phaseform

Deformable Phase Plate (DPP) – a New Technology for Plug-and-Play Adaptive Optics

Pouya Rajaeipour, Ph.D.
Phaseform GmbH, Freiburg, Germany

Phaseform GmbH

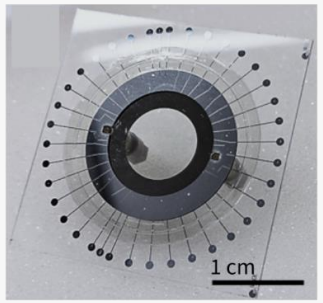
phaseform

Developing refractive technologies for Adaptive Optics

- 2014: DPP Proof-of-principle at Uni Freiburg
- 2016-2019: DFG grant for lab prototypes
- March 2020: EXIST Transfer of Research Grant for commercialization
- September 2020: Phaseform founded as an independent spin-off from the Micro-Optics chair from the IMTEK of the Uni Freiburg

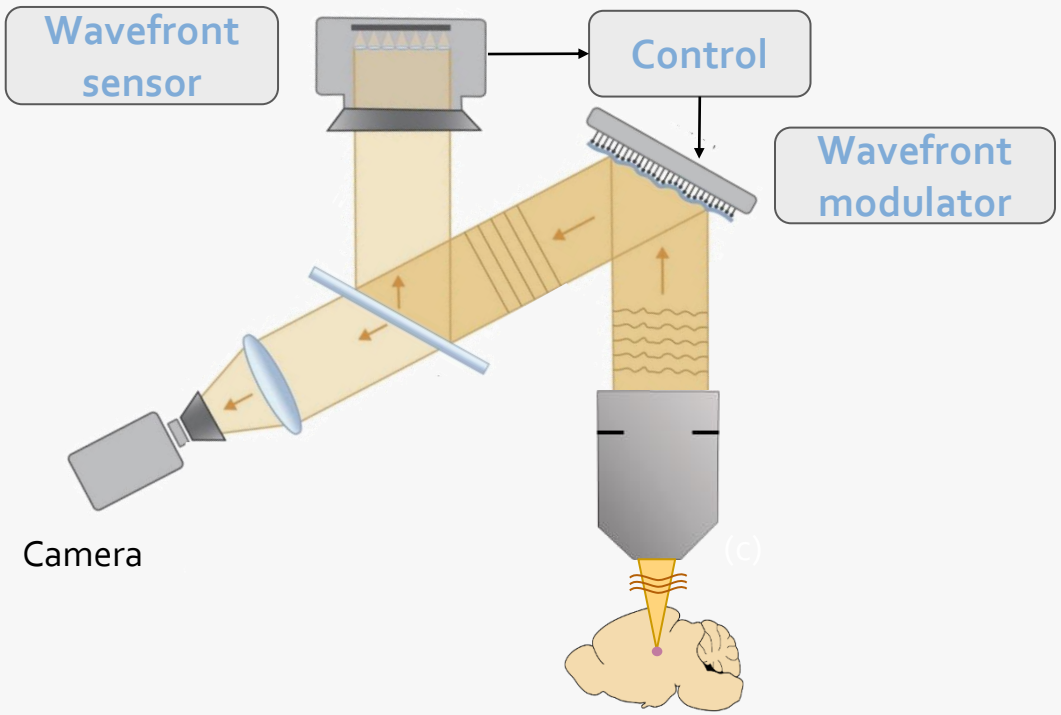
UNI FREIBURG

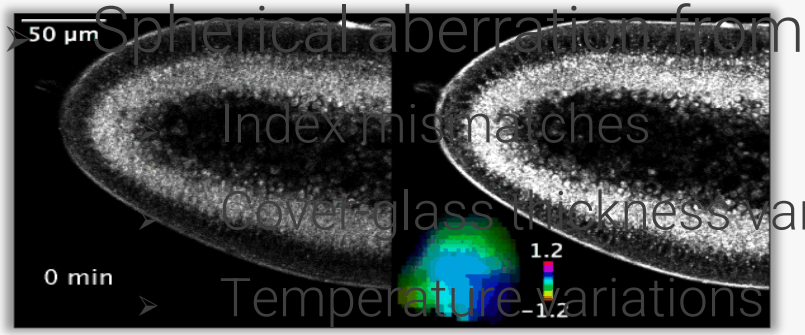
IMTEK



First implementation of DPP
Banerjee, Rajaeipour et al., *Applied Optics* (2018)

Adaptive Optics in Microscopy





- Spherical aberration from
  - Index mismatches
  - Coverglass thickness variations
  - Temperature variations

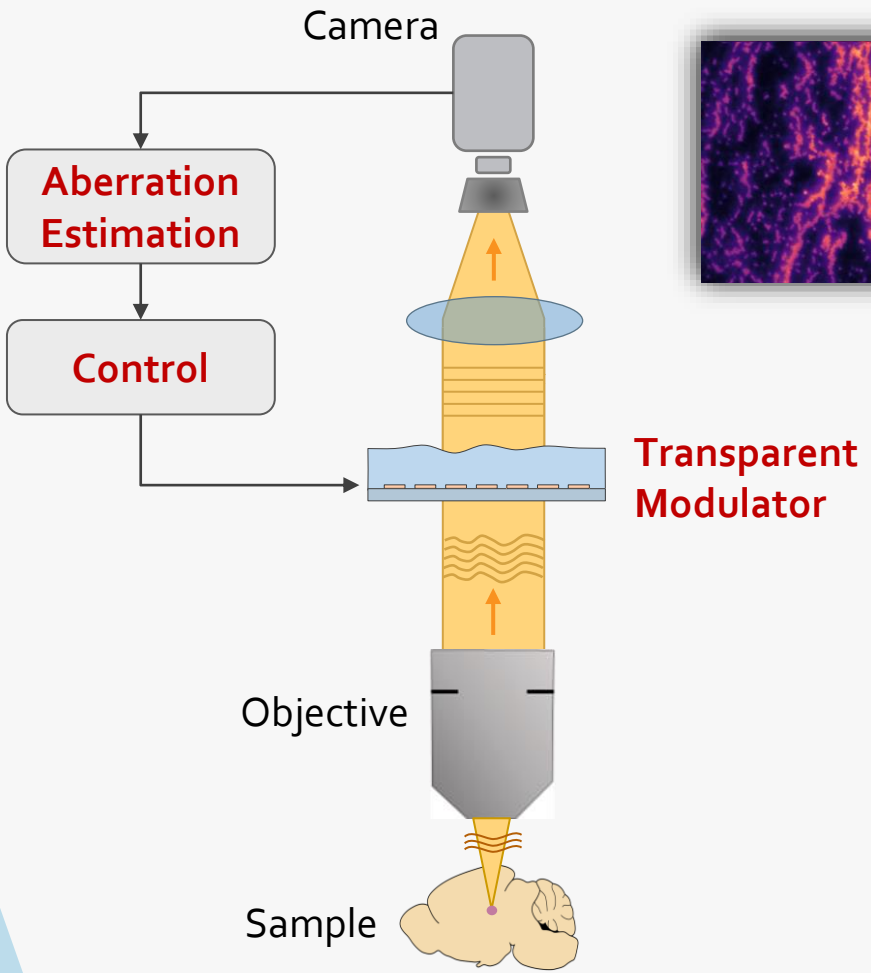
Olivier et al., Opt. Lett. 34(20), 3145-7 (2009).

- Large imaging-depth
- Complex aberrations from
  - Sample inhomogeneity
  - Instrument aging

Débarre et al., Opt. Lett. 34(16), 2495-7 (2009)

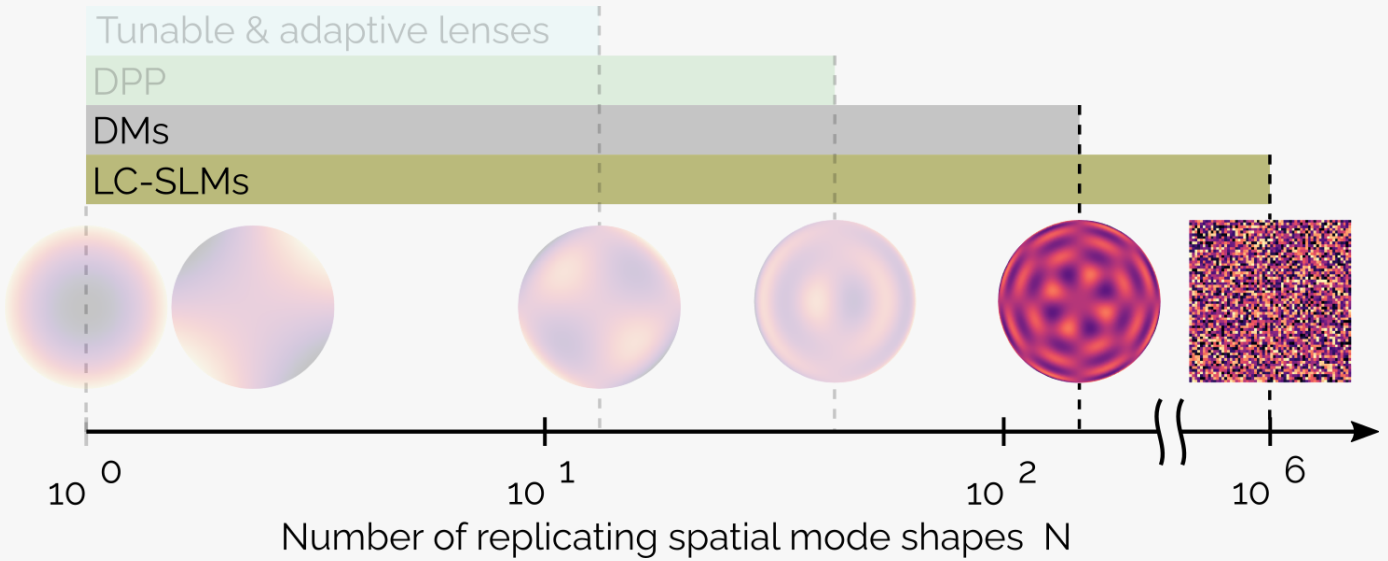
- Point spread function (PSF) engineering

