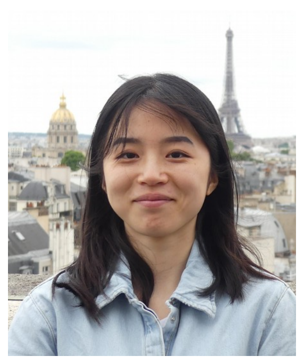
Phase Conjugation of Multiply Scattered Fluorescent Light with a Wavefront Sensor

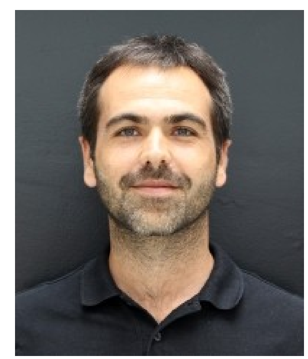
Marc Guillon
Université Paris Cité

Tengfei Wu



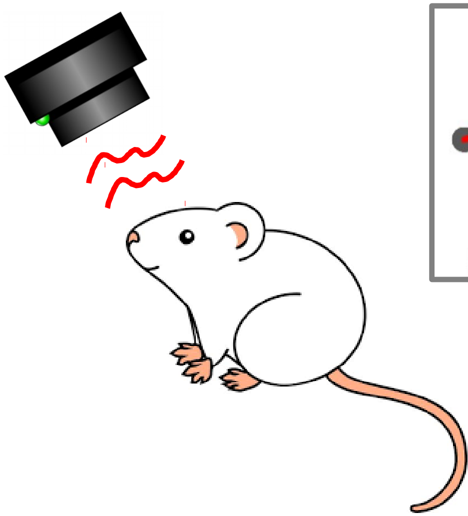
Yixuan Zhang

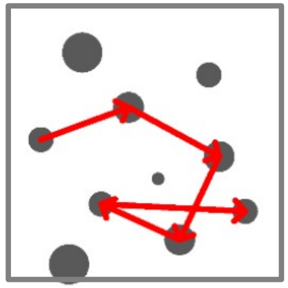
Baptiste Blochet



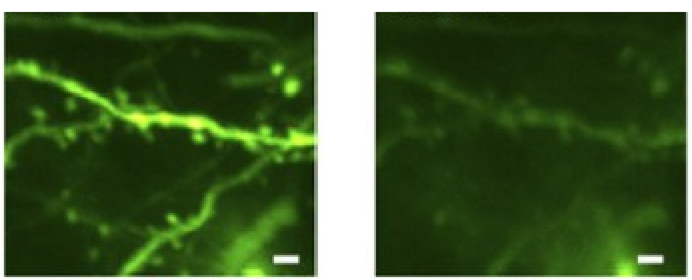
Pascal Berto

Image degradation through scattering biological samples





With aberrations

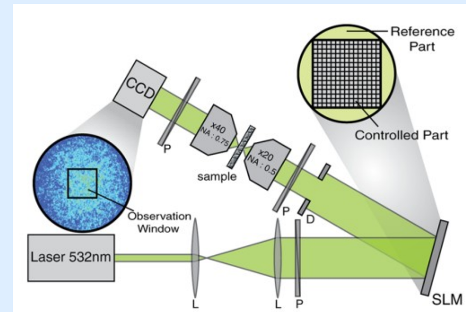


V. Ntziachristos, Nat. Methods, 7(8) (2010)
N. Ji, Nat. Methods,14(4) (2017)

Selected for a Viewpoint in *Physics*
PRL **104,** 100601 (2010) PHYSICAL REVIEW LETTERS week ending 12 MARCH 2010

Measuring the Transmission Matrix in Optics: An Approach to the Study and Control of Light Propagation in Disordered Media

S. M. Popoff, G. Lerosey, R. Carminati, M. Fink, A. C. Boccara, and S. Gigan
Institut Langevin, ESPCI ParisTech, CNRS UMR 7587, ESPCI, 10 rue Vauquelin, 75005 Paris, France
(Received 27 October 2009; revised manuscript received 11 January 2010; published 8 March 2010)



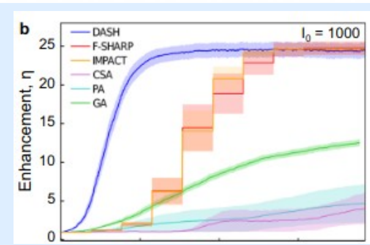
See also : A. Badon et al. Sci. Adv. 6(30), 2020

Iterative optimization + NLO

ARTICLES
PUBLISHED ONLINE: 26 DECEMBER 2016 | DOI: 10.1038/NPHOTON.2016.252

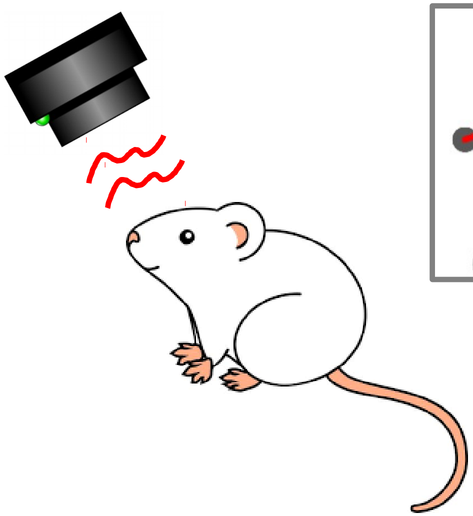
Scattering compensation by focus scanning holographic aberration probing (F-SHARP)

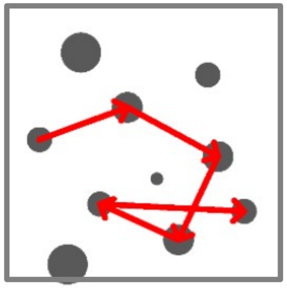
Ioannis N. Papadopoulos[1], Jean-Sébastien Jouhanneau[2], James F. A. Poulet[2] and Benjamin Judkewitz[1]*



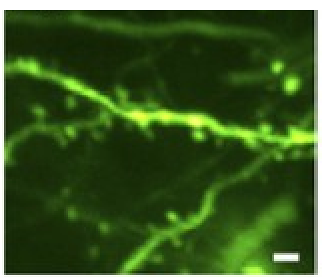
M.A.May et al. Nat. Commun. 2021

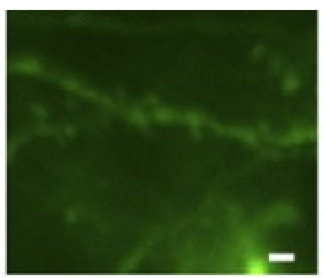
Image degradation through scattering biological samples





With aberrations



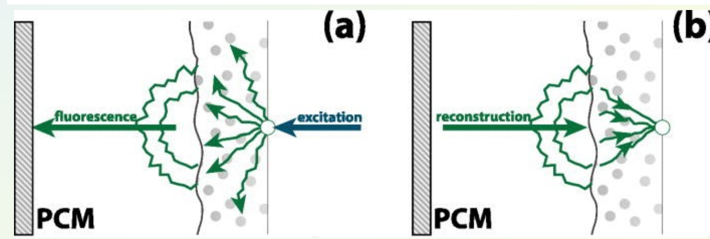


One possible solution :

nature photonics | REVIEW ARTICLE
PUBLISHED ONLINE: 27 AUGUST 2015 | DOI: 10.1038/NPHOTON.2015.140

Guidestar-assisted wavefront-shaping methods for focusing light into biological tissue

