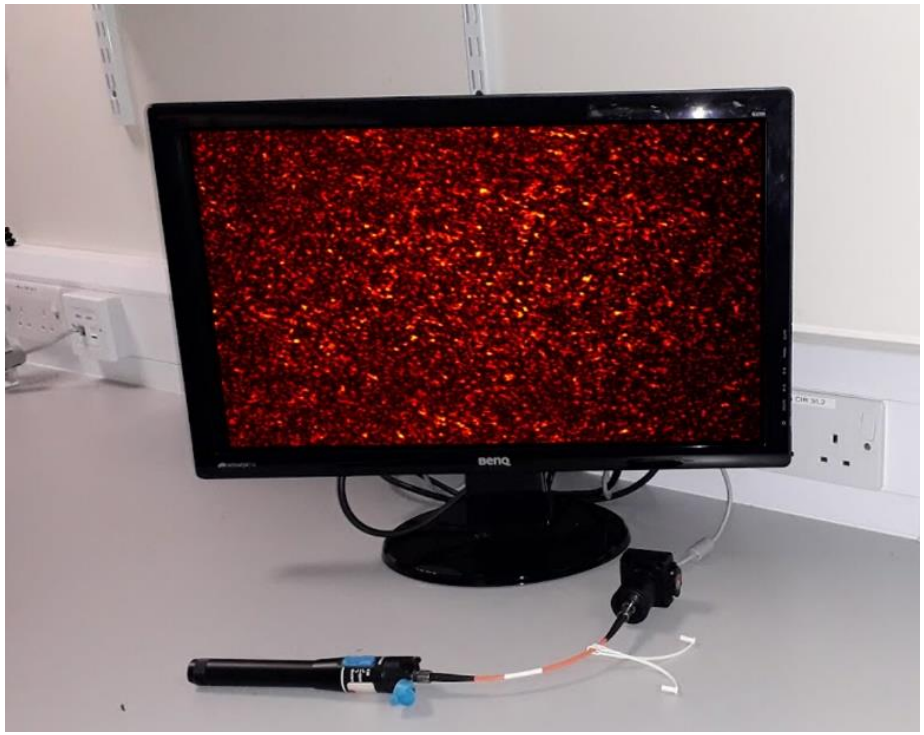
- A speckle pattern is an intensity pattern produced by the mutual interference of a set of wave fronts.
- It occurs in diffuse reflections of monochromatic light.



- Speckle is undesirable for many applications but contains useful information that can be exploited in some applications.

Speckle-based spectrometer / wave-meter

- Exploits the speckle pattern produced by interference between the guided modes of a multimode fiber.



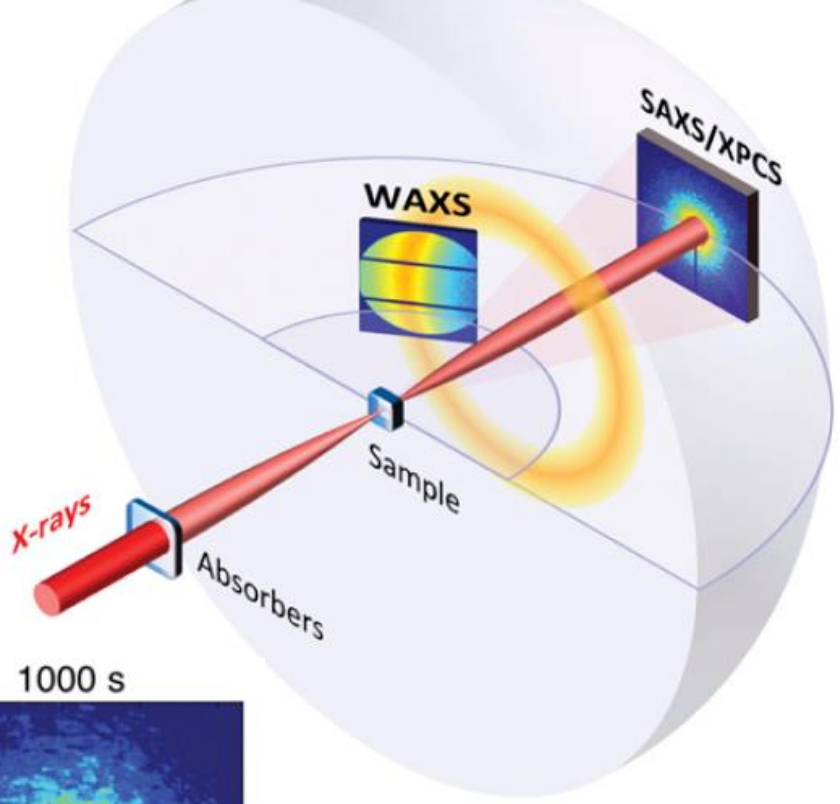
Attometer precision demonstrated by Dholakia' group (march 2019)

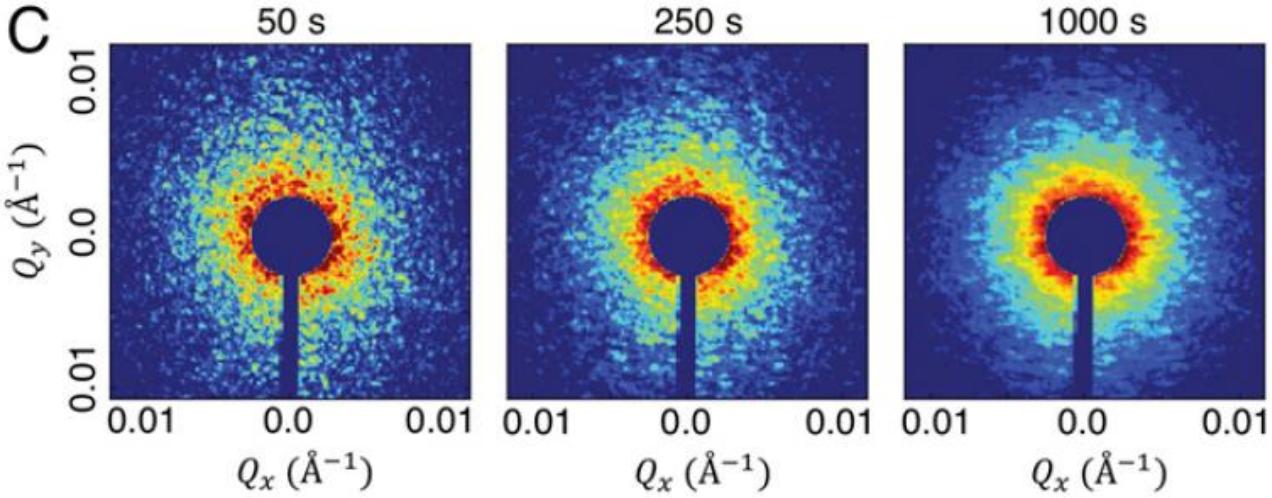
Laser light is passed through the optical fiber (orange), and is recorded on the camera. The speckle pattern produced is shown on the screen.

Source: phys.org

B. Redding and H. Cao, "Using a multimode fiber as a high-resolution, low-loss spectrometer," Opt. Lett. 37, 3384 (2012).