Refractive Adaptive Optics

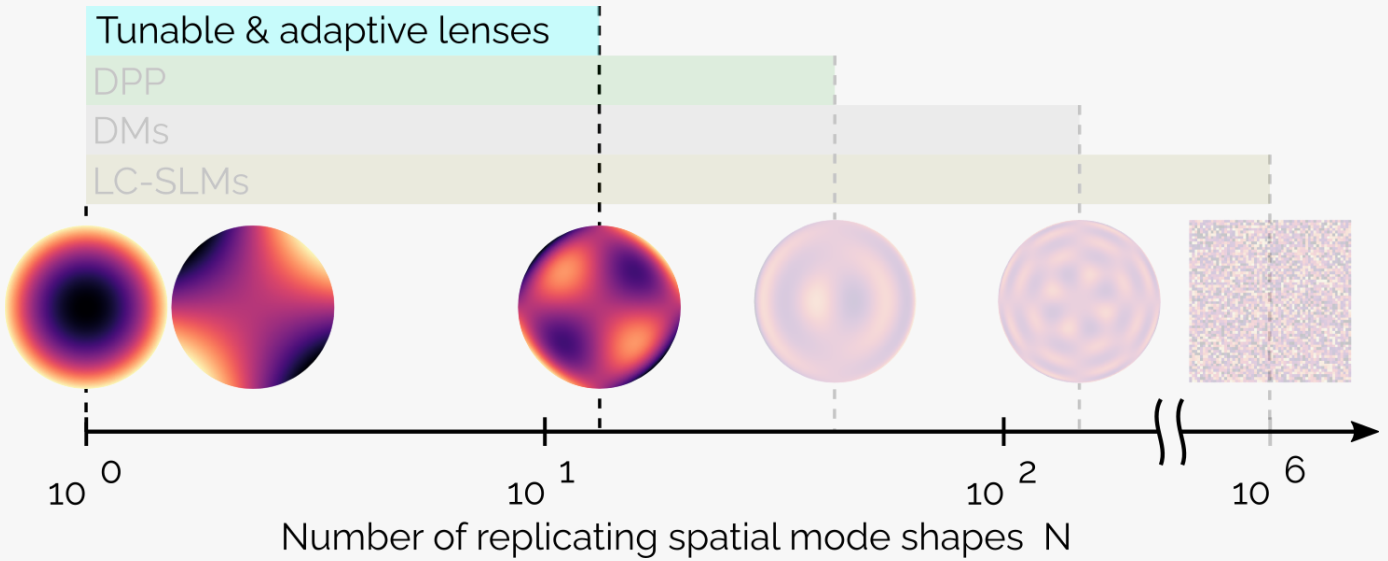


- Direct AO integration into instruments
- Advantages
  - Compact and plug-and-play
  - Usable in existing instruments
  - Stackable for volumetric correction
- Potential applications
  - Life-science microscopy
  - Ophthalmology
  - Laser machining
  - Free-space optical communications