Roarke Horstmeyer*, Haowen Ruan and Changhuei Yang

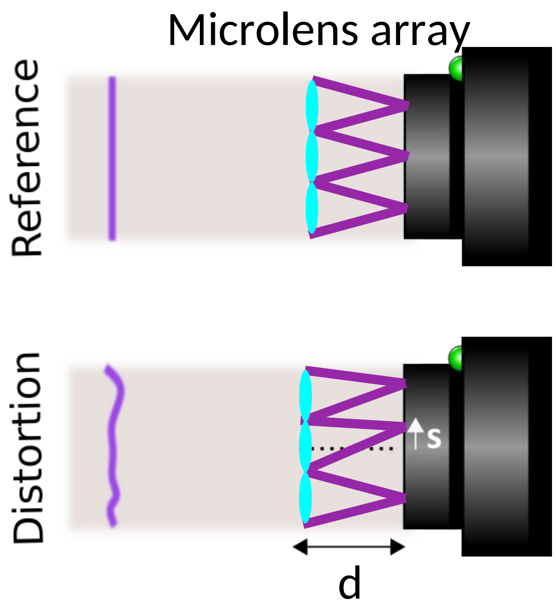


I. Vellekoop et al. Appl. Phys. Lett. 2012

V. Ntziachristos, Nat. Methods, 7(8) (2010)
N. Ji, Nat. Methods,14(4) (2017)

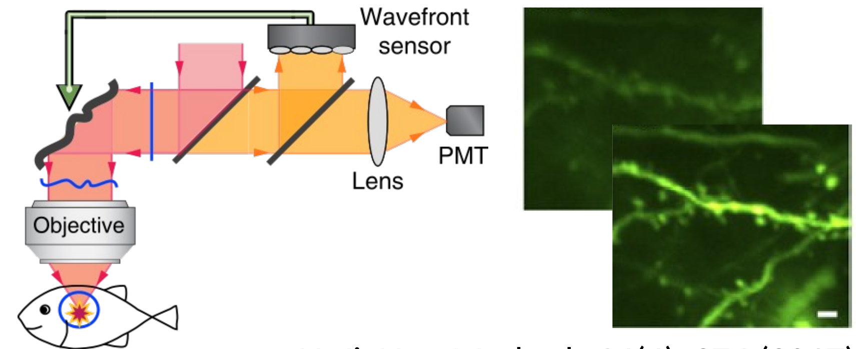
Wavefront measurement

Direct wavefront measurement

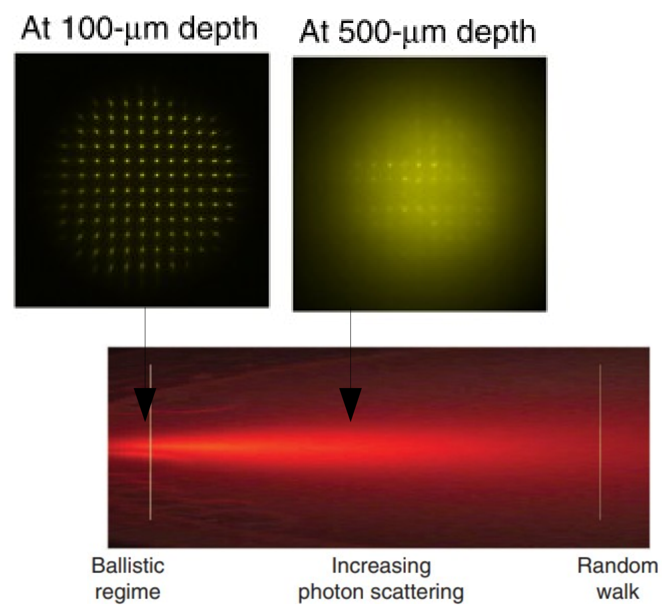


$$\frac{\nabla_{\perp}\varphi}{k_0} \simeq \frac{\mathbf{s}}{d}$$

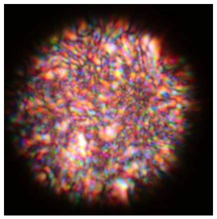
Advantages of Shack-Hartmann WFS :
- simple and robust
- compatible with broadband guide stars
- no need for a reference beam



N. Ji, Nat. Methods 14(4), 374 (2017)



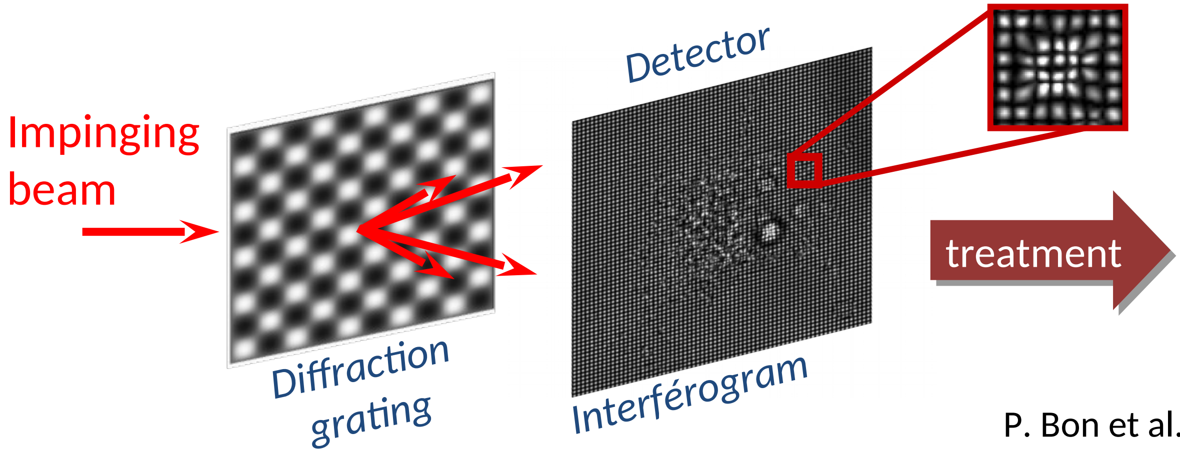
Speckle

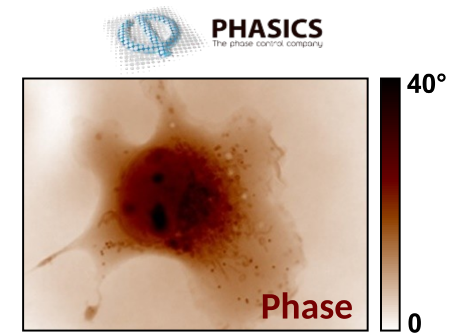


Drawback of Shack-Hartmann WFS :
Only measure low-order aberrations...

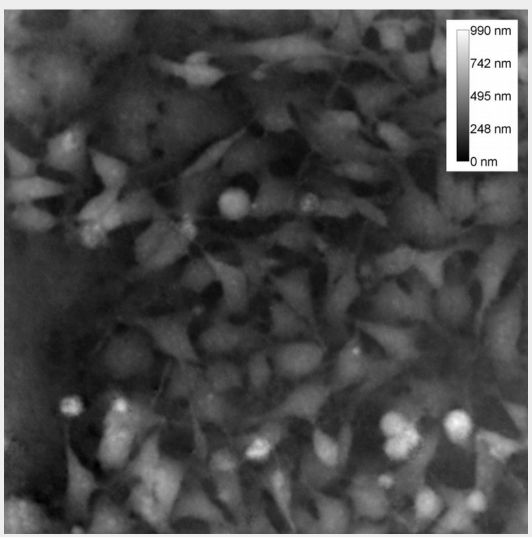
WFS enables High-resolution phase imaging…

Quadri-wave lateral shearing interferometry

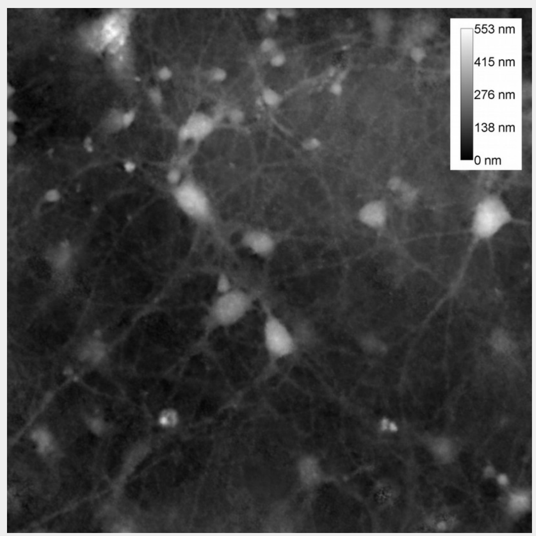




P. Bon et al., Opt. Express 17(15), 13080 (2009)



HeLa cells (x40)



Neurons (x40)

Unpublished data (Collab. with M. Kappes & M. Oheim)

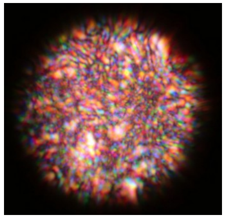
…of smooth patterns

Can a high-resolution WFS solve
the high-resolution adaptive optics problem
and compensate multiple-scattering?

Remaining difficulties :

- The presence of (screw) phase dislocations in speckles

- Limited spectral bandwidth of multiply scattering samples

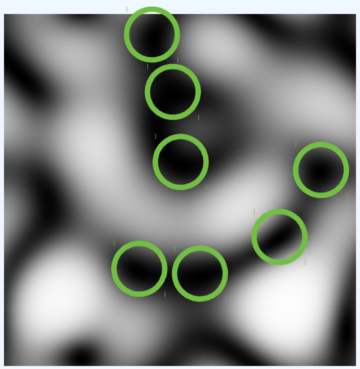


- The low photon budget of fluorescence signals

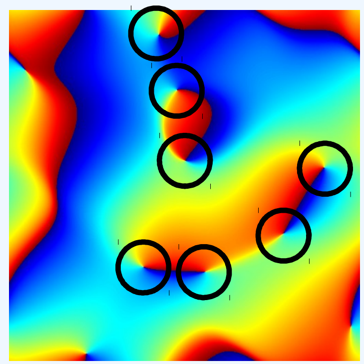
Topological phase singularities in speckle patterns

Speckle

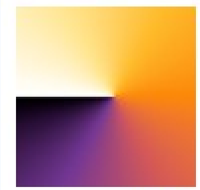
Intensity



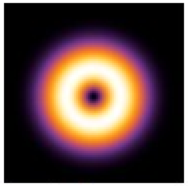
phase



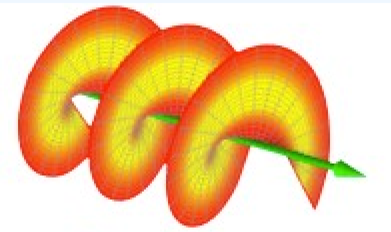
Optical vortex



phase



intensity



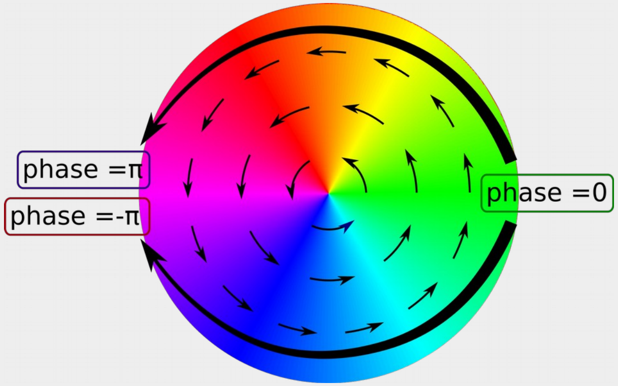
3D wavefront

Optical vortex density in speckles [1]: ~ 1.25 PSF^{-2}

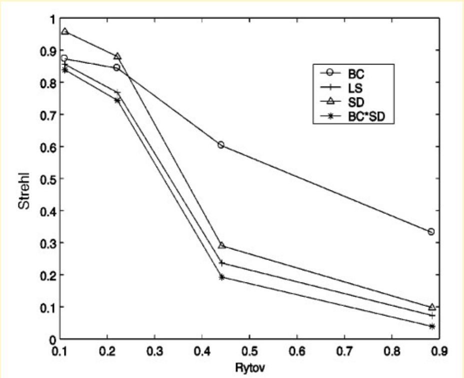
[1] I. Freund, Waves Random Media 8, 119 (1998)