Speckle patterns generated by scattering particles and recorded with different exposure times can be used to extract information about the dynamics of the sample.

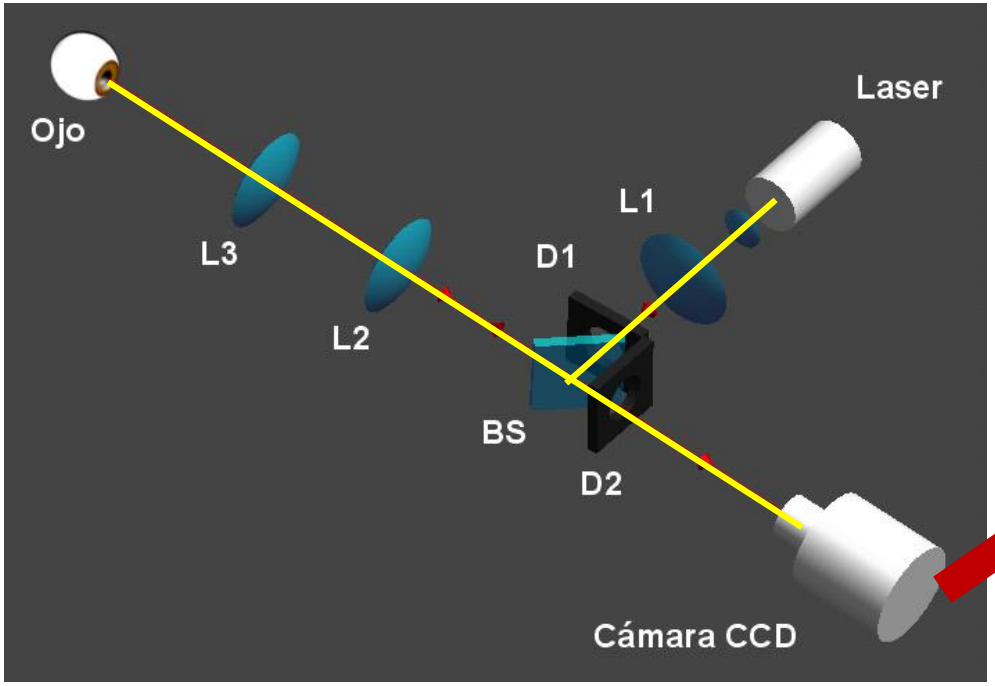




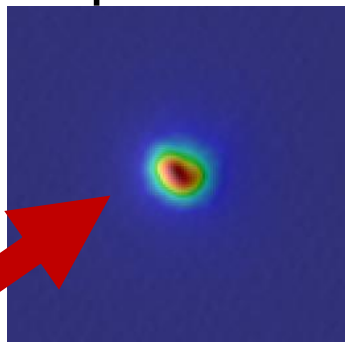
F. Perakis et al, Diffusive dynamics during the high-to-low density transition in amorphous ice, PNAS 114, 8193 (2017).

Our motivation: speckle in double-pass retina imaging

- Image of a **point source** projected on the retina after reflection from retina (therefore, double pass through the ocular media).



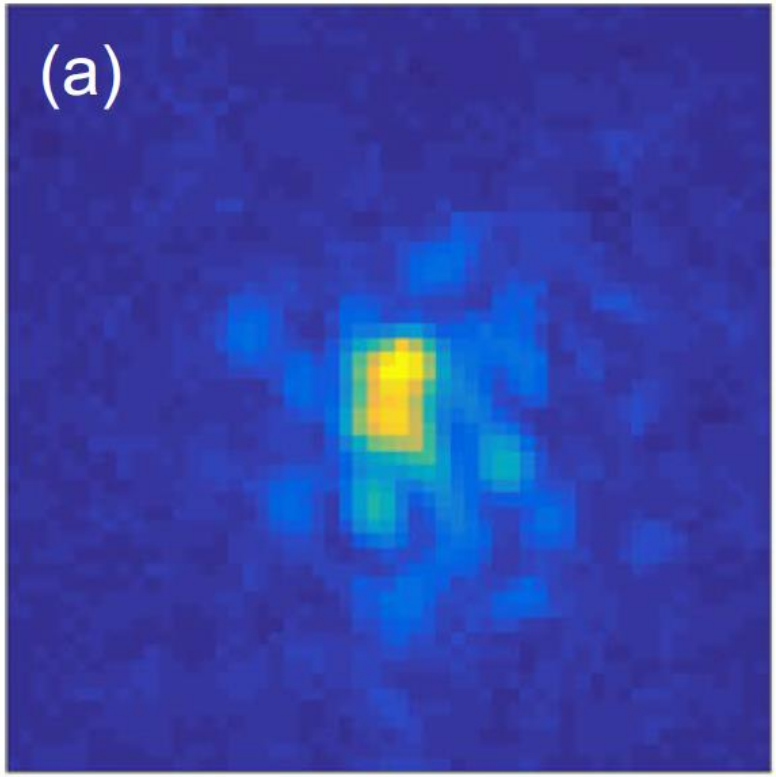
"ideal output" from CCD:
Point spread function



Measures the optical quality of the eye.

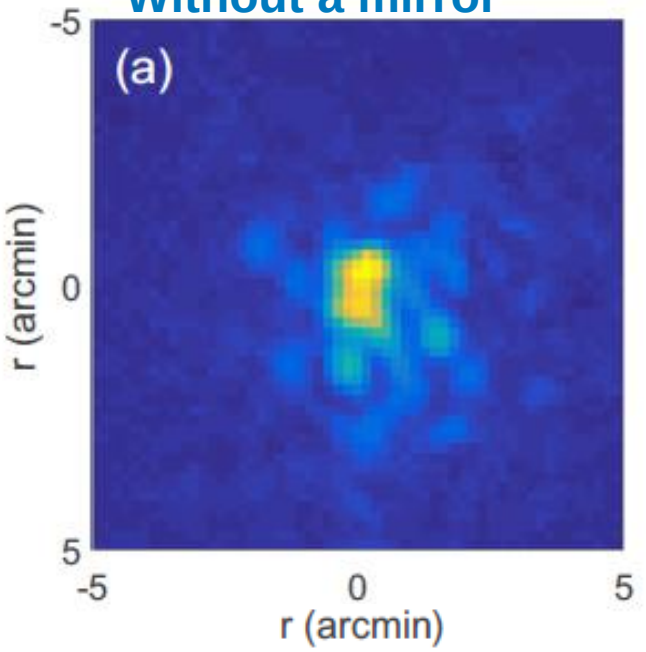
2-3% retinal reflection → laser light (limited in wavelength and power by the patient's comfort).

- **Problem**: the roughness of the retina in the scale of the wavelength of the laser light produces speckle.