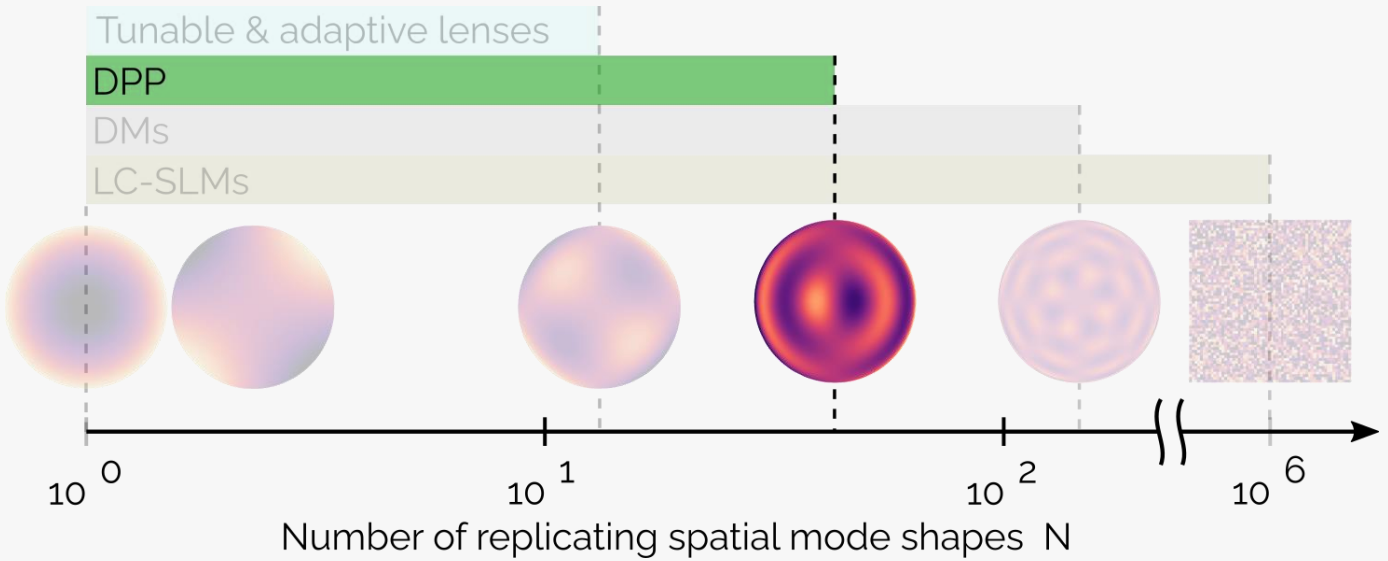
Encyclopedia of Wavefront Modulators



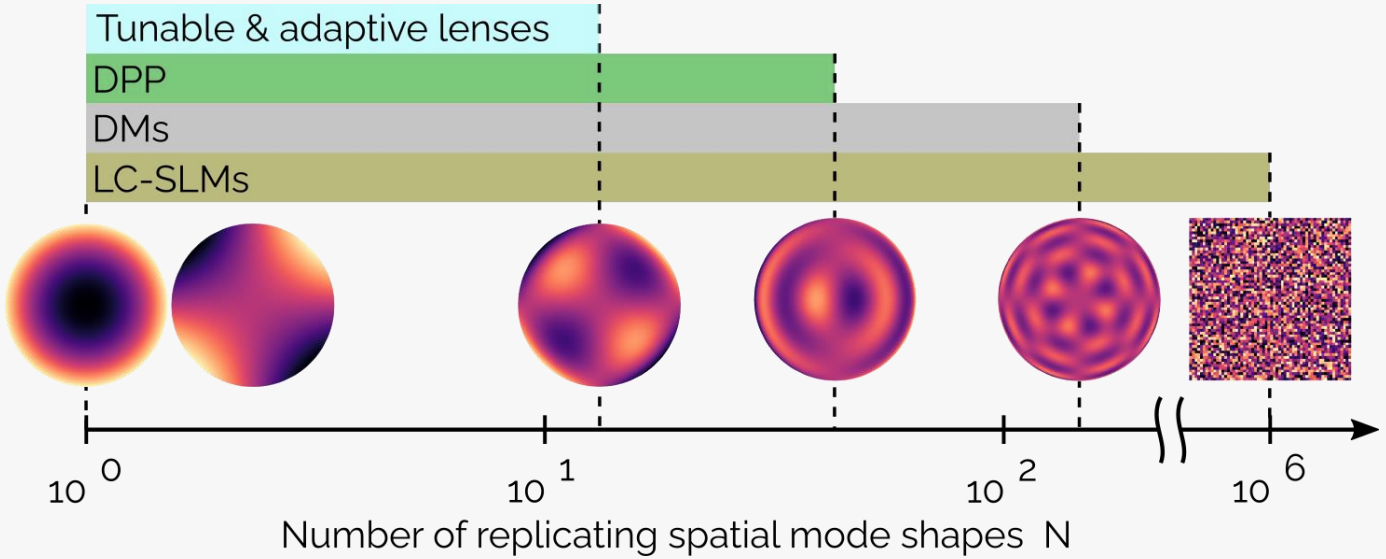
Encyclopedia of Wavefront Modulators



Encyclopedia of Wavefront Modulators

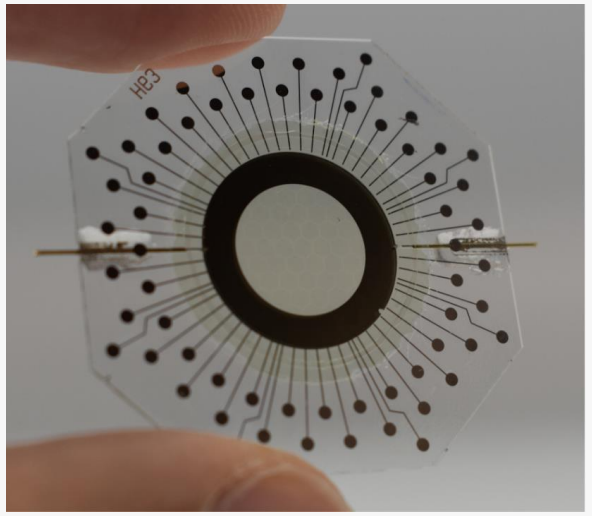


Encyclopedia of Wavefront Modulators



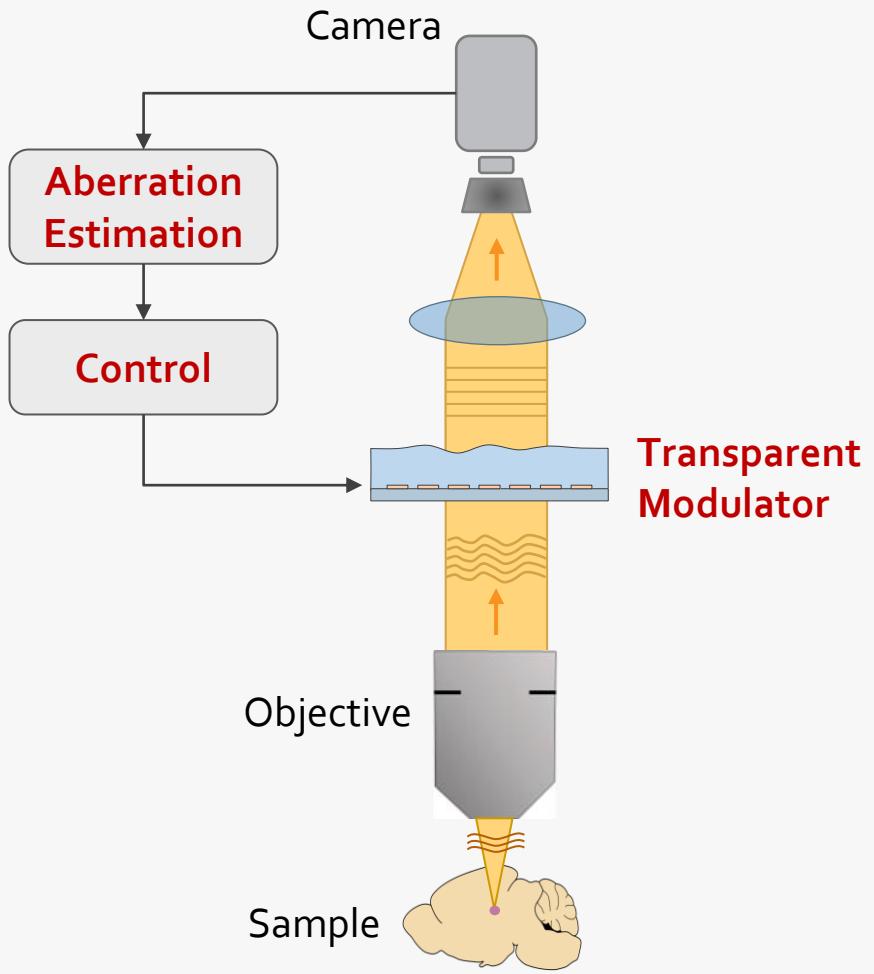
Outline

- Deformable Phase Plate technology
  - Working principle
  - Scalable manufacturing
  - Highlight of properties
- Refractive Adaptive Optics System
- Demonstrated applications of DPP
  - Fully refractive AO widefield microscope
  - Cascading multiple DPPs
  - Refractive objective add-on
  - Sample conjugate AO with DPP
  - DPP for multi-photon microscopy



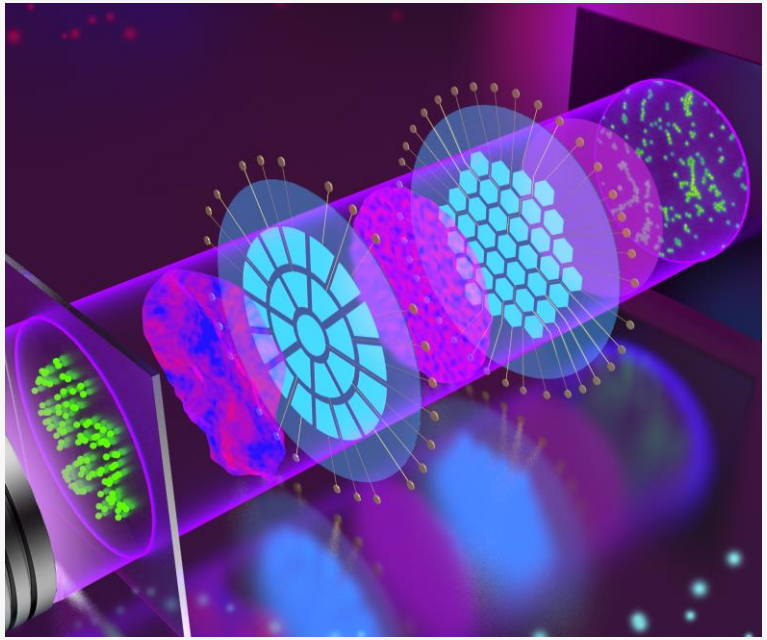
Outline

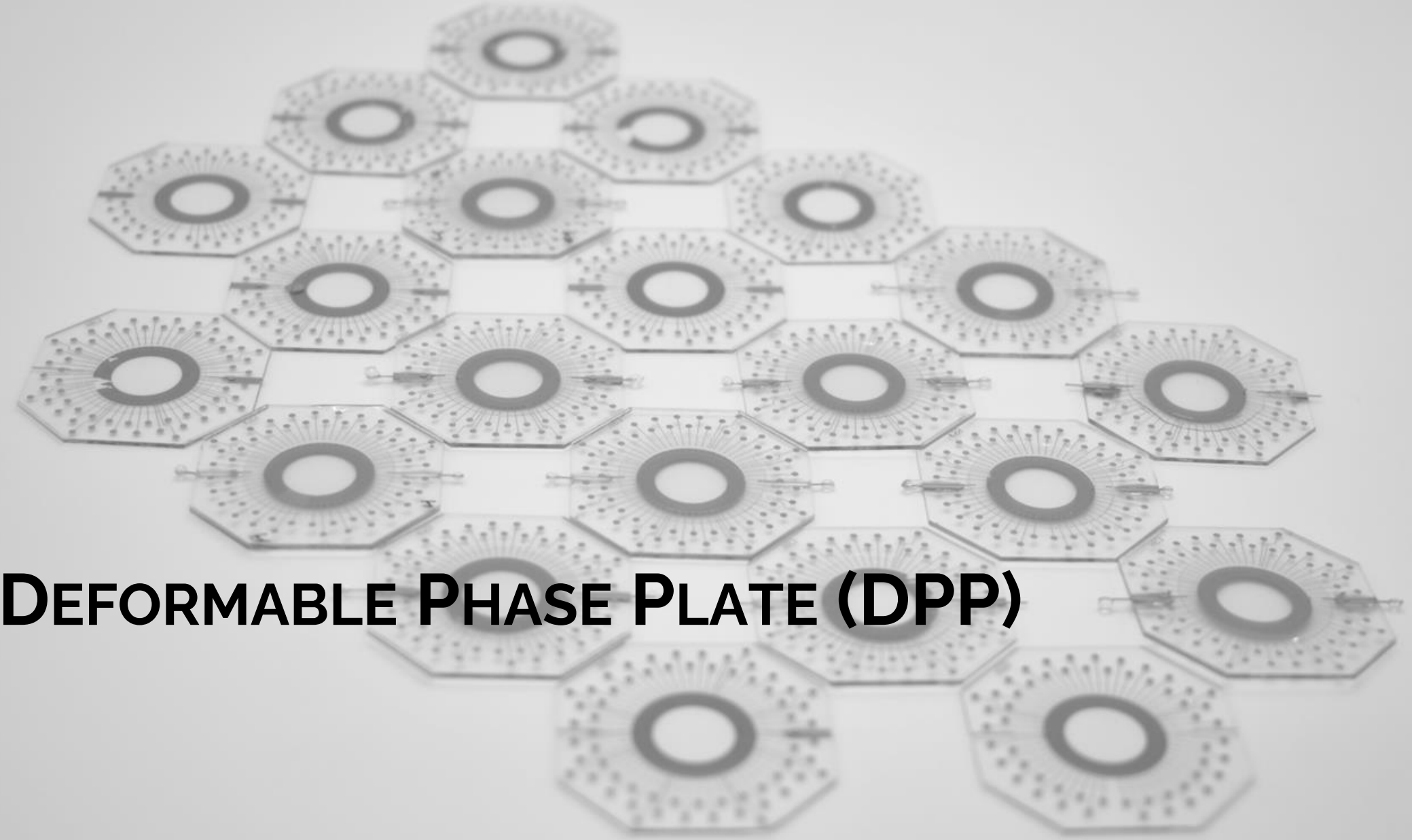
- Deformable Phase Plate technology
  - Working principle
  - Scalable manufacturing
  - Highlight of properties
- Refractive Adaptive Optics system
- Demonstrated applications of DPP
  - Fully refractive AO widefield microscope
  - Cascading multiple DPPs
  - Refractive objective add-on
  - Sample conjugate AO with DPP
  - DPP for multi-photon microscopy



Outline

- Deformable Phase Plate technology
  - Working principle
  - Scalable manufacturing
  - Highlight of properties
- Refractive Adaptive Optics System
- Demonstrated applications of DPP
  - Fully refractive AO widefield microscope
  - Cascading multiple DPPs
  - Refractive objective add-on
  - Sample conjugate AO with DPP
  - DPP for multi-photon microscopy

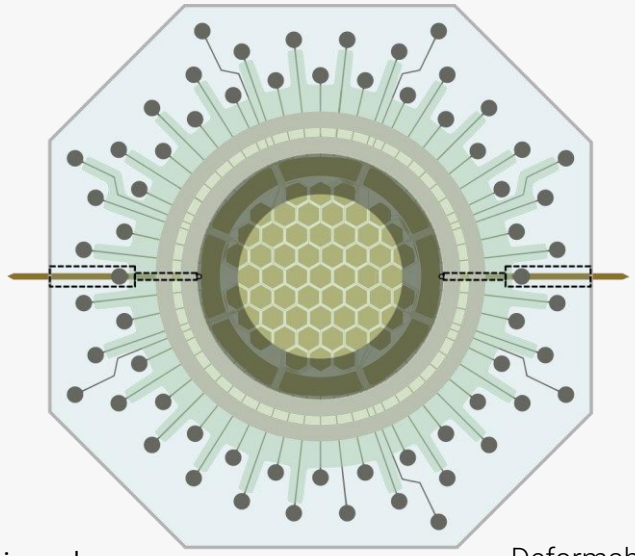


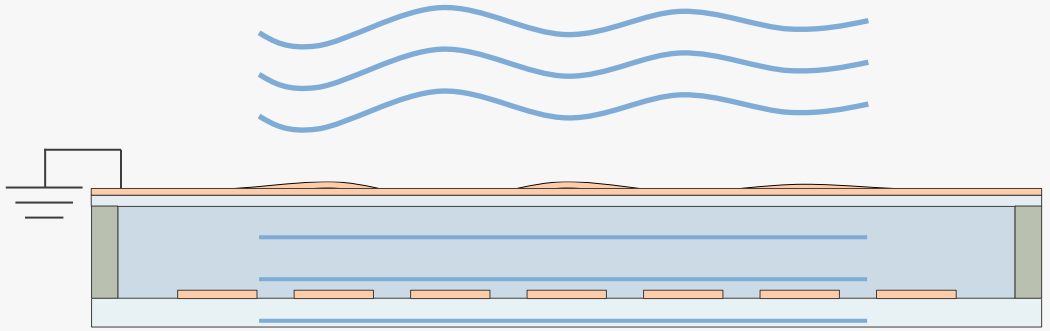


Deformable Phase Plate (DPP)