Problem: non-conservative vector field

$$\frac{\nabla_\perp \varphi}{k_0} \simeq \frac{\mathbf{s}}{d}$$

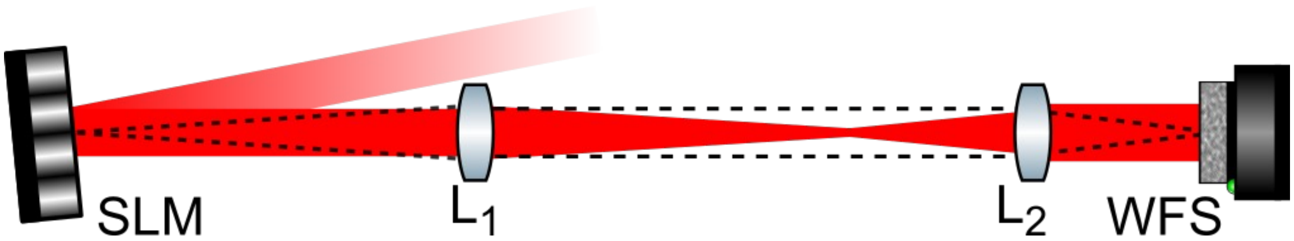


Optical vortices degrades adaptive optics performances in astronomy



G.A.Tyler, JOSA 17(10) 1828 (2000)

Vortex reconstruction with a WFS

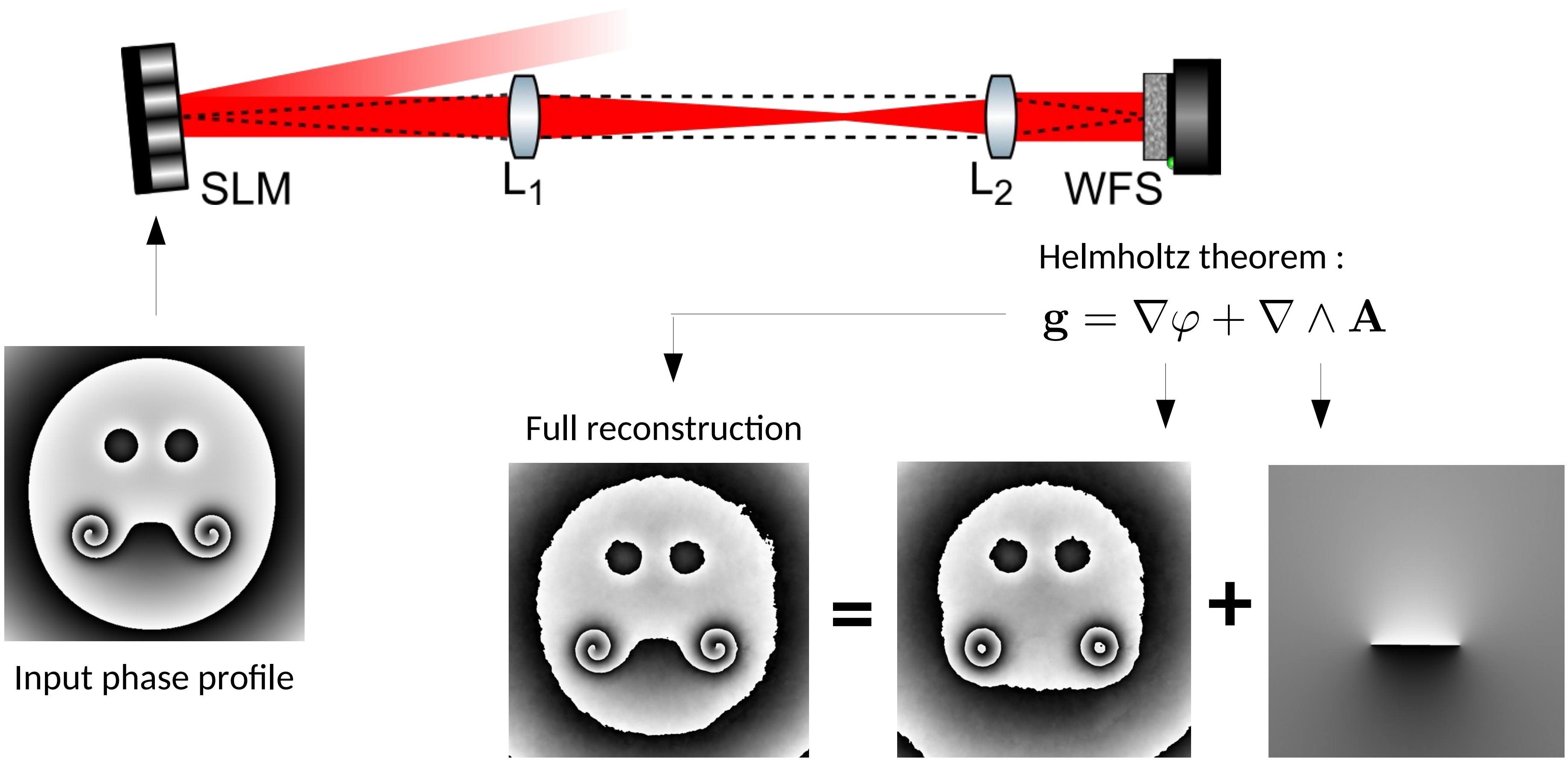


Input phase profile

$$\mathbf{g} = \nabla\varphi$$

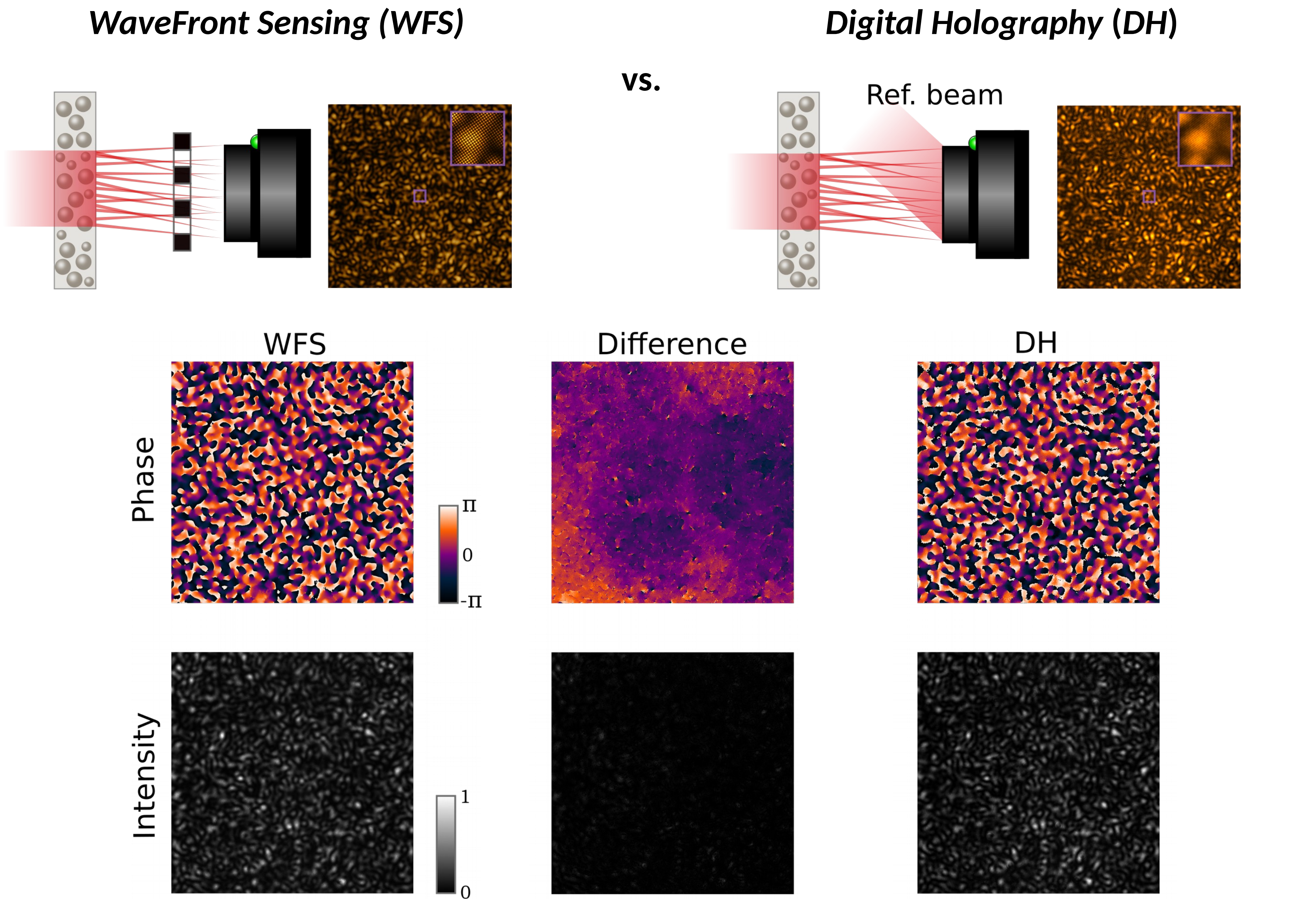
T. Wu, P. Berto, M. Guillon, **Appl. Phys. Lett.** 118, 251102 (2021)

Vortex reconstruction with a WFS



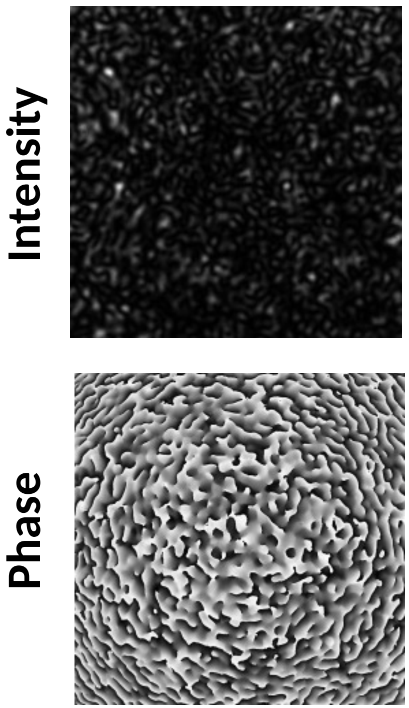
T. Wu, P. Berto, M. Guillon, **Appl. Phys. Lett.** 118, 251102 (2021)