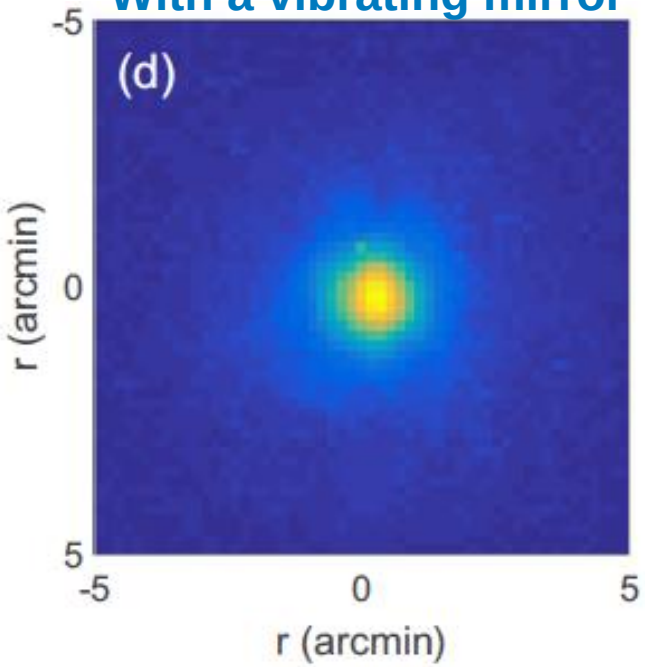


- **Solution**: Placing a vibrating mirror in the light beam (that moves the beam in the retina but not in the camera) + averaging several images.

Without a mirror



With a vibrating mirror



Our **goal**: find an all-optical solution

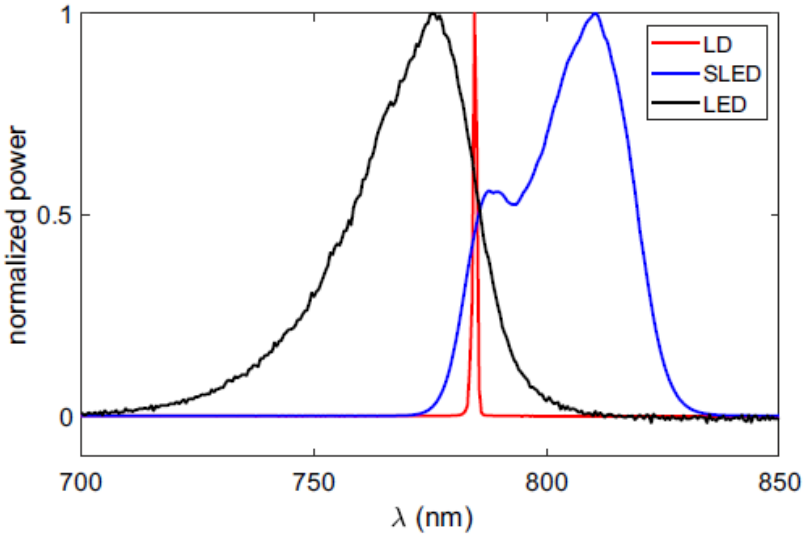
- **Cheap** solution **but** vibrating mechanical parts are undesirable (long-term misalignment).

D. Halpaap et al., "Speckle reduction in double-pass retinal images", Sci. Rep. 9, 4469 (2019).

All optical speckle reduction strategies

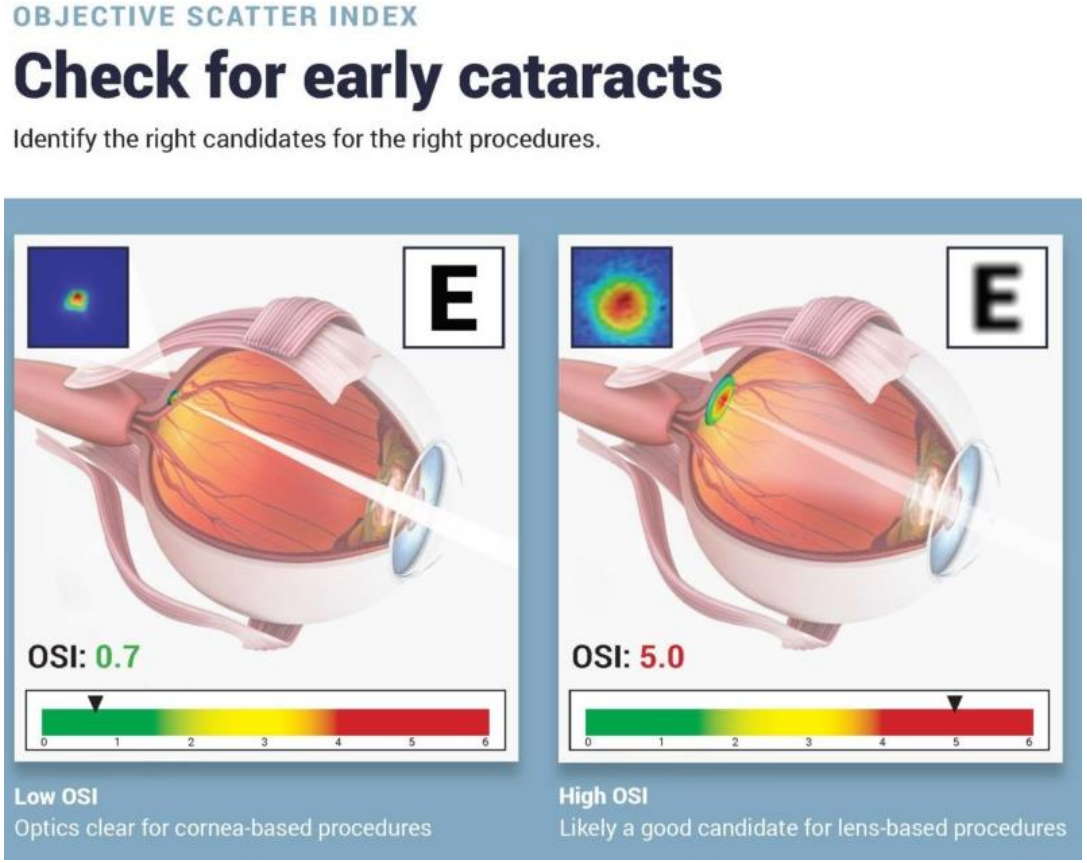
- We tested the chaotic output emitted by a diode laser with optical feedback, optical injection or current modulation, but the light is not sufficiently broad-band.

- We tested alternative light sources: super-luminiscent diode (SLED) and a LED.
- LED too low power.
- SLED too expensive.