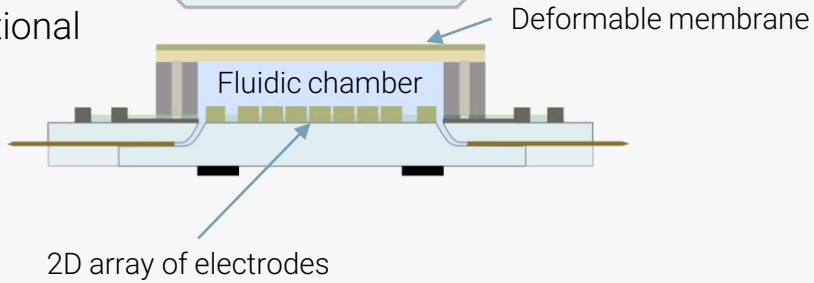
Deformable Phase Plate Concept

Top view





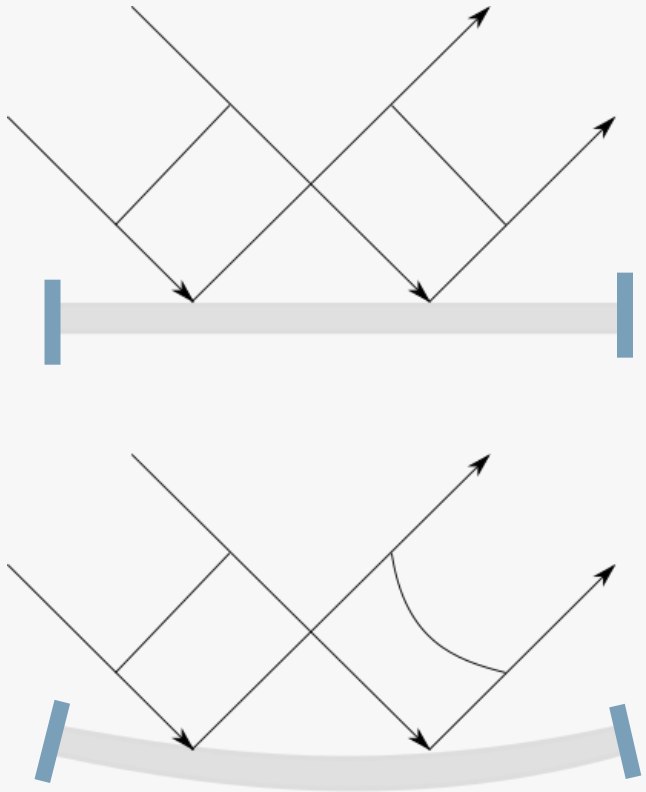
Cross-sectional view



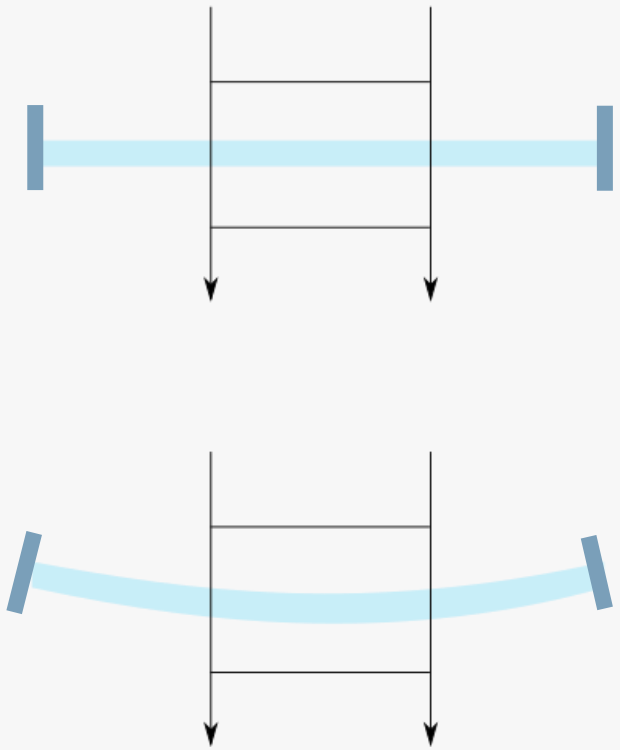
$$\Phi(x,y) = \frac{2\pi}{\lambda} d(x,y)\left(n_{liquid} - n_{air}\right)$$

Relaxed Packaging

- Reflective elements



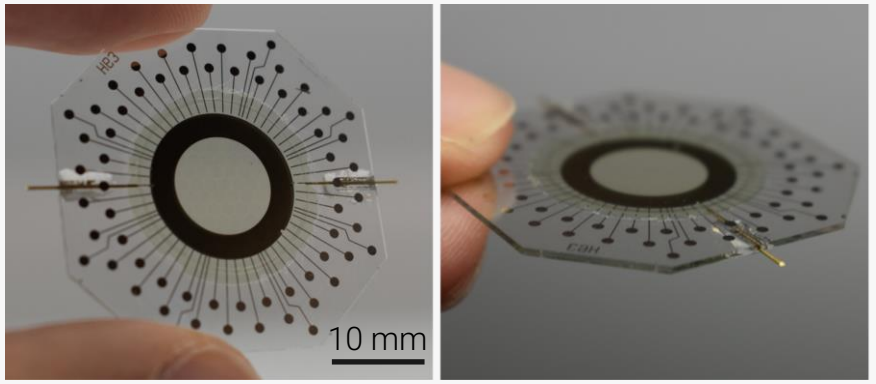
- Transmissive DPP

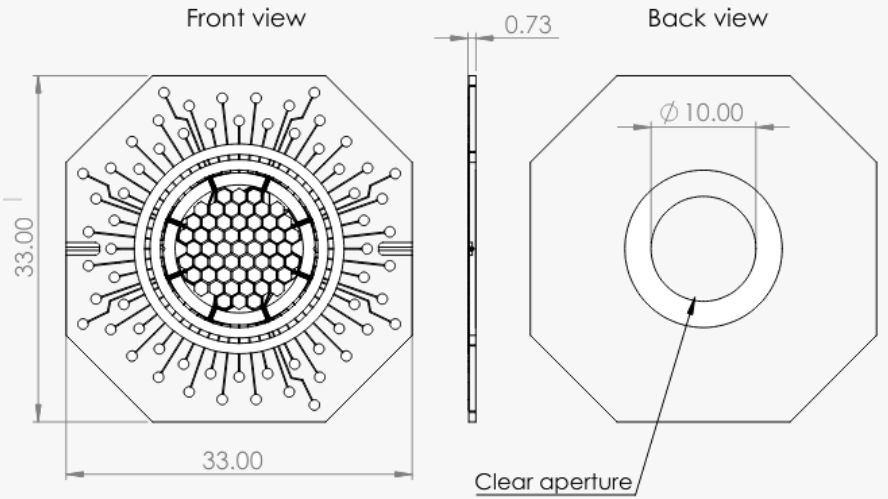


Realized DPP

Technical core features:

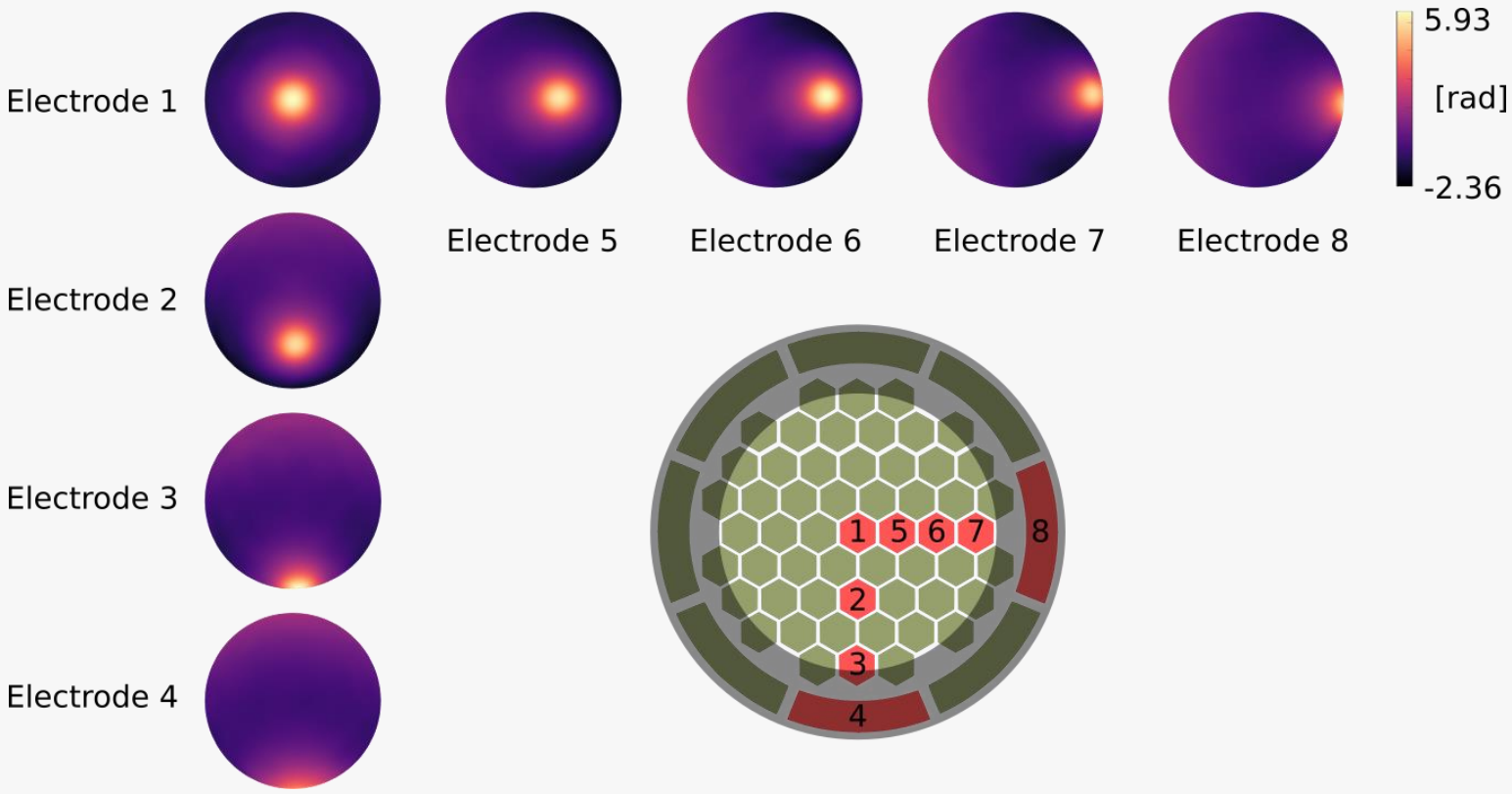
- Transmissive: easy integration in novel devices
- Optical efficiency: non-polarizing, diffraction-free
- Scalable: MEMS-based, robust manufacturing
- 63 electrodes: high order aberration correction