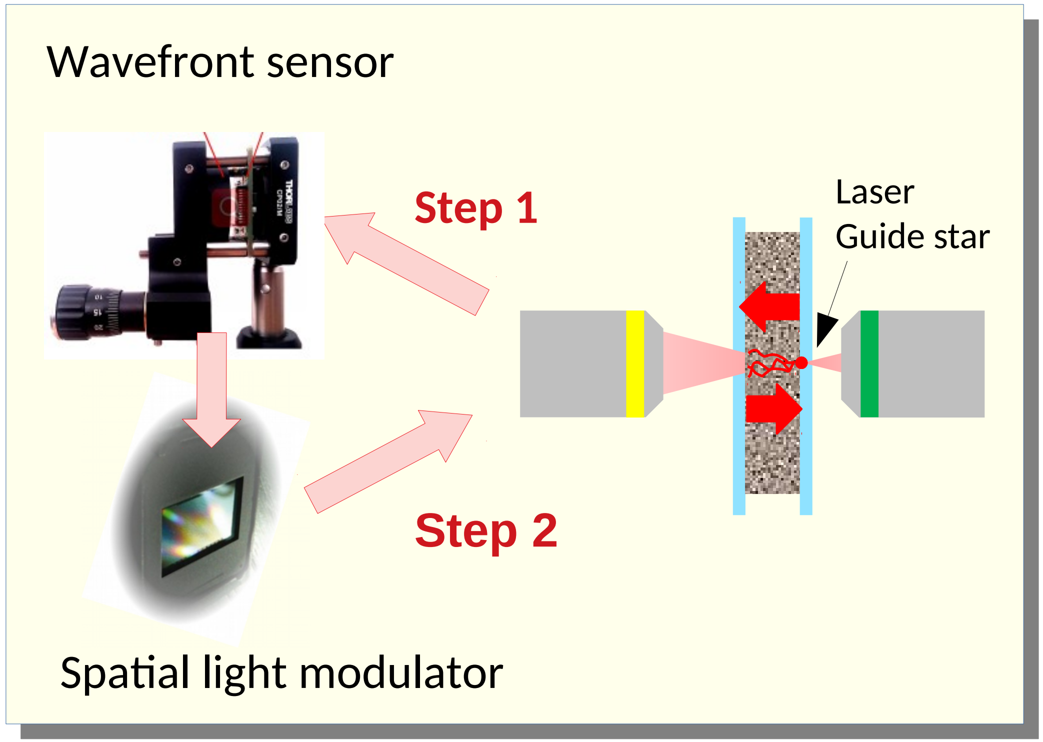
Validation and optimization of complex field measurement with WFS

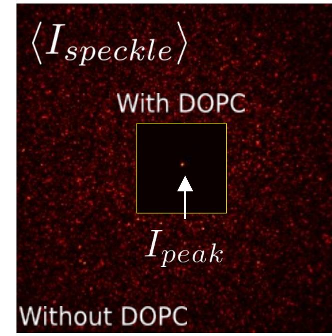


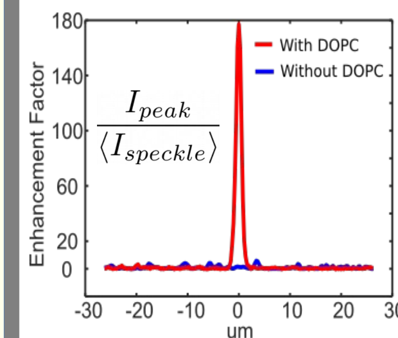
Digital optical phase conjugation through scattering sample with WFS