D. Halpaap et al., "Speckle reduction in double-pass retinal images", Sci. Rep. 9, 4469 (2019).

Commercial instrument for measuring the optical quality of the eye



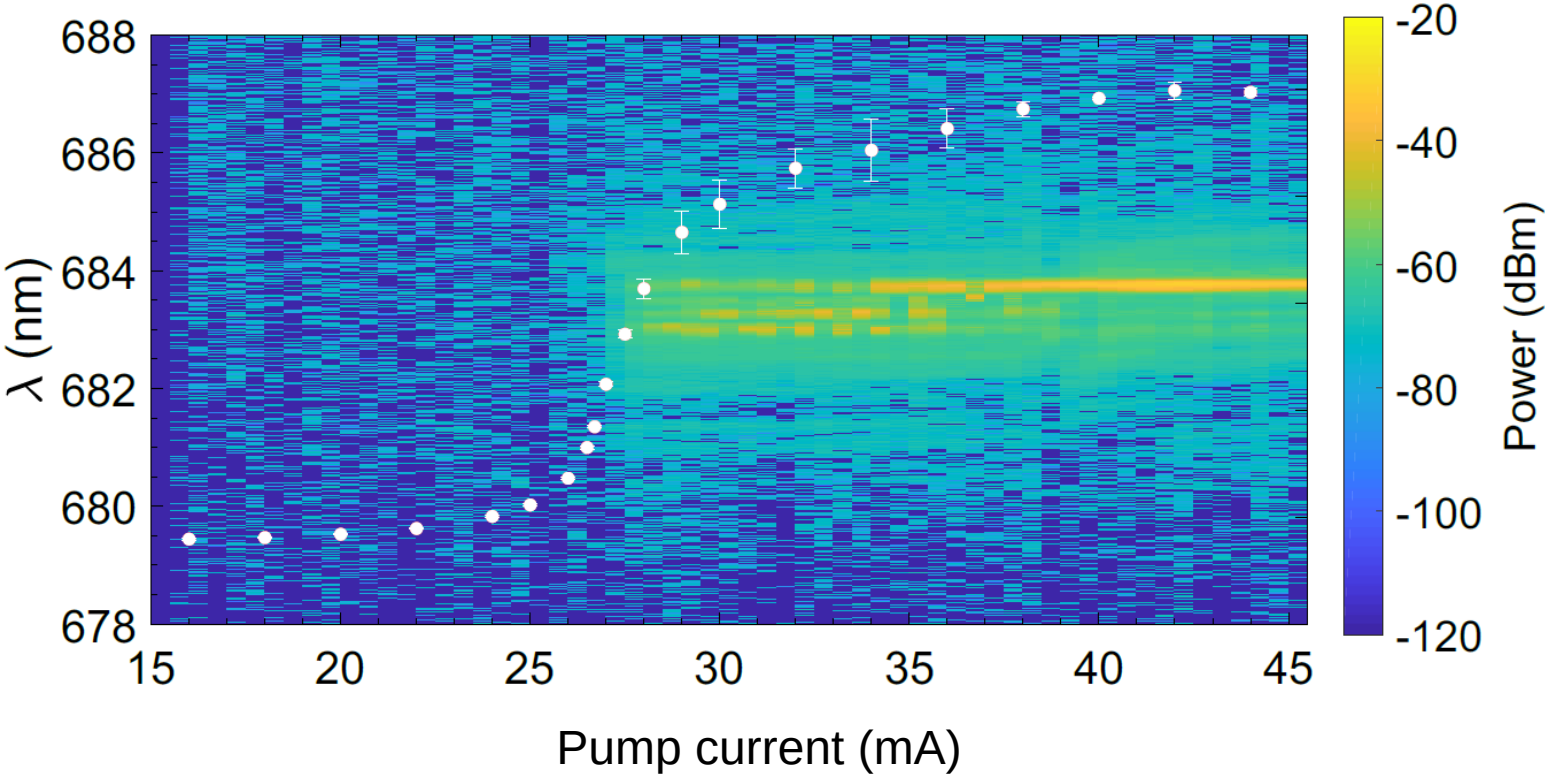
Laser requirements: minimum power that enters the eye 5 mWs (10-15 mWs for cataracts), $\lambda \approx 780$ nm (infrared-red)

Source: Visiometrics (https://www.visiometrics.com/)

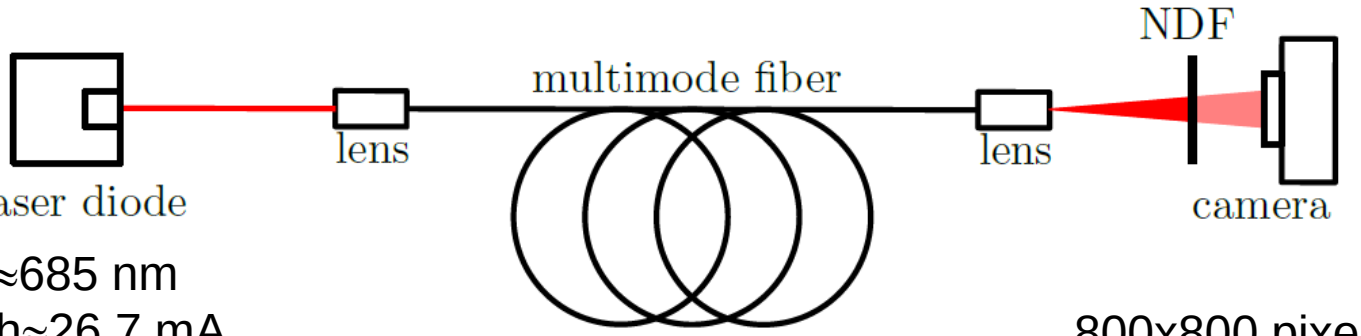
Alternative approach for speckle reduction

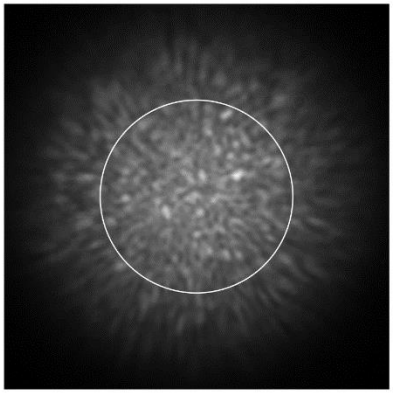
To find the optimal **image acquisition parameters**

- Laser pump current
- Exposure time of the CCD camera



Experimental setup and speckle measure





λ≈685 nm
Th≈26.7 mA

core diameter 200 μm,
NA=0.39

800x800 pixels, each pixel
maximum digital value is 255

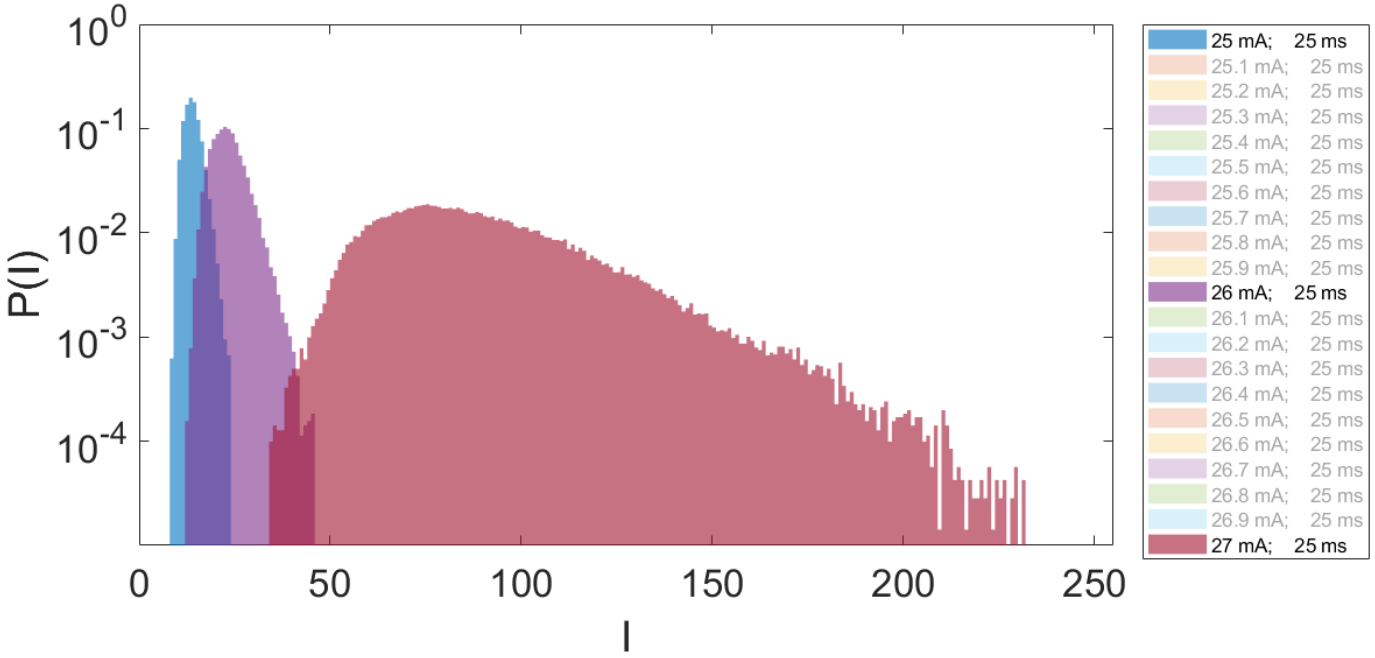
Speckle contrast $C = \frac{\sigma_I}{\langle I \rangle}$