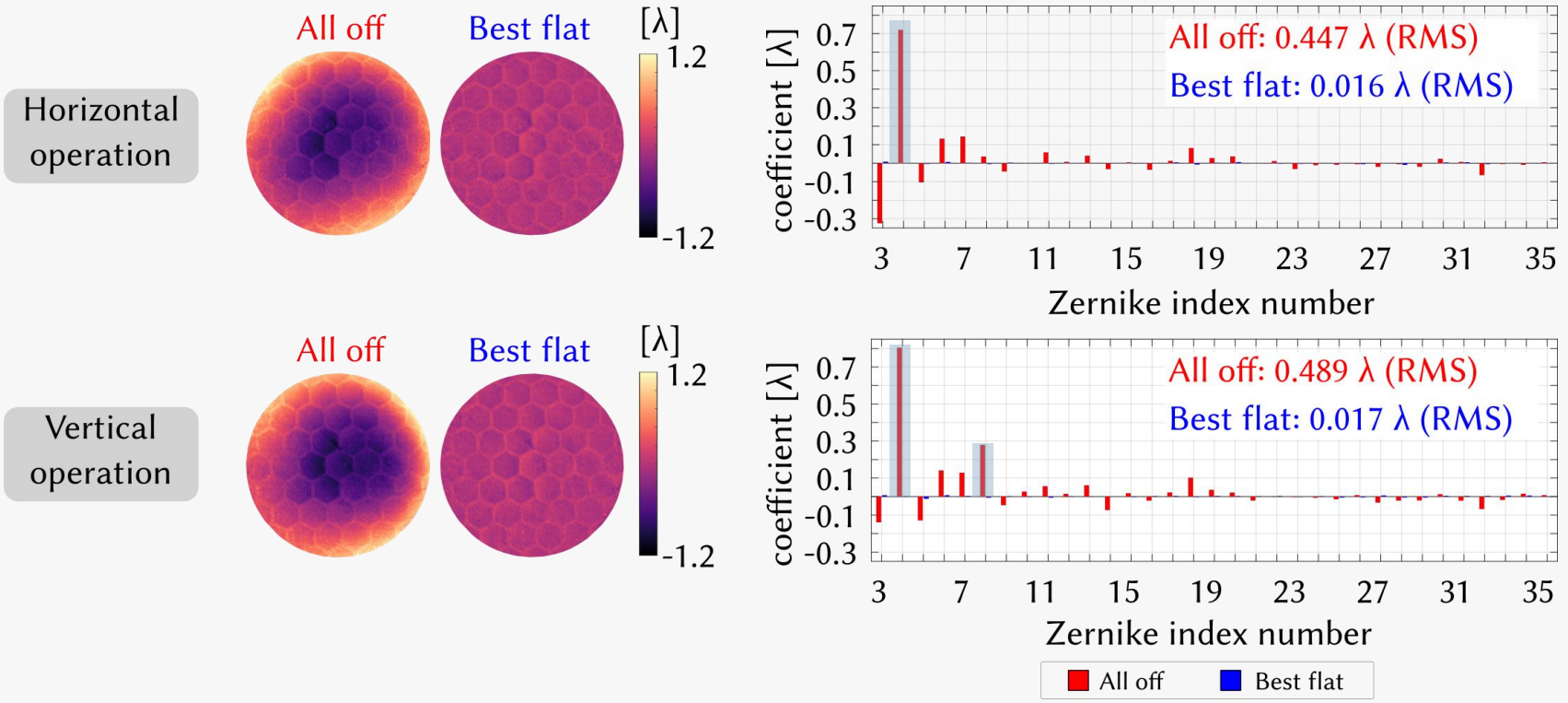


Journal of Optical Microsystems 1.3 (2021)