Experimental results---spinal cord with 720um thickness

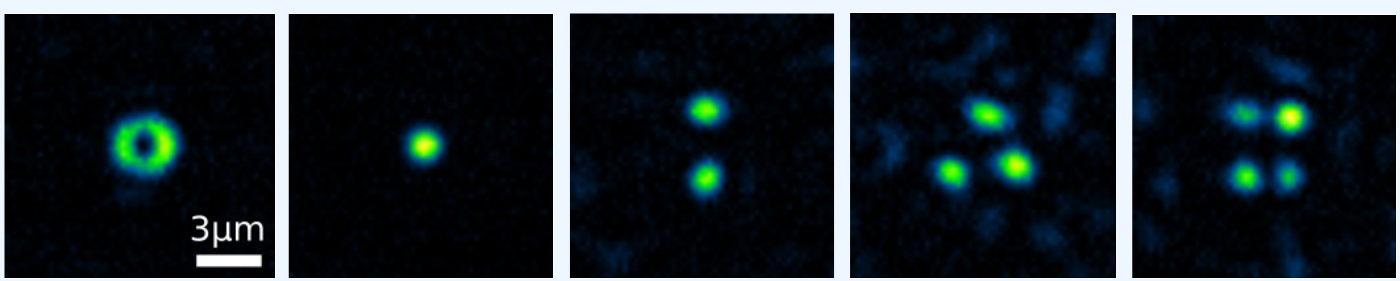






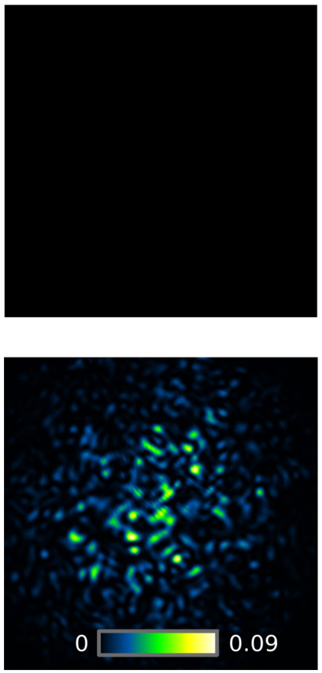


Wavefront shaping for in-depth light patterning

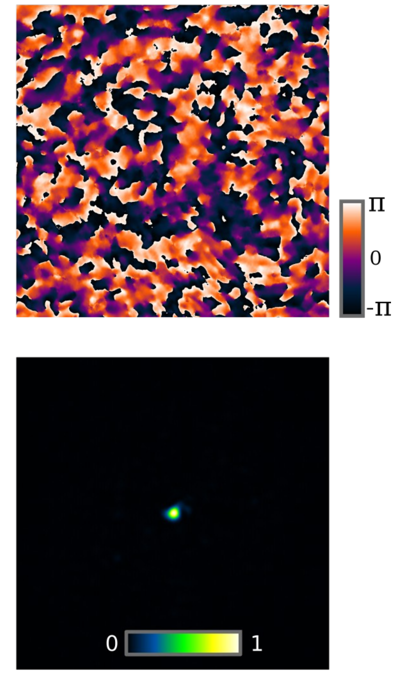


The Importance of optical vortices for phase conjugation

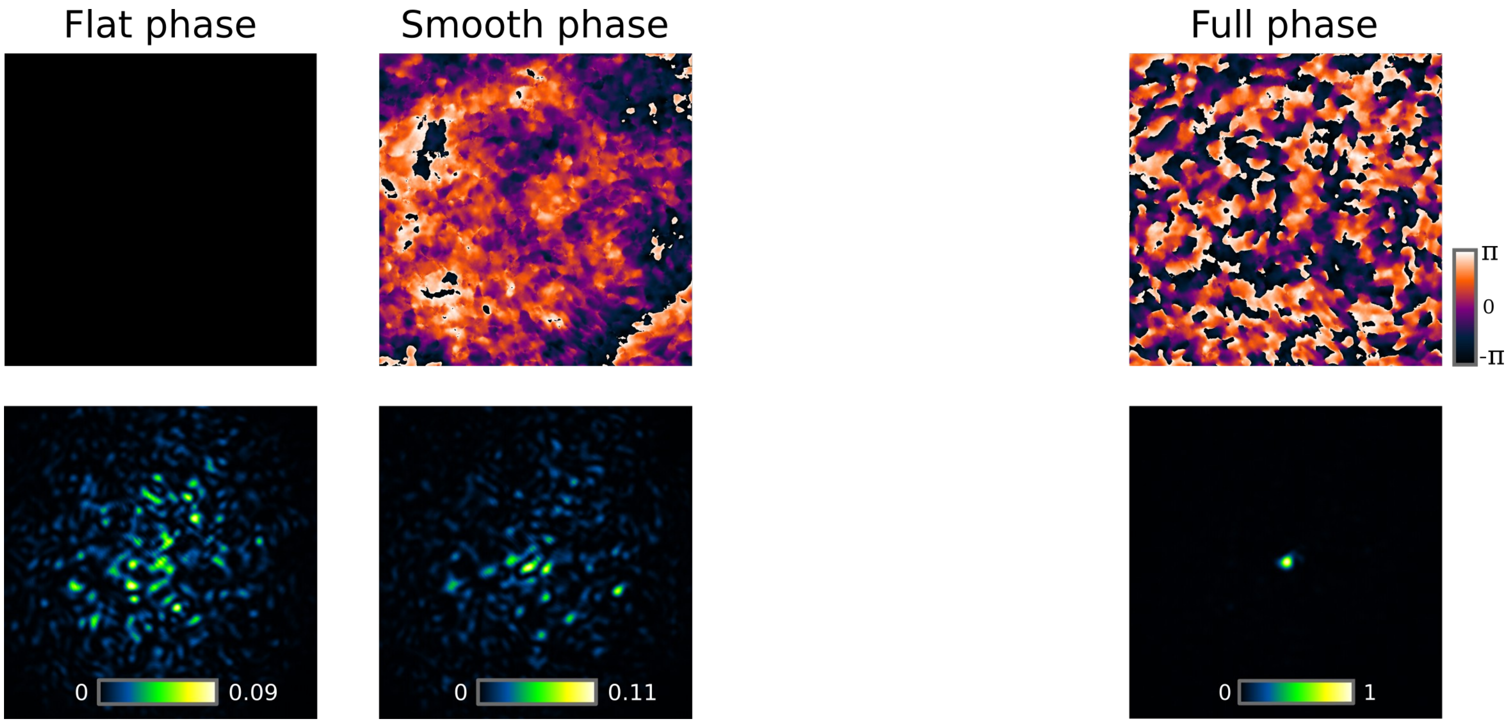
Flat phase



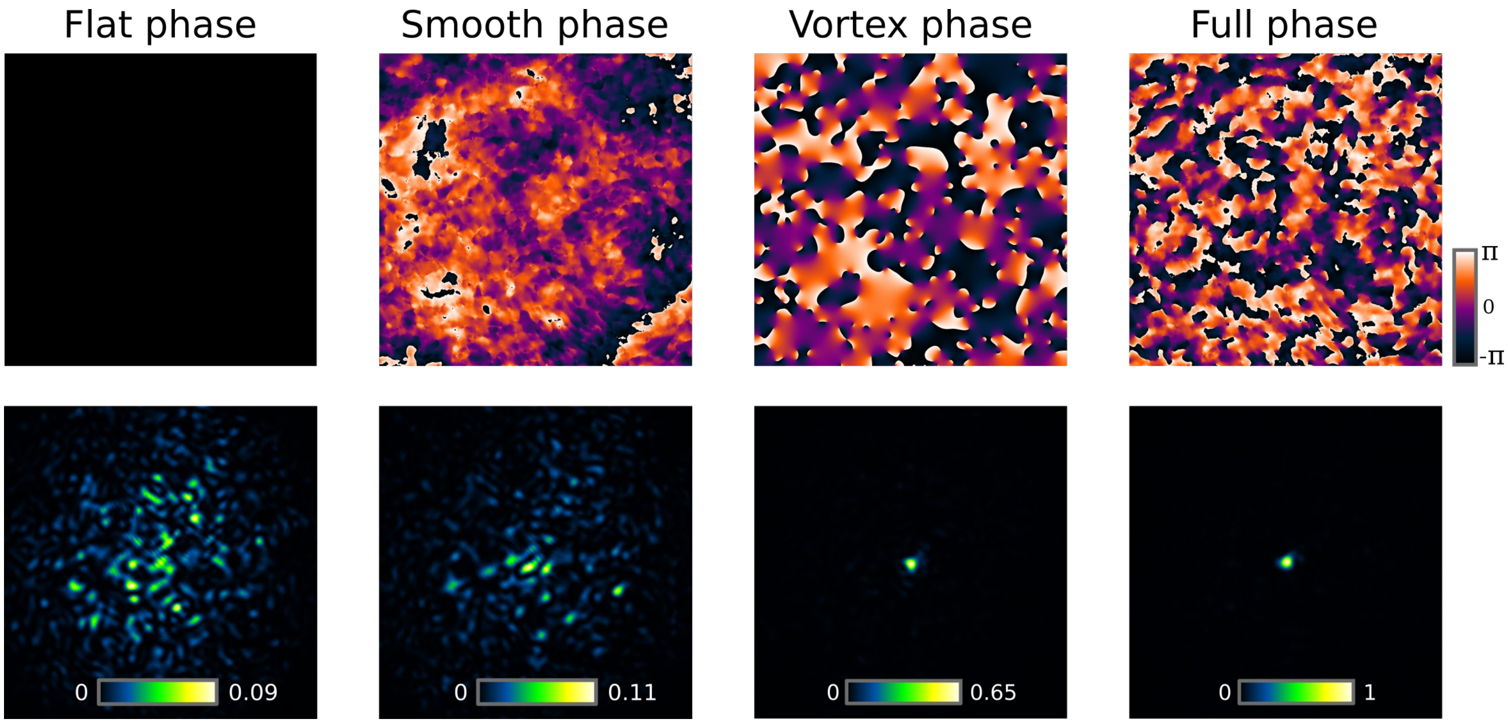
Full phase



The Importance of optical vortices for phase conjugation



The Importance of optical vortices for phase conjugation



Using a fluorescent guide-star?

Two main challenges :

- low photon budget
- Spectral width and Stokes’ shift

Using a fluorescent guide-star?

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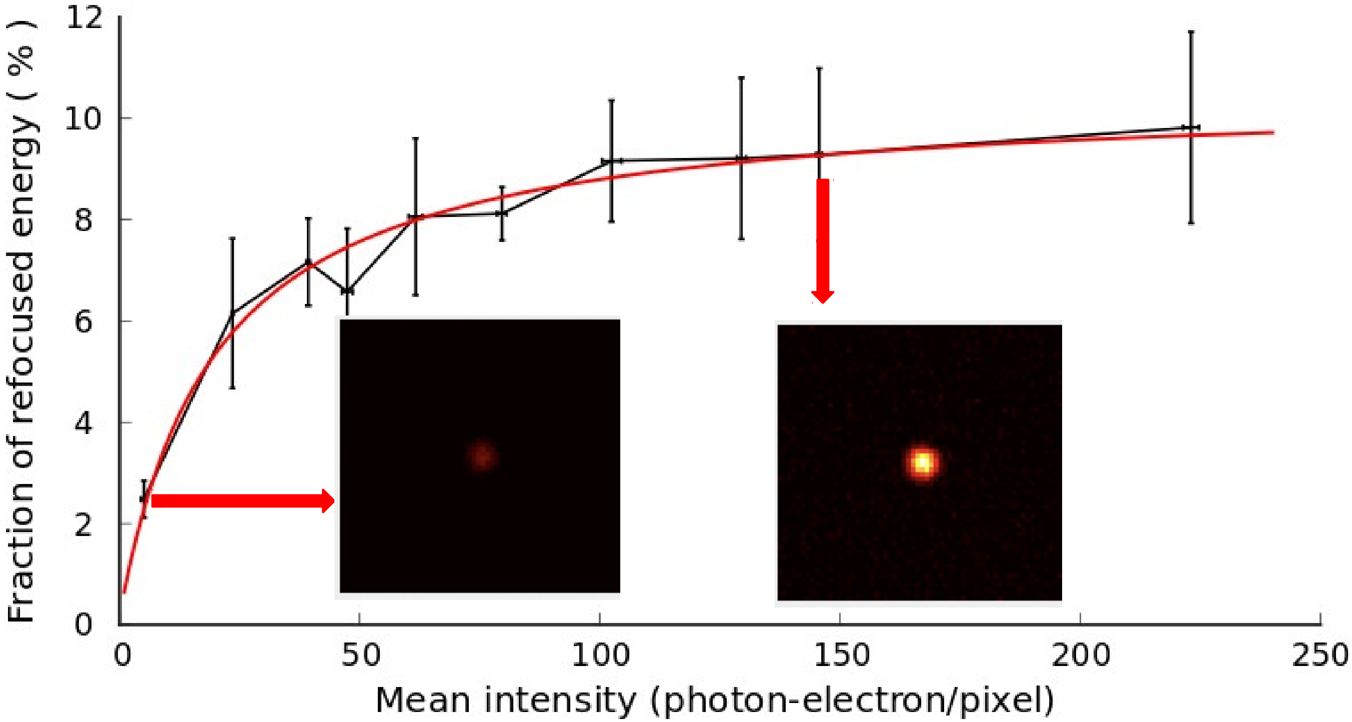


Theoretical model [1]

$$\eta = \frac{1}{\frac{1}{M} + \frac{\alpha}{I}}$$

Limitation : readout noise of the camera

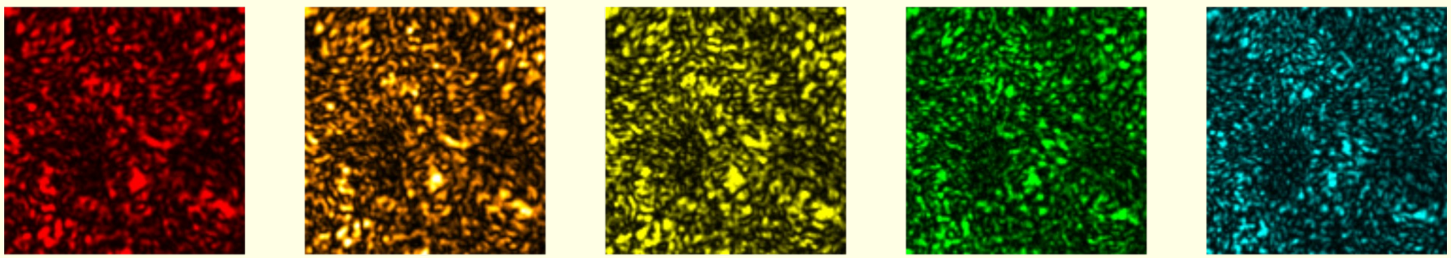
Requirement : ~ 10^8 photons for 3000 spatial modes (Camera: 1e-/px RMS readout noise)

[1] M. Jang, C. Yang, I.M. Vellekoop, Phys. Rev. Lett. 118, 093902 (2017)

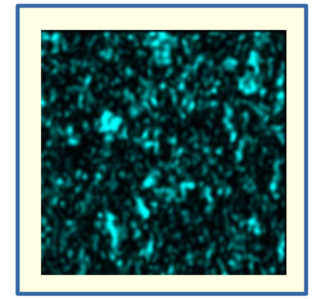
Using a fluoresent guide-star?