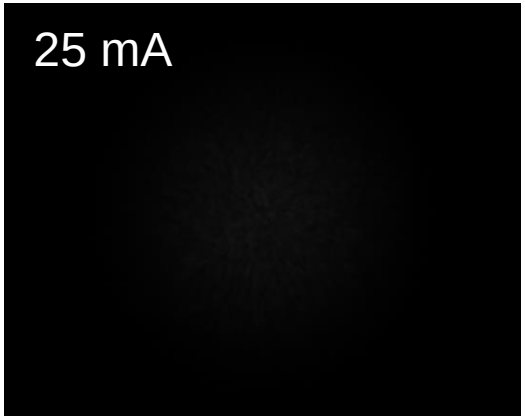
Standard deviation of the intensity

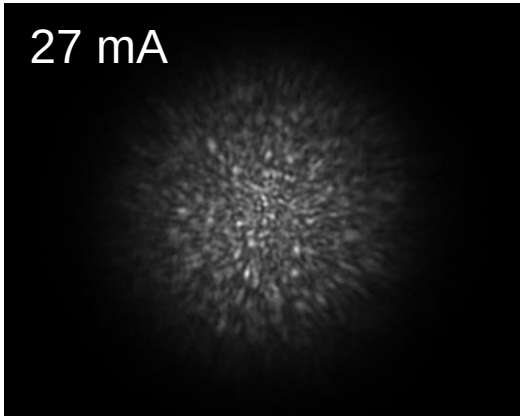
Mean value of the intensity

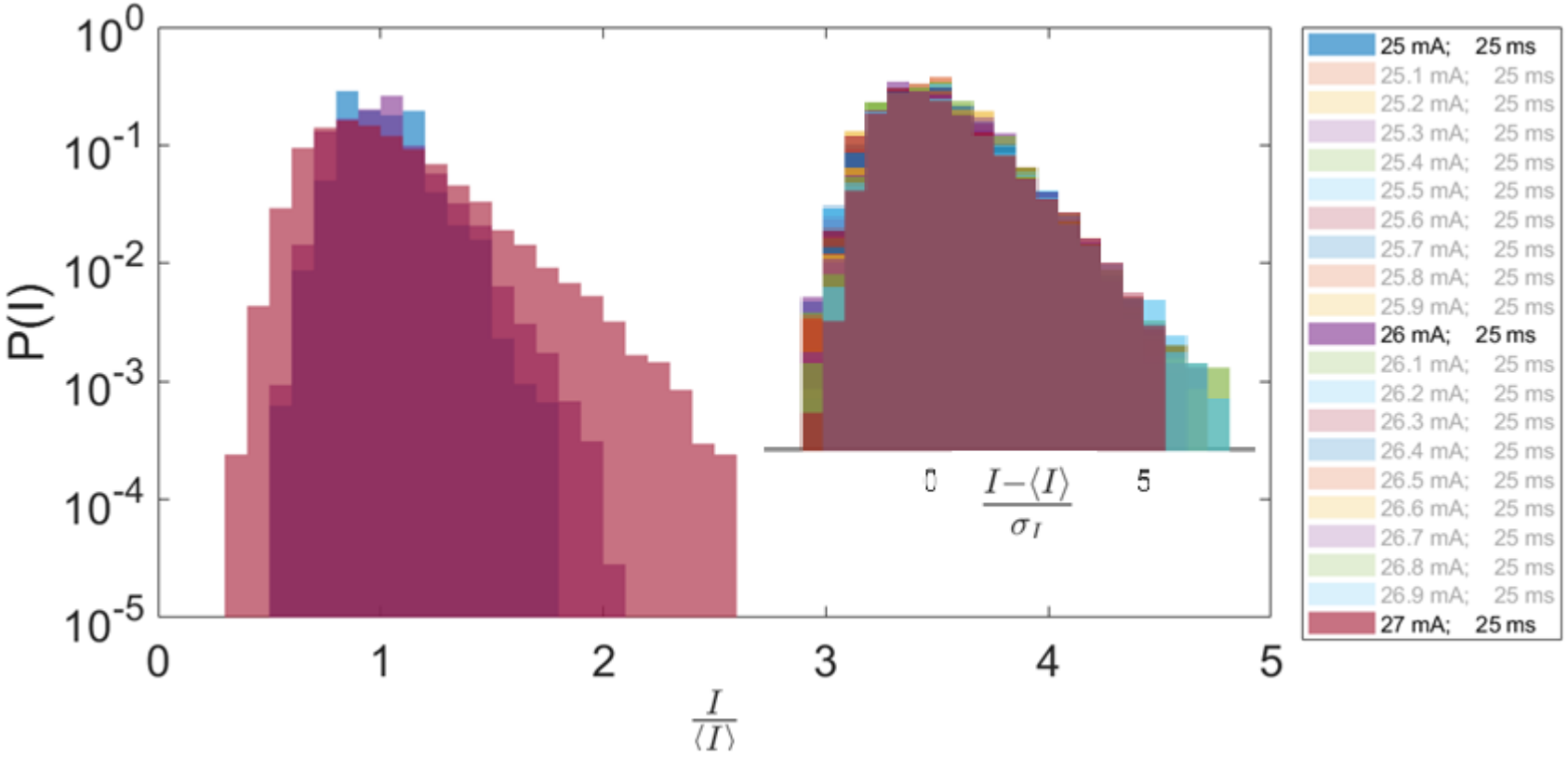
Computed inside a circle of radius 200 pixels

Results: intensity statistics in dependence of the laser pump current (at constant Exp. Time, 25 ms)