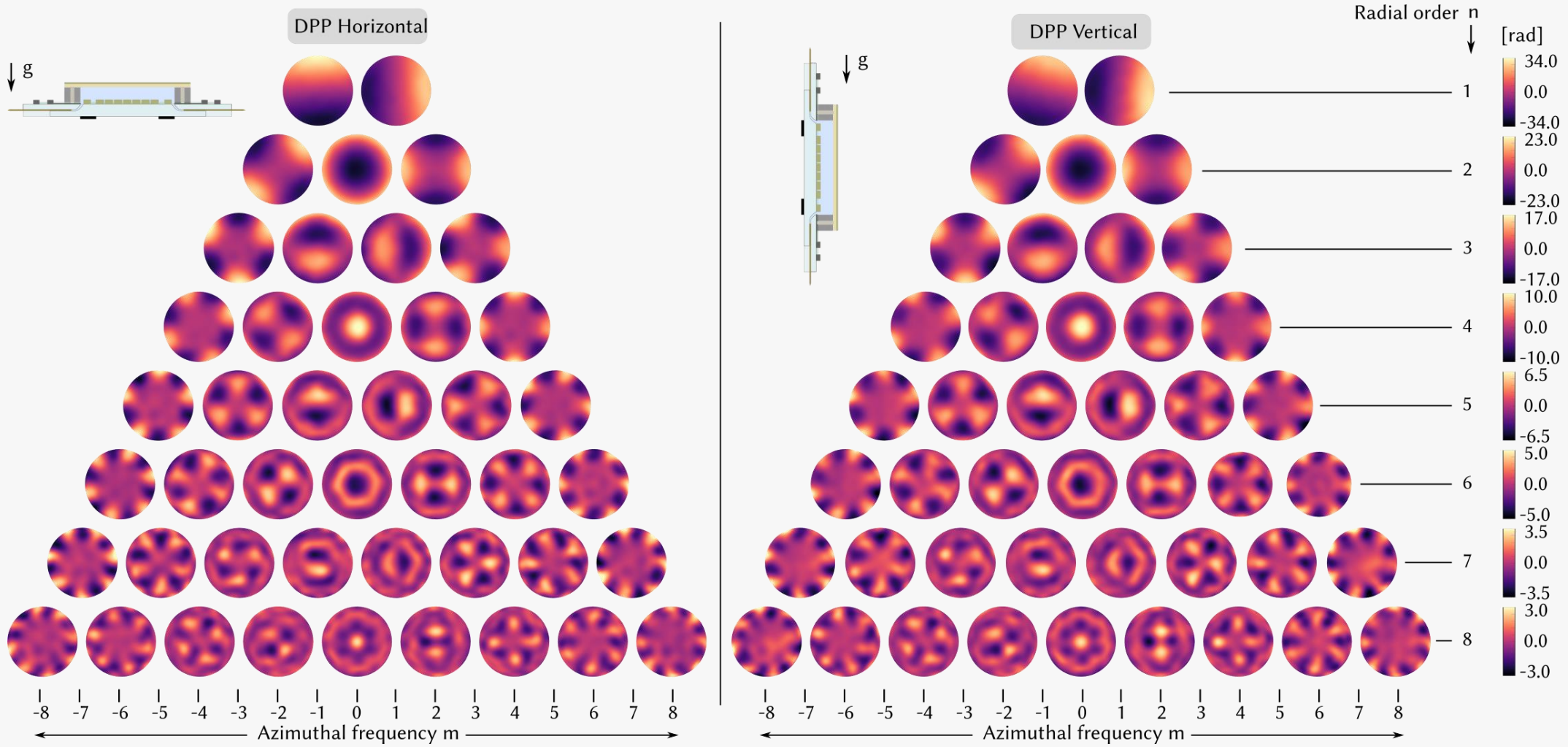
Localized Influece Functions



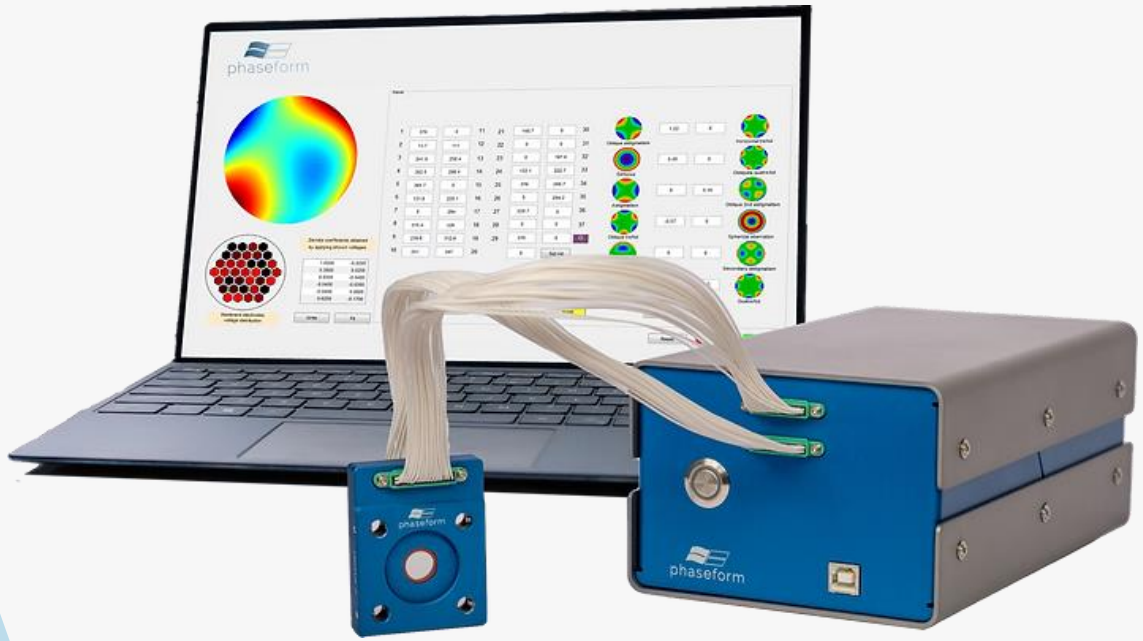
Initial Flatness & Open-loop Best Flat

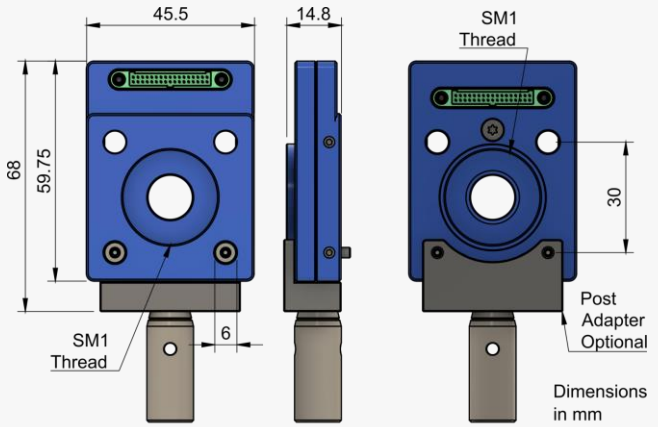


Zernike Mode Replication

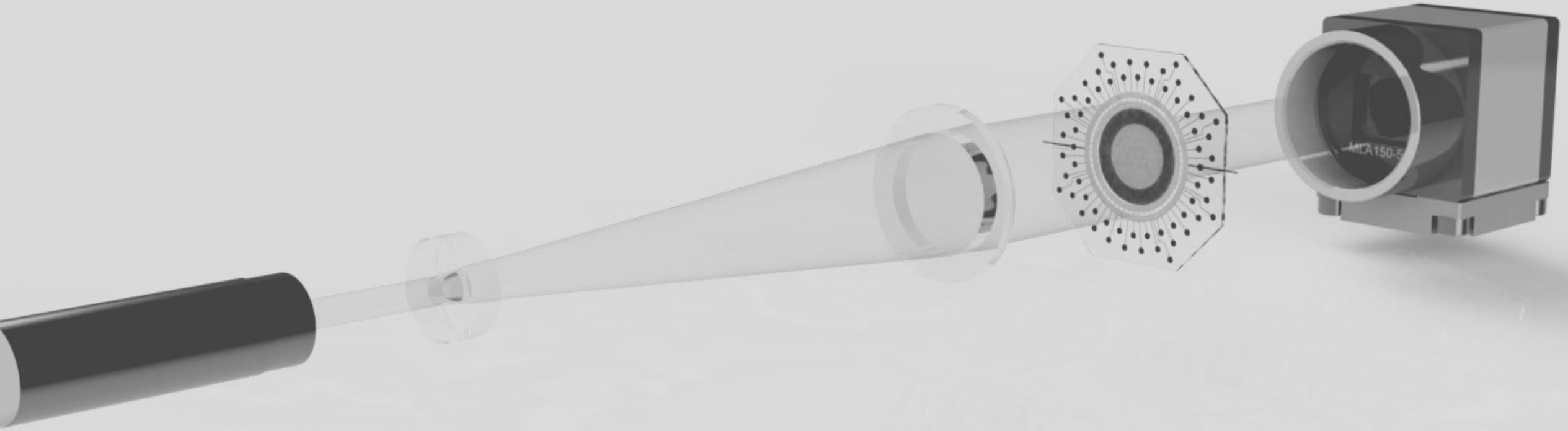


Phaseform DELTA 7



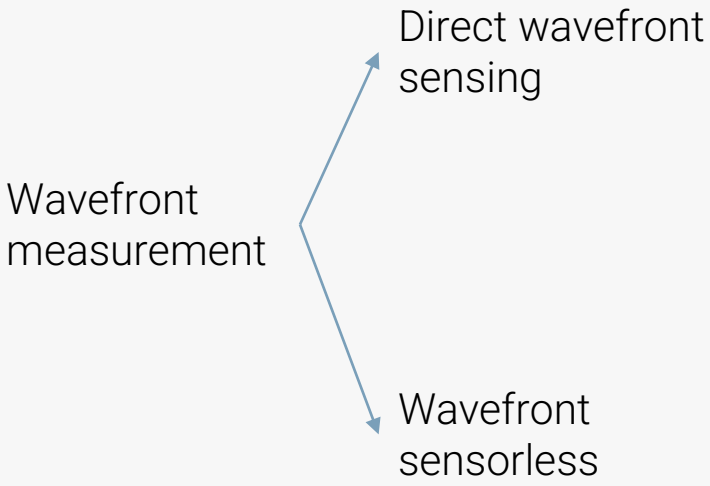


Wavefront modulator type	DPP (refractive, 2D, continuous-sheet, optofluidic)
Number of actuators	63
Optical aperture	10 mm ⌀
Thickness in optical path	0.8 mm
Mounting	30 mm cage system, SM1 tubing
Highest order of correction	7th radial order Zernike
Transmission range	visible - NIR, custom coatings possible
Accessories	driving electronics, open-loop control software