Two main challenges :
- low photon budget
- Spectral width and Stokes' shift

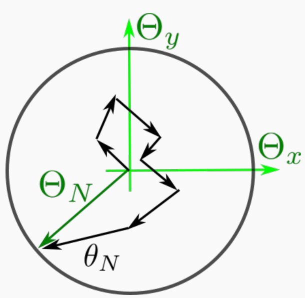
Chromatic correlations in forward scattering media $(\ell_s \ll L \ll \ell^*)$

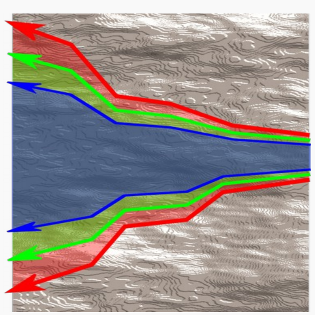

λ=678nm λ=645nm λ=591nm λ=530nm λ=486nm

Δλ > 100nm for 1 mm-thick fixed brain slice [1]

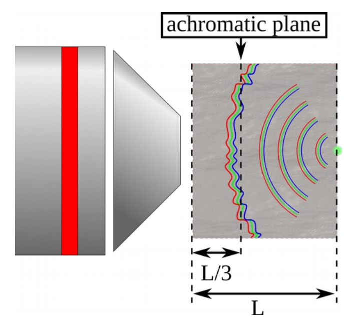


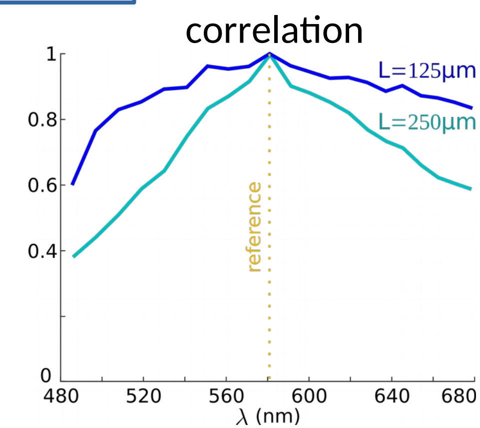
Homothetic random walk in the k-space [2]





Spectral width [2,3] : $\Delta\lambda \simeq \frac{\lambda^2 \ell^*}{L^2}$





[1] A.G. Vesga et al., Opt. Express 27 (2019)
[2] L. Zhu et al., Optica 7, 338 (2020)
[3] P. Arjmand et al., Opt. Express 29(5), 6963 (2021)

Using a fluorescent guide-star?

Two main challenges :

- low photon budget
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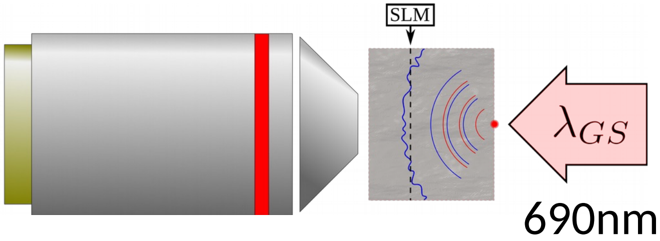
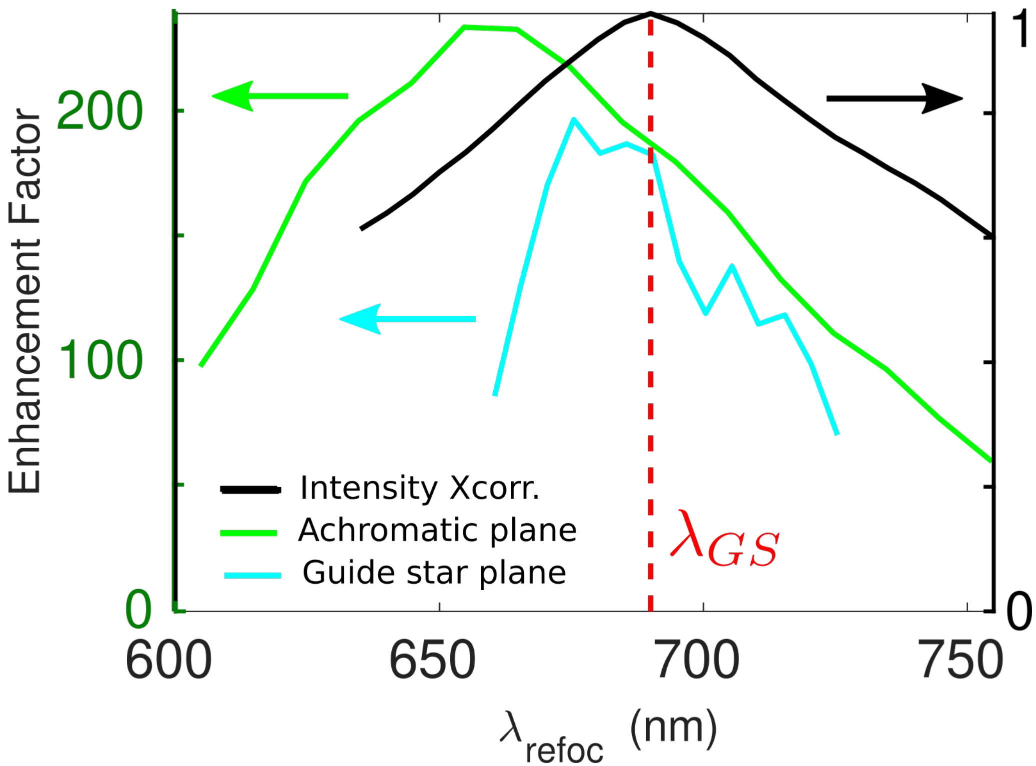
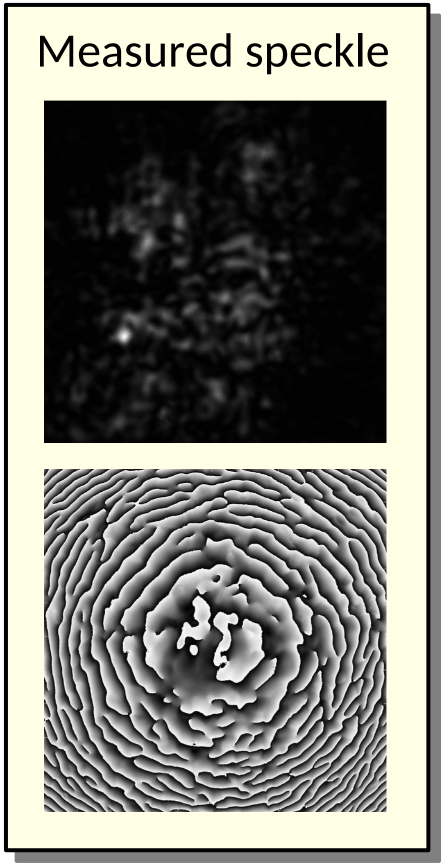




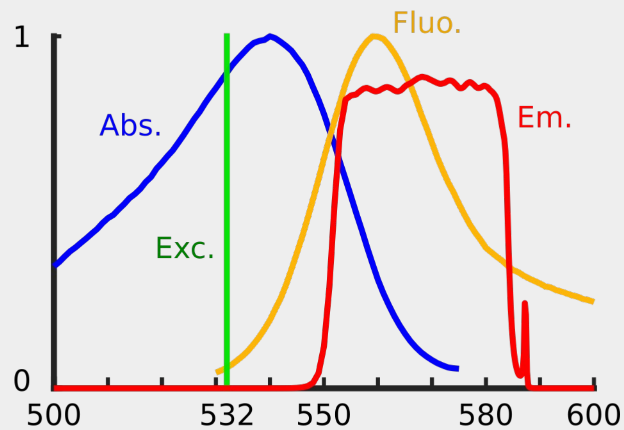


Sample: 500µm of parafilm (g =0.77, ls =170µm@532nm **)

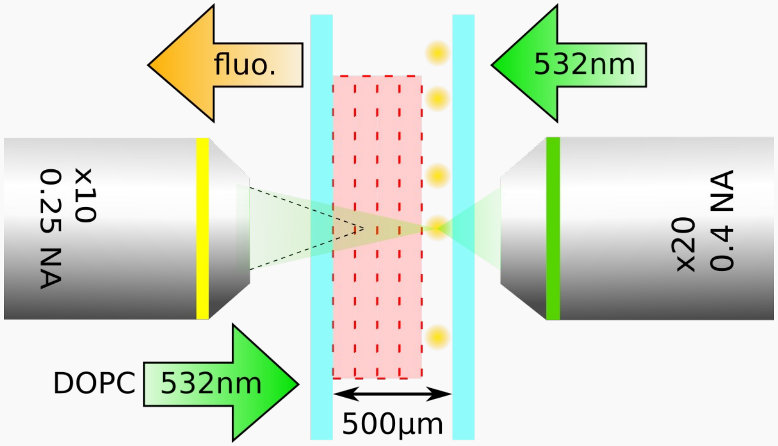
**A. Boniface, et al., Optica 6, 1381–1385 (2019)

Using a fluorescent guide-star!

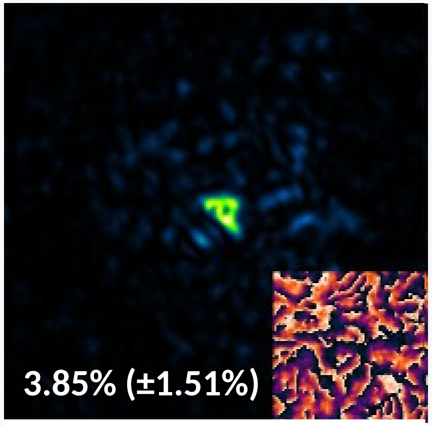
1µm yellow fluorescent beads



SLM & WFS conjugated to the achromatic plane



Result : DOPC of 532nm laser light
from fluorescence (565nm/30nm) light
through forward multiply scattering sample



Full phase reconstruction

Sample :
L = 500µm of paraffin
l_s = 170µm @ 532nm
G = 0.77

Summary & perspectives

- Summary

  → Single-shot high resolution WFS allows measuring to complex wavefronts (speckles)

  → Scattering compensation possible by WFS-based phase conjugation

  → Phase conjugation of fluorescent light possible thanks to the large spectral correlation width of forward scattering media $(\ell_s \ll L \ll \ell^*)$