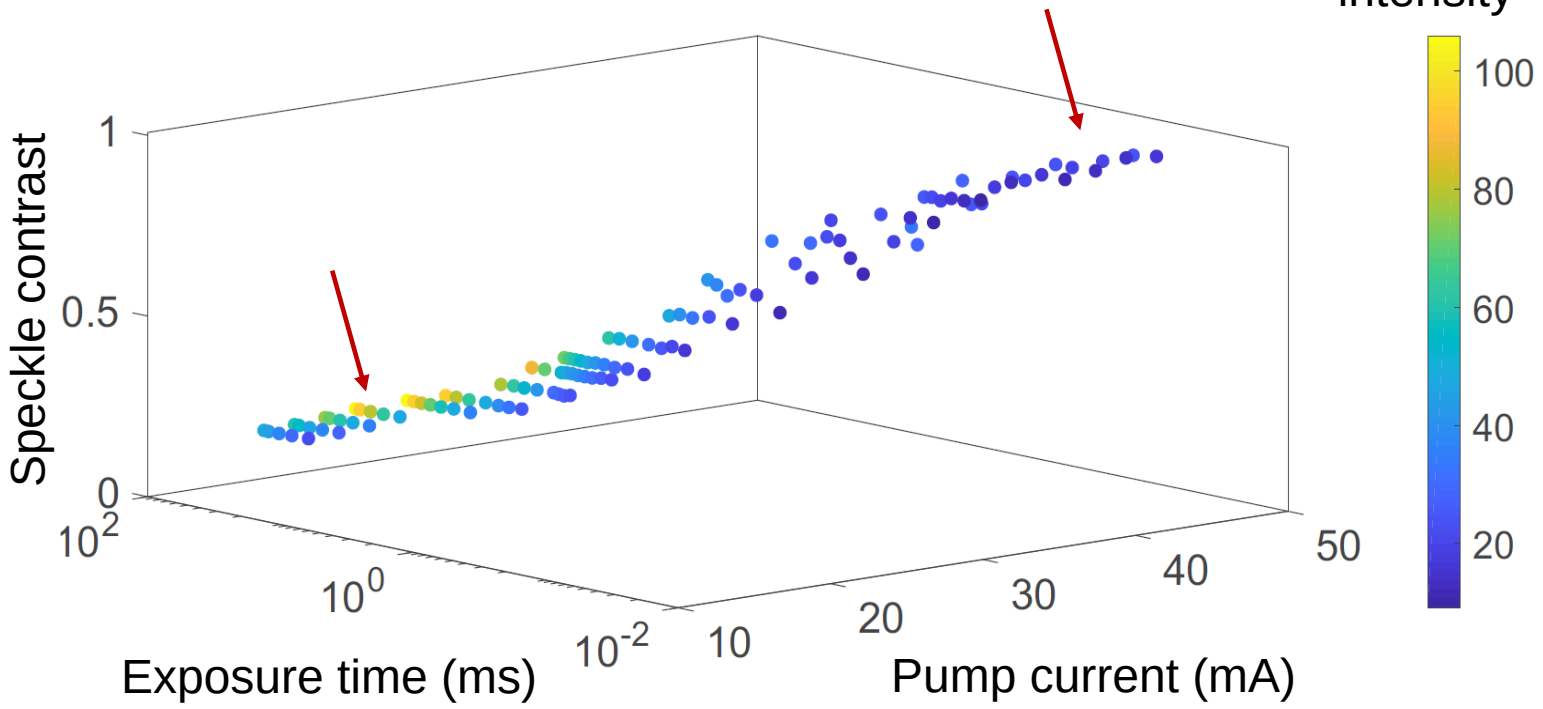


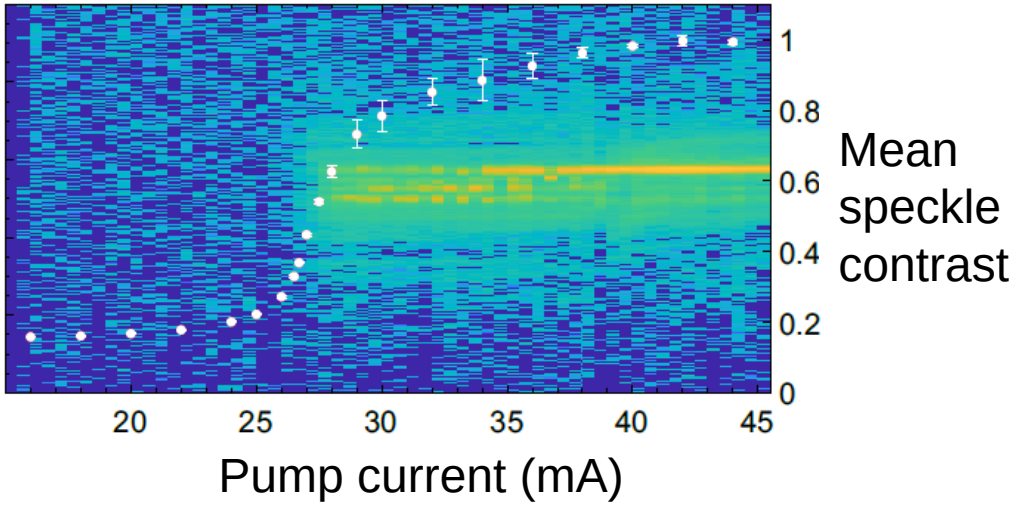




Consistent with the sum of independent (uncorrelated) speckle patterns.