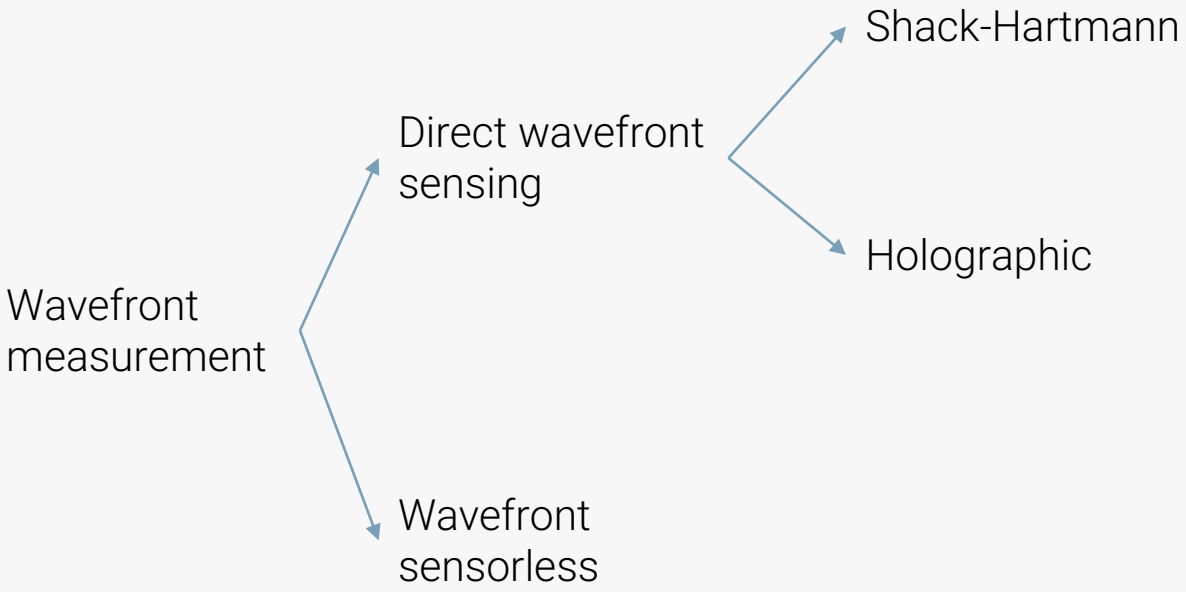


Optofluidic Adaptive Optics

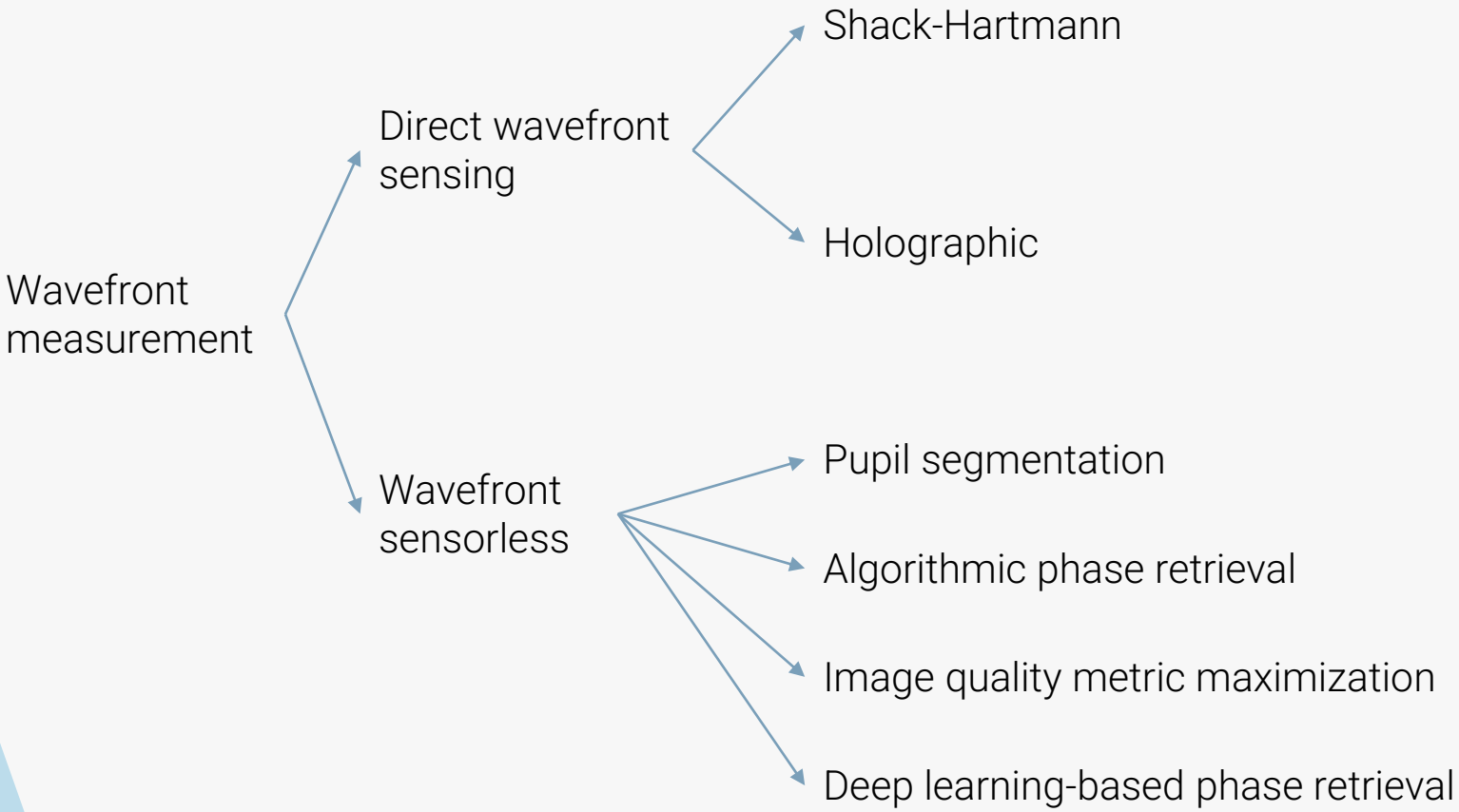
Aberration measurement techniques



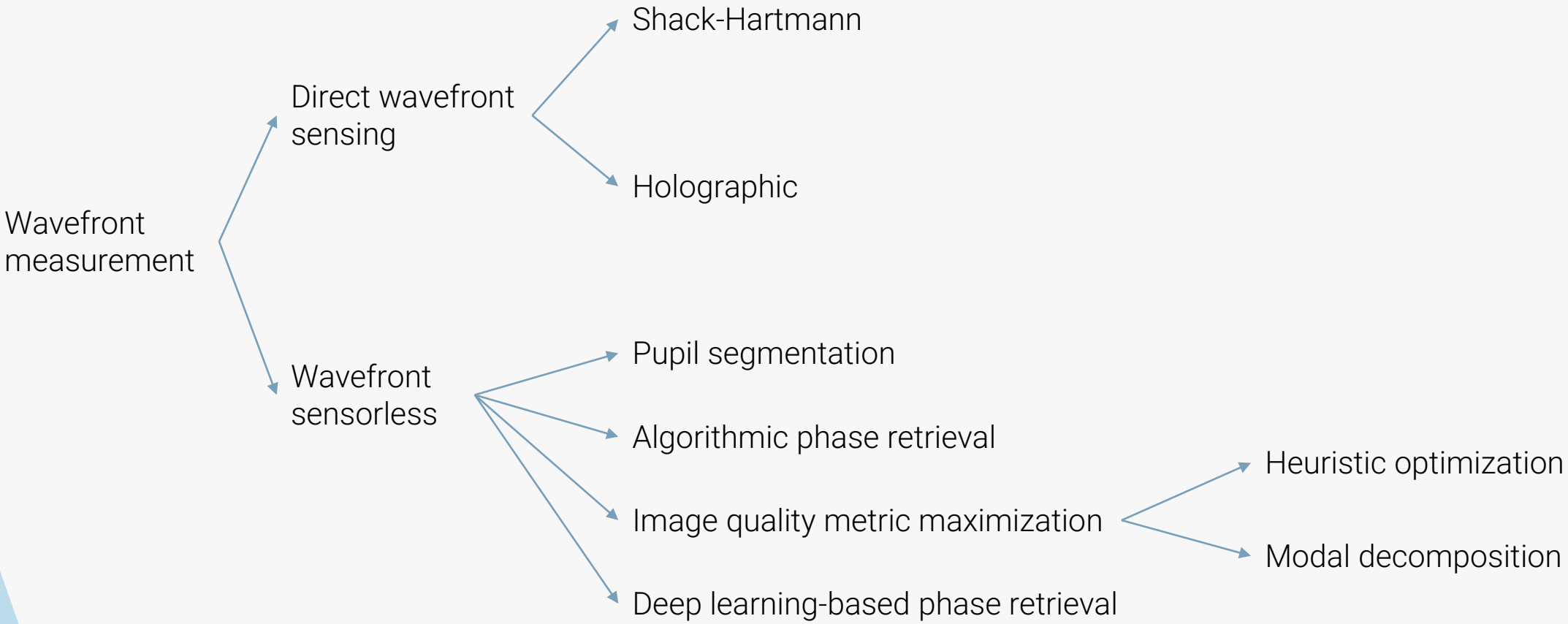
Aberration measurement techniques



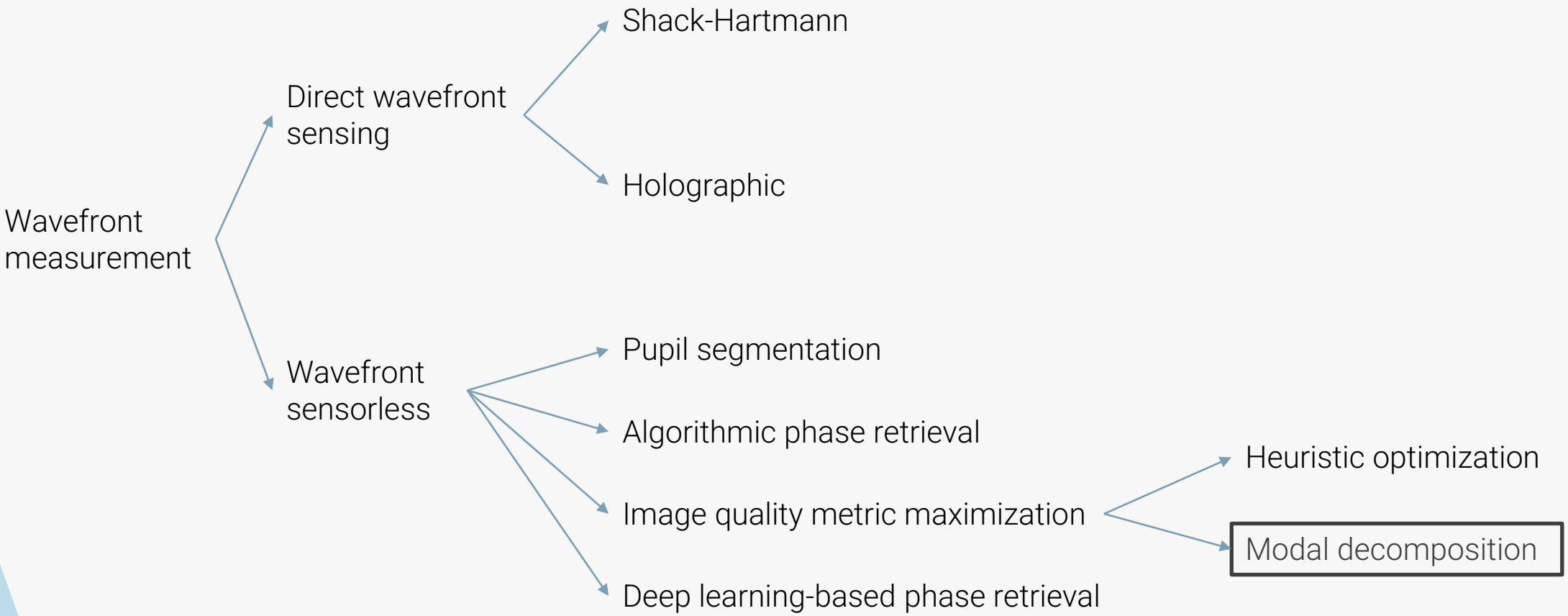
Aberration measurement techniques



Aberration measurement techniques



Aberration measurement techniques



Aberration measurement techniques

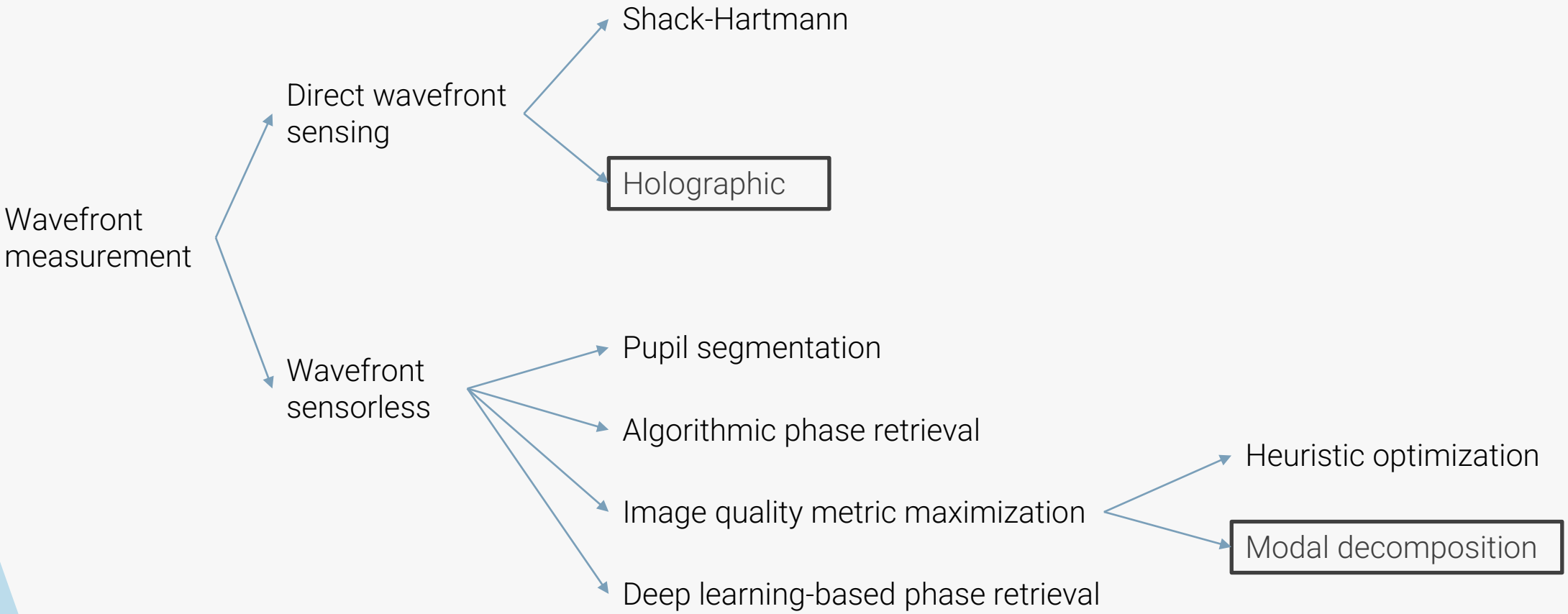
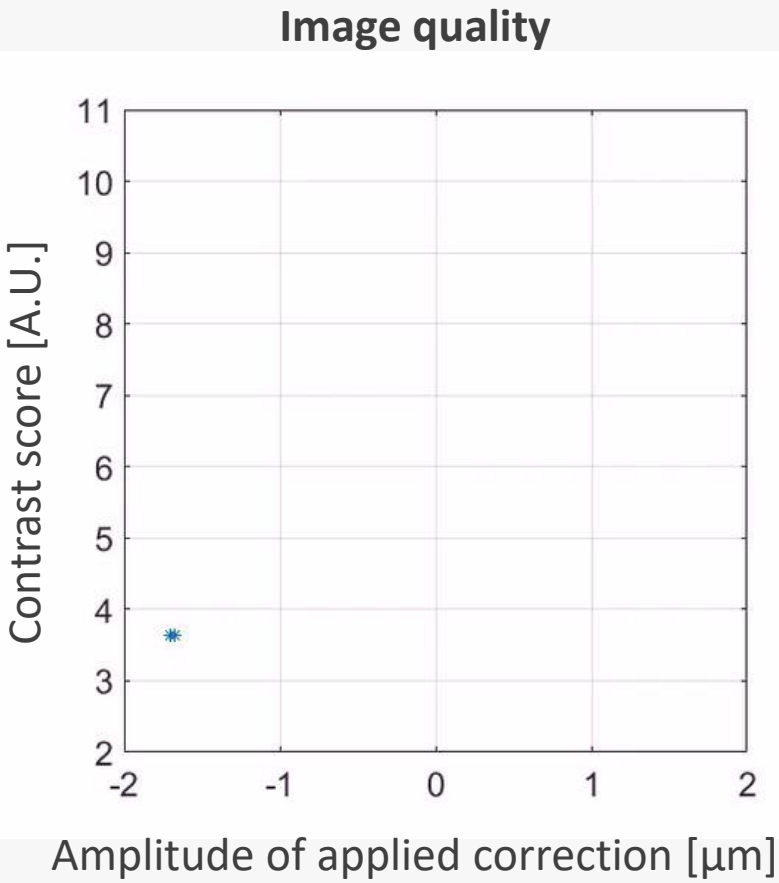
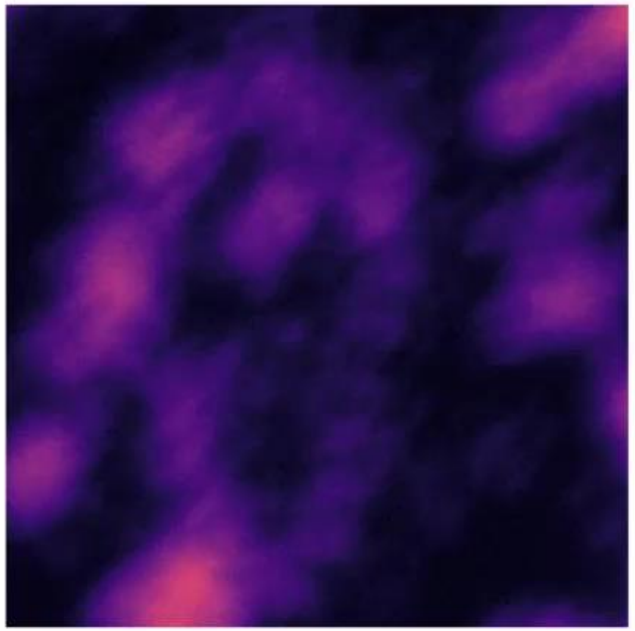
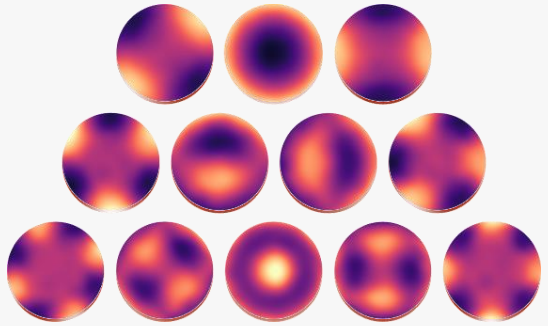