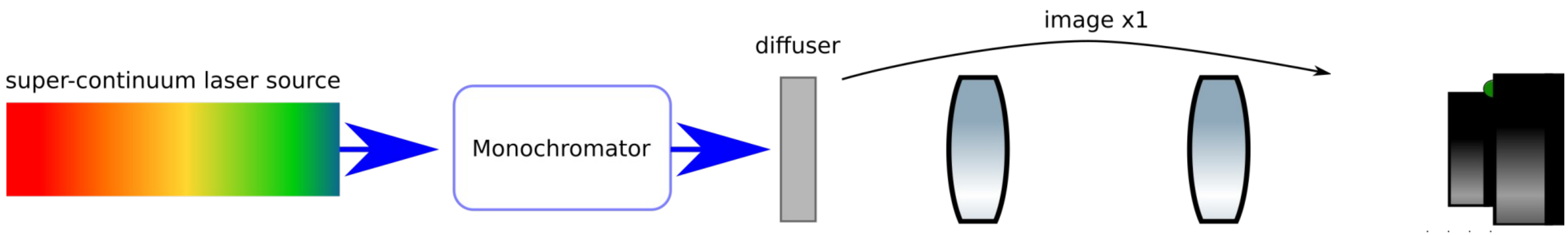
- Next steps

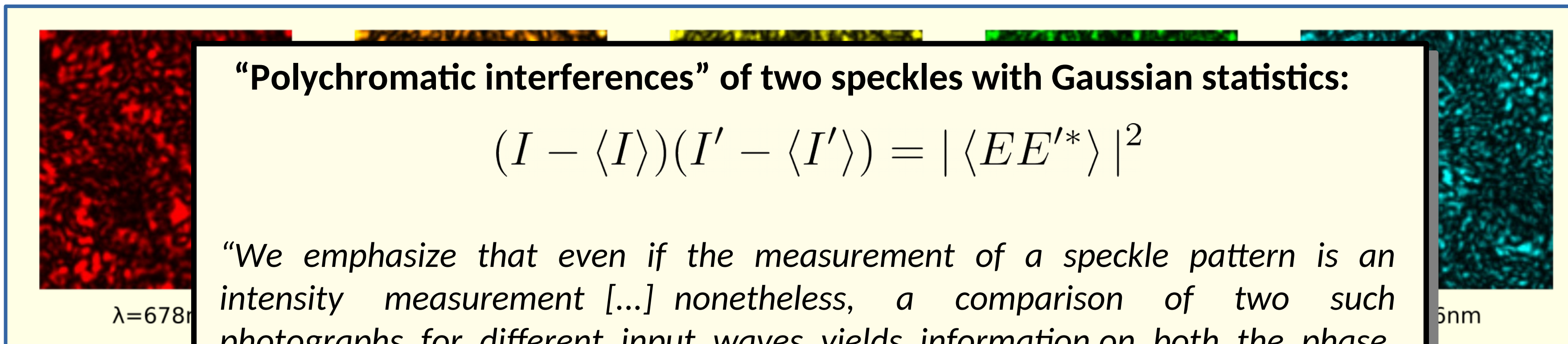
  → In depth fluorescent imaging / photo-excitation

Chromatic "memory effect" in forward multiply scattering samples

$$(\ell_s \ll L \ll \ell^*)$$

Δλ > 100nm for 1 mm-thick fixed brain slice [1]



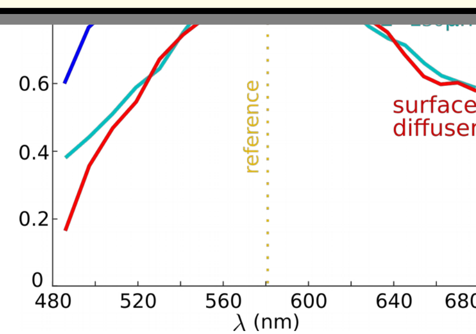


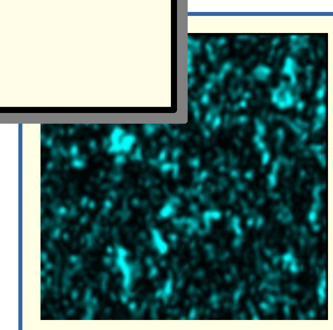
"Polychromatic interferences" of two speckles with Gaussian statistics:

$$(I - \langle I \rangle)(I' - \langle I' \rangle) = |\langle EE'^* \rangle|^2$$

"We emphasize that even if the measurement of a speckle pattern is an intensity measurement [...] nonetheless, a comparison of two such photographs for different input waves yields information on both the phase and amplitude differences of these waves."

I. Freund, Physica A 168, 49(1990)

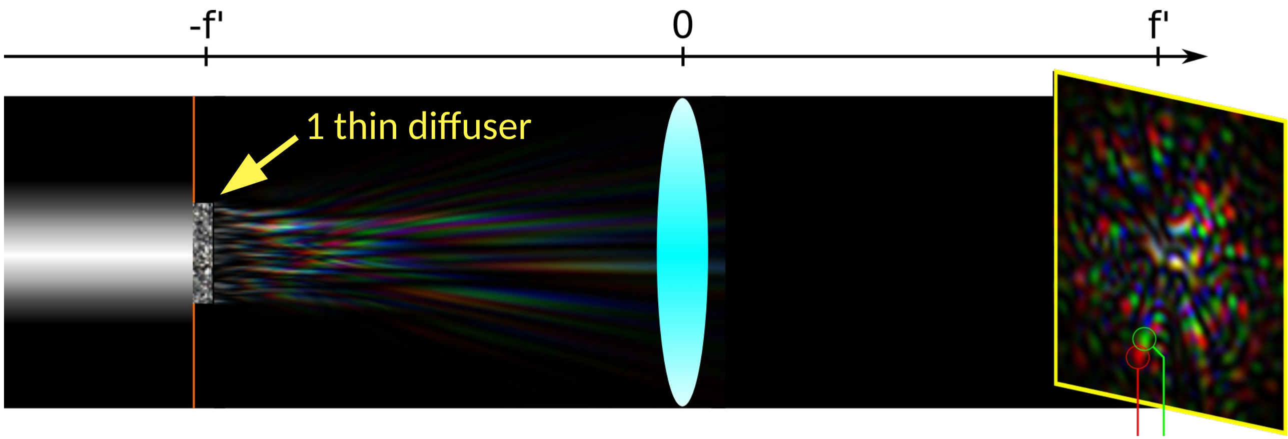


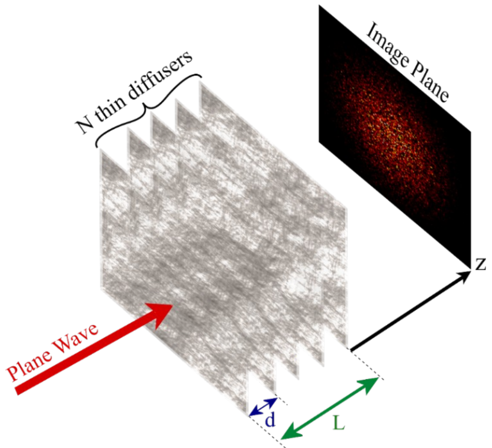


[1] A.G. Vesga et al., Opt. Express 27 (2019)
[2] L. Zhu et al., Optica 7, 338 (2020)
[3] P. Arjmand et al., Opt. Express 29(5), 6963 (2021)

Thin phase plate diffuser

$$T = e^{ik\delta(\mathbf{r})} \simeq 1 + ik\delta(\mathbf{r})$$



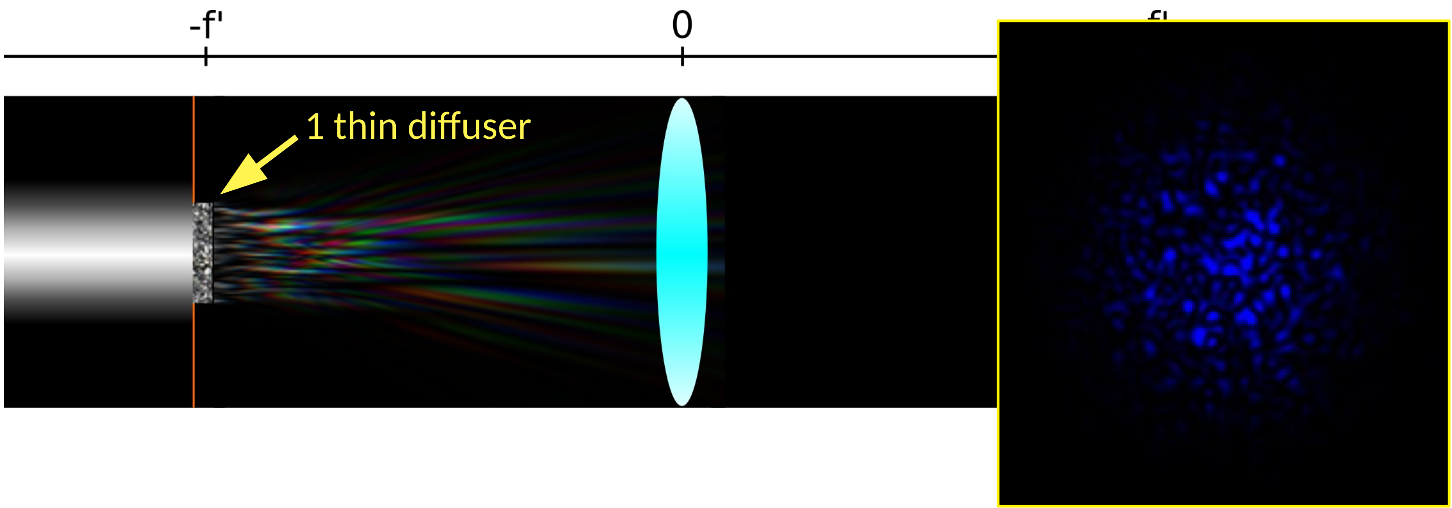


Fraunhofer diffraction (at infinity) :

$$\tilde{E}(X,Y) = -\frac{e^{2ikf}}{i\lambda f}\int E(x,y)e^{ik\frac{xX+yY}{f}}dxdy$$

Thin phase plate diffuser

$$T = e^{ik\delta(\mathbf{r})} \simeq 1 + ik\delta(\mathbf{r})$$



Fraunhofer diffraction (at infinity) :