Influence of the exp. time and pump current

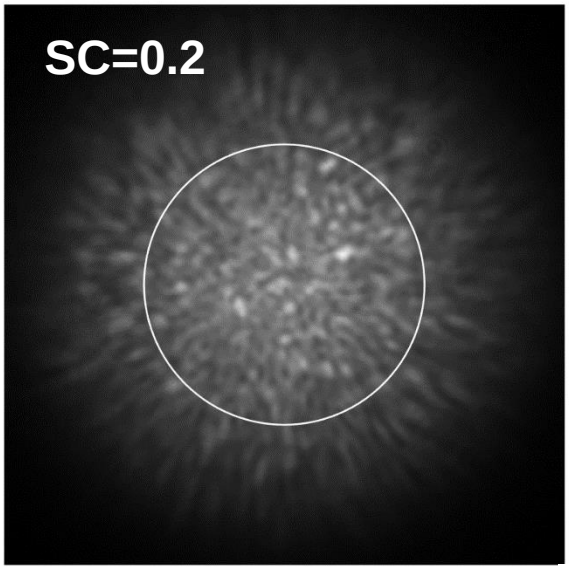


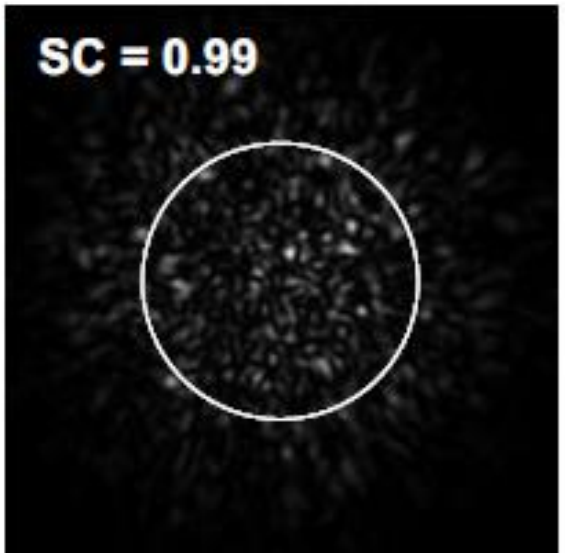


24 mA & 45 ms

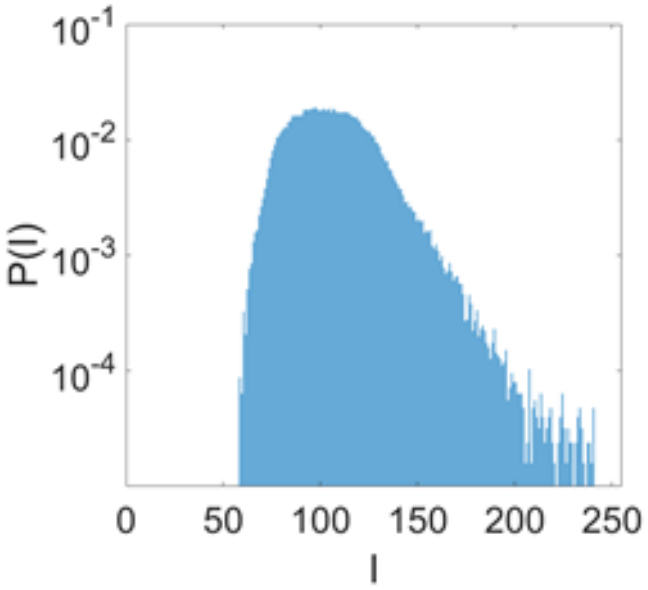
44 mA & 0.03 ms

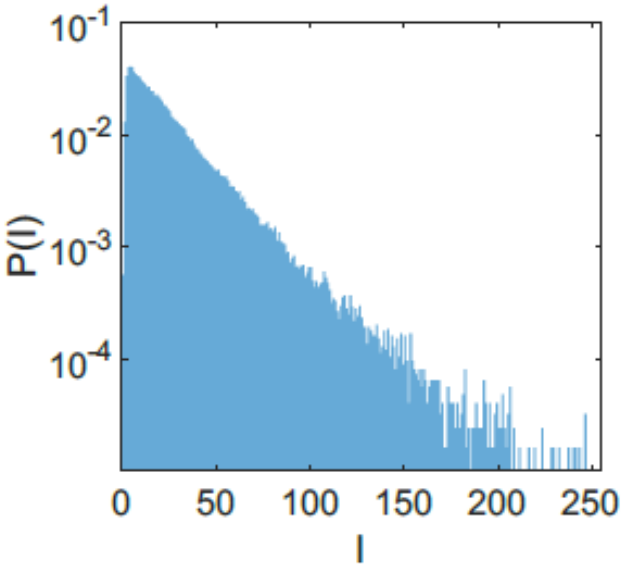
⟨I⟩=106



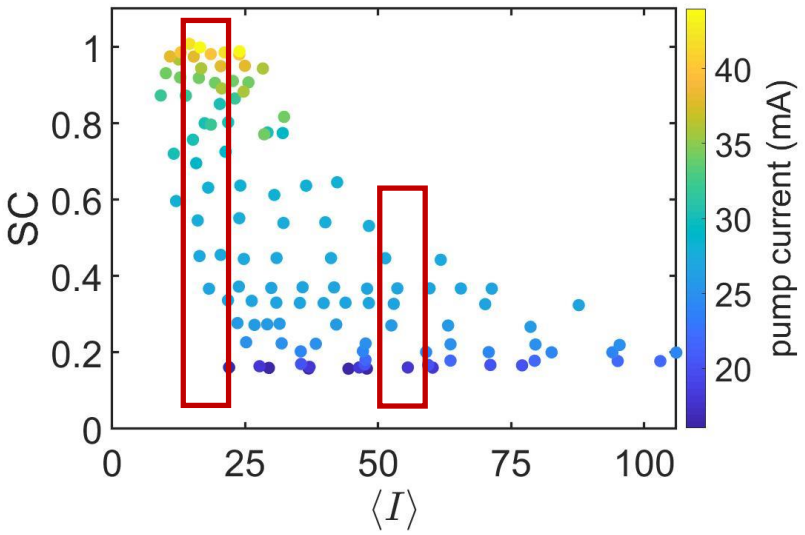


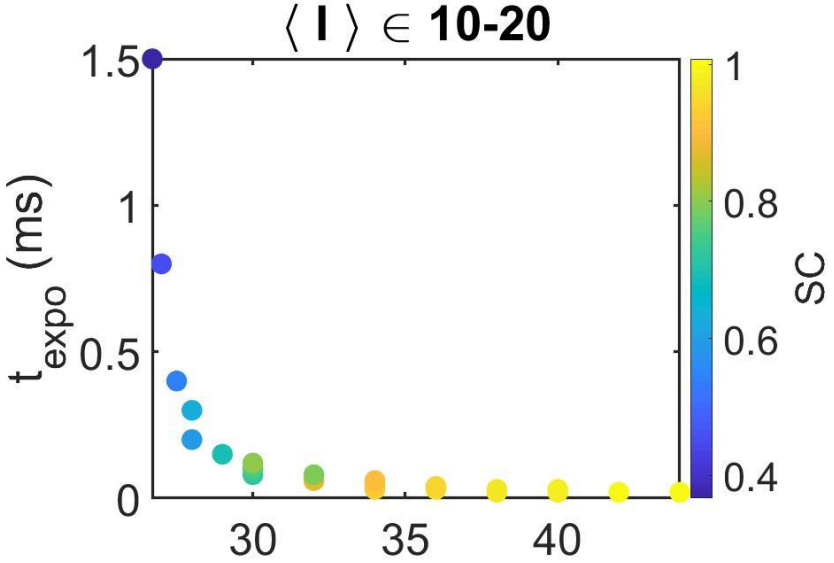
⟨I⟩=24

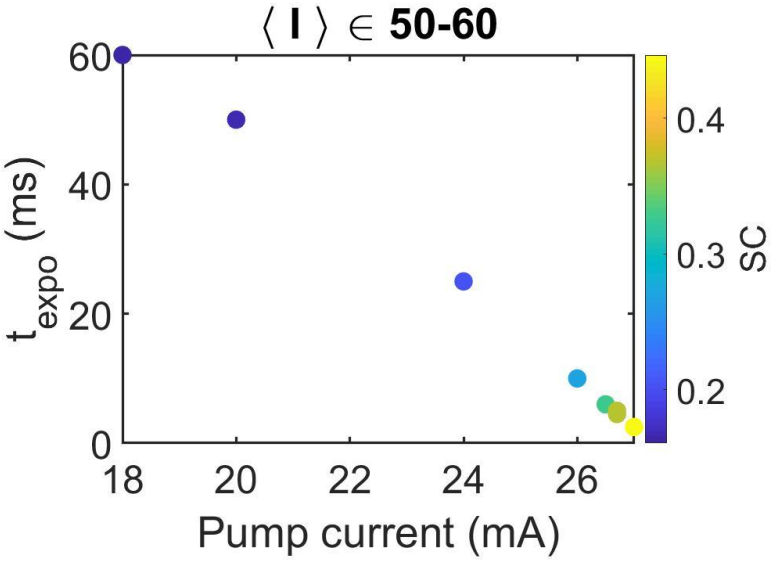




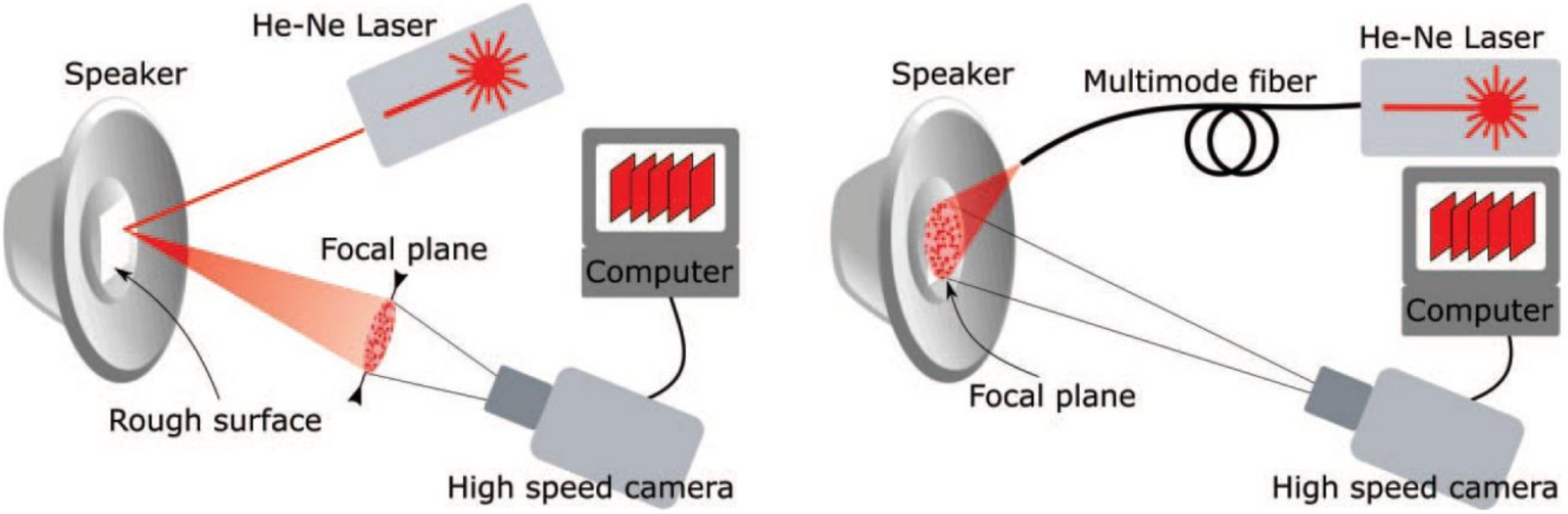
How to obtain images with different SC and similar mean intensity?







Ongoing work: detection of audio signals



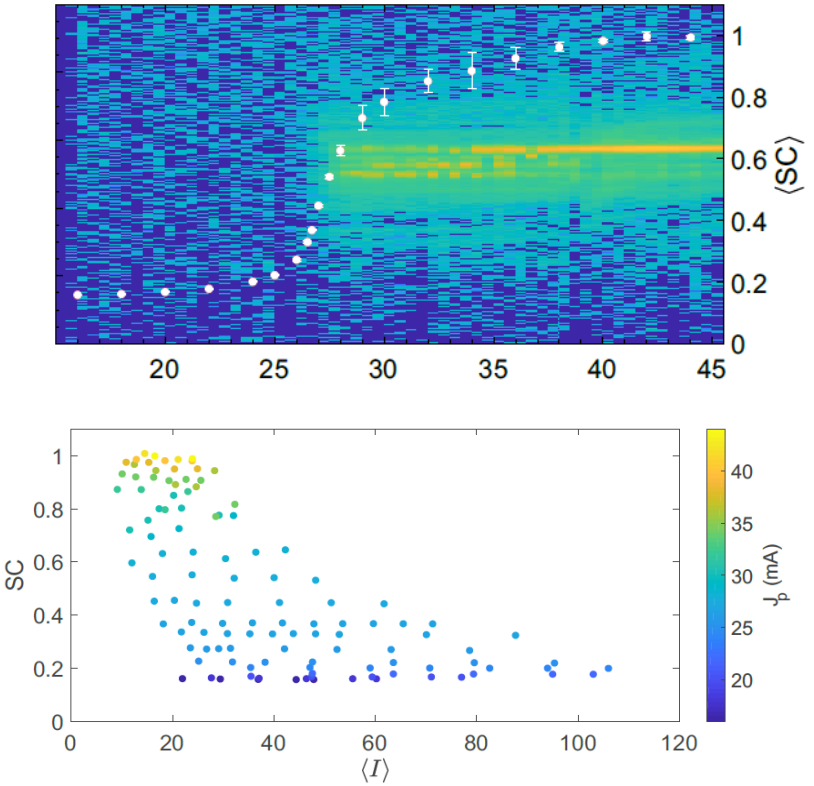
I. Robles-Urquijo et al., Proc. SPIE 10323, 103237W-1, 2017

- Record videos of time-varying speckle patterns.
- Machine learning algorithms can then be used to extract "time-varying" features that allow recovering the sound.

The Visual Microphone: Passive Recovery of Sound from Video