Image quality metric maximization

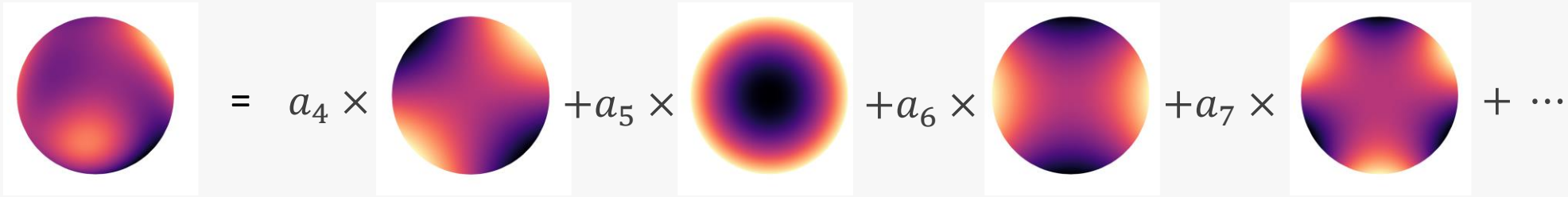






Modal decomposition approach

- Decomposing wavefront errors into an orthogonal set of aberration modes



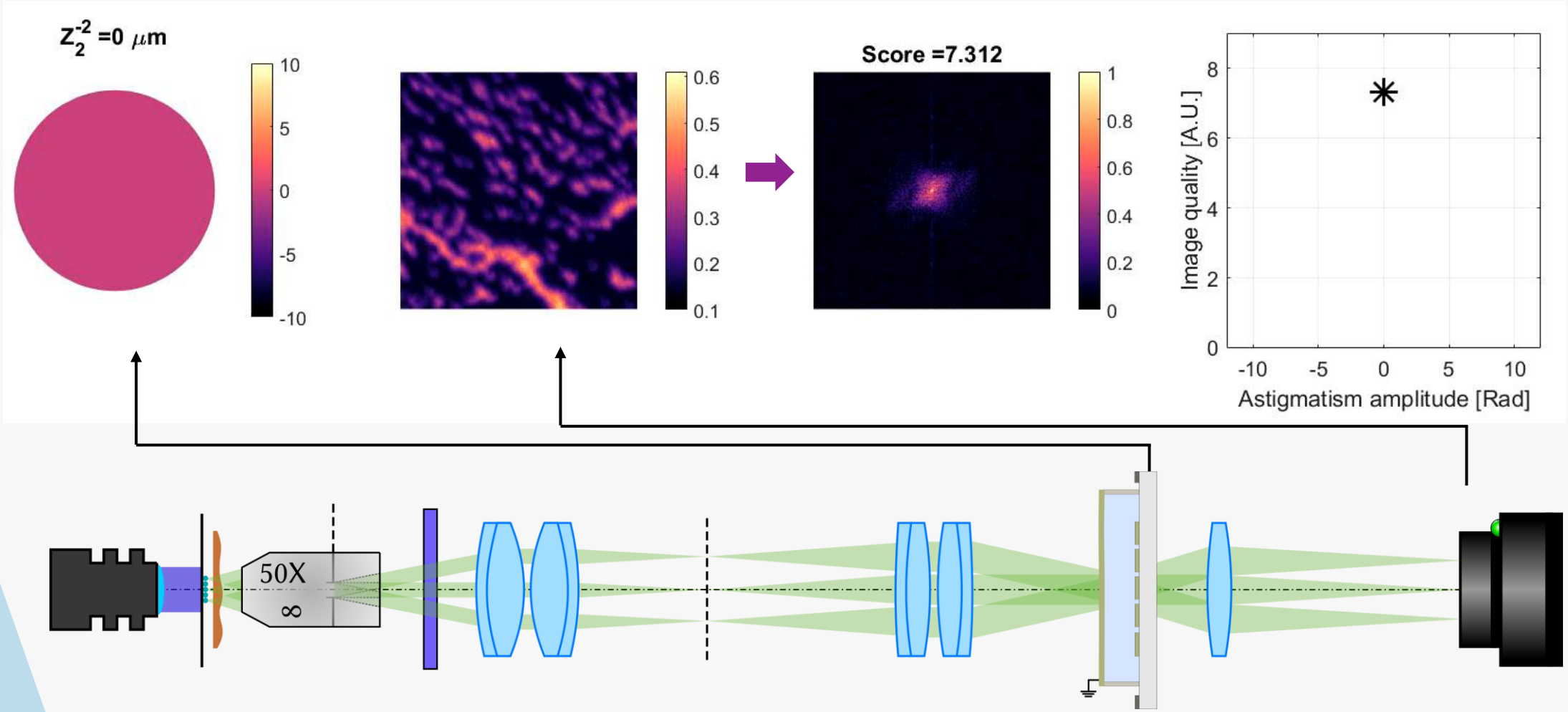
- Defining an image quality metric

$$Image\ Quality\ Score = f(a_4, a_5, a_6, a_7, \dots)$$

Based on Booth et al. *PNAS* (2002)

Modal decomposition approach

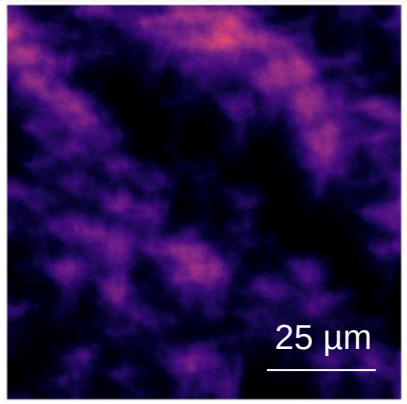
- Example: correcting for a single aberration mode



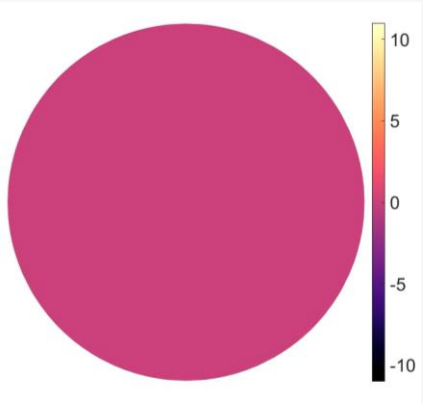
Modal decomposition approach

- Example: correcting for multiple aberration modes