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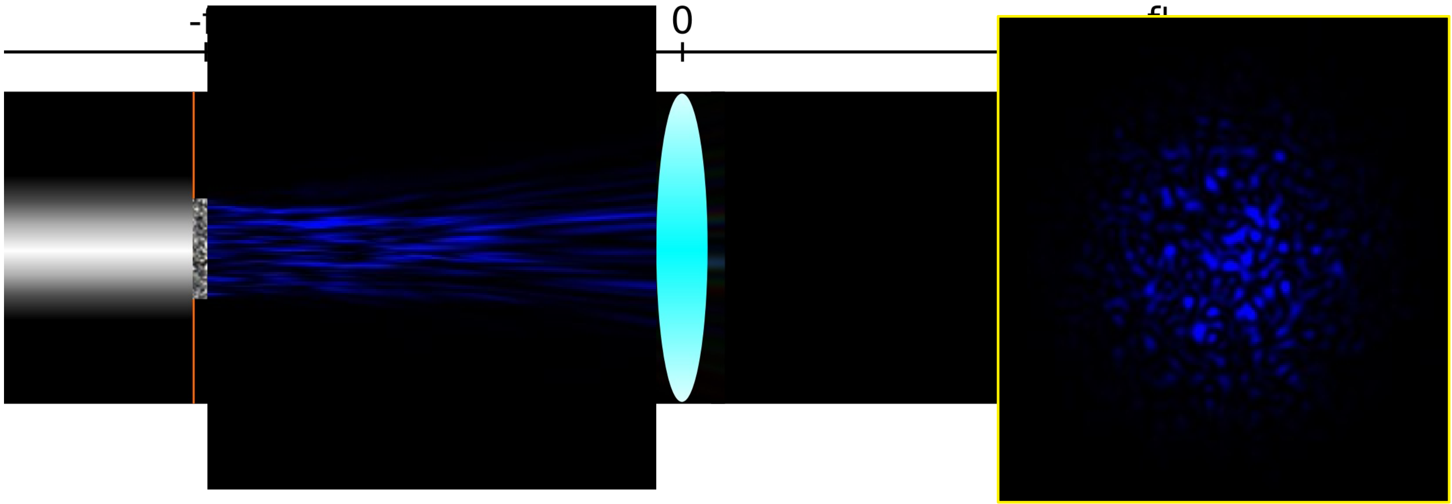
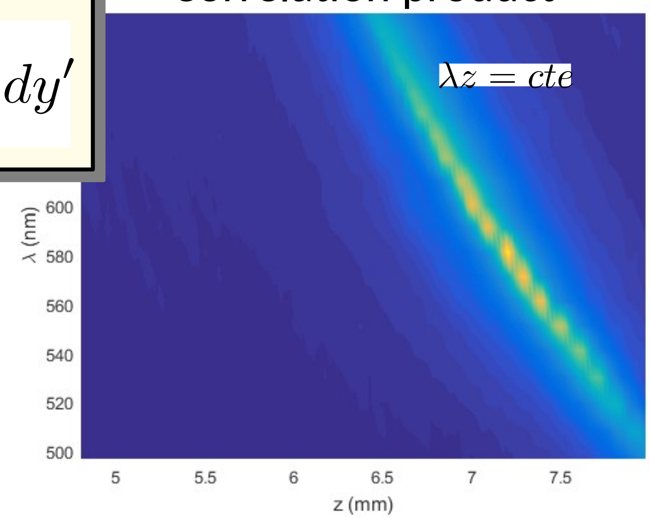


Fresnel diffraction :

$$E(x,y,z) = \frac{e^{ikz}}{i\lambda z}\int E(x,y,0)\,e^{i\pi\frac{(x-x')^2+(y-y')^2}{\lambda z}}\,dx'dy'$$

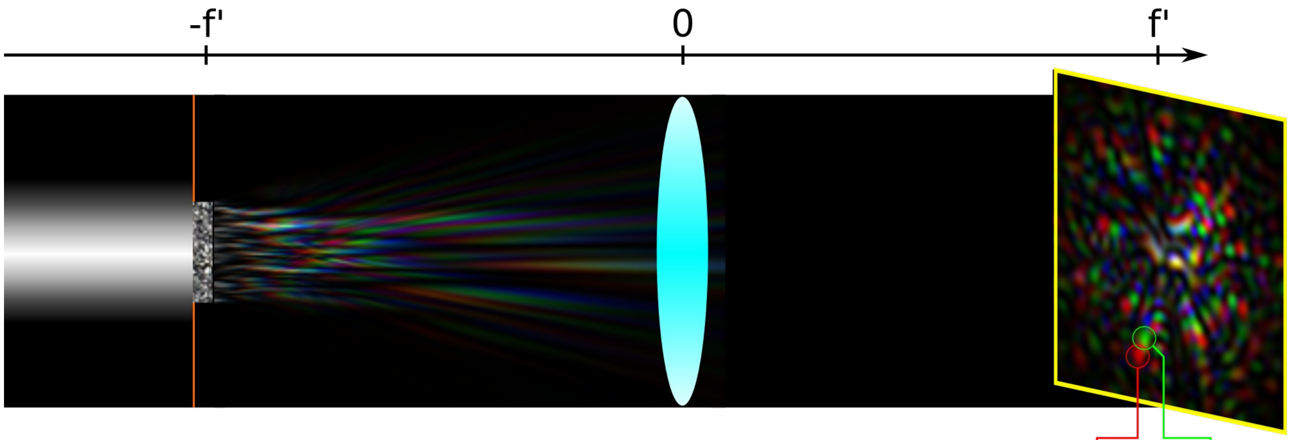
***Chromato-axial** "memory effect"*

Correlation product



Thin phase plate diffuser

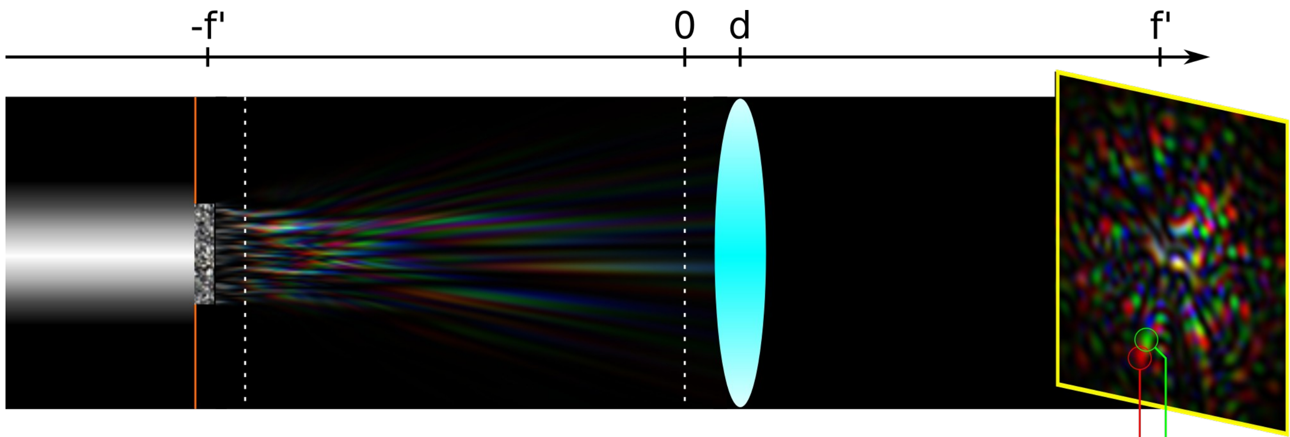
$$T = e^{ik\delta(\mathbf{r})} \simeq 1 + ik\delta(\mathbf{r})$$



$$\Delta\varphi = \varphi - \varphi = 0$$

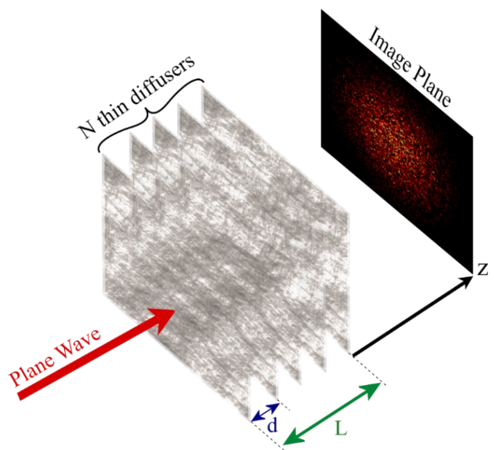
Thin phase plate diffuser

$$T = e^{ik\delta(\mathbf{r})} \simeq 1 + ik\delta(\mathbf{r})$$

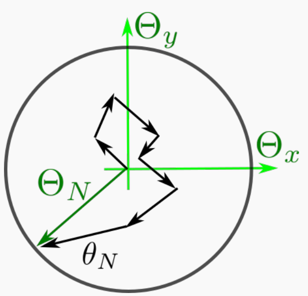


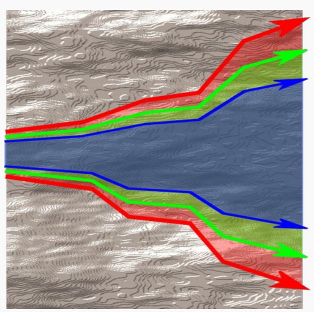
$$\Delta\varphi = \varphi - \varphi = (k - k)\frac{k}{k} d \frac{\theta^2}{2}$$

stack of thin scattering planes



Homothetic random walk in the k-space [2]





Spectral width [2,3] : $\Delta\lambda \simeq \frac{\lambda^2 \ell^*}{L^2}$

[1] L. Zhu et al., Optica 7, 338 (2020)
[2] P. Arjmand et al., Opt. Express 29(5), 6963 (2021)

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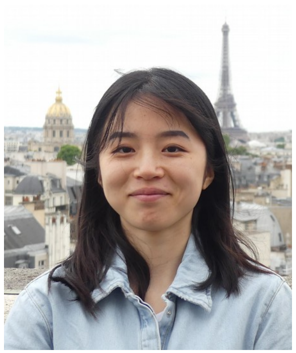

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Zhang

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Thank you for your attention!

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