http://people.csail.mit.edu/mrub/papers/VisualMic_SIGGRAPH2014.pdf

Take home message

- The speckle contrast changes abruptly near the laser threshold.
- A careful selection of the image acquisition parameters (laser pump current, exposure time) allows controlling (to a degree) the amount of speckle.



- This can be useful for applications where speckle needs to be suppressed or enhanced.

D. Halpaap

M. Vilaseca

J. Tiana

Sensing applications in collaboration with P. Amil (UPC), C. Barcellona and A. Buscarino (Univ. Catania)

Reference:

D. Halpaap et al., “Speckle reduction in double-pass retinal images”, Sci. Rep. 9, 4469 (2019).

THANK YOU FOR YOUR ATTENTION !

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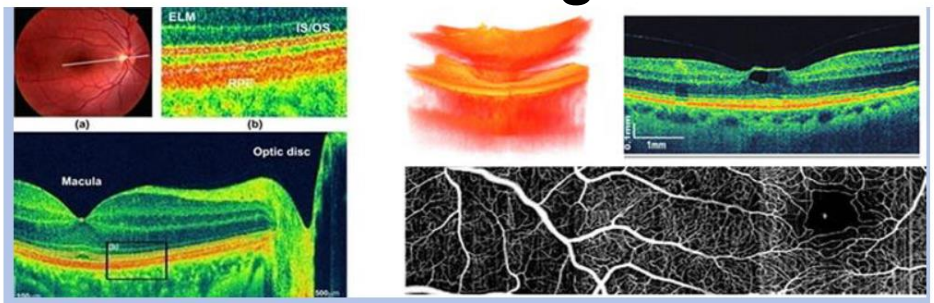

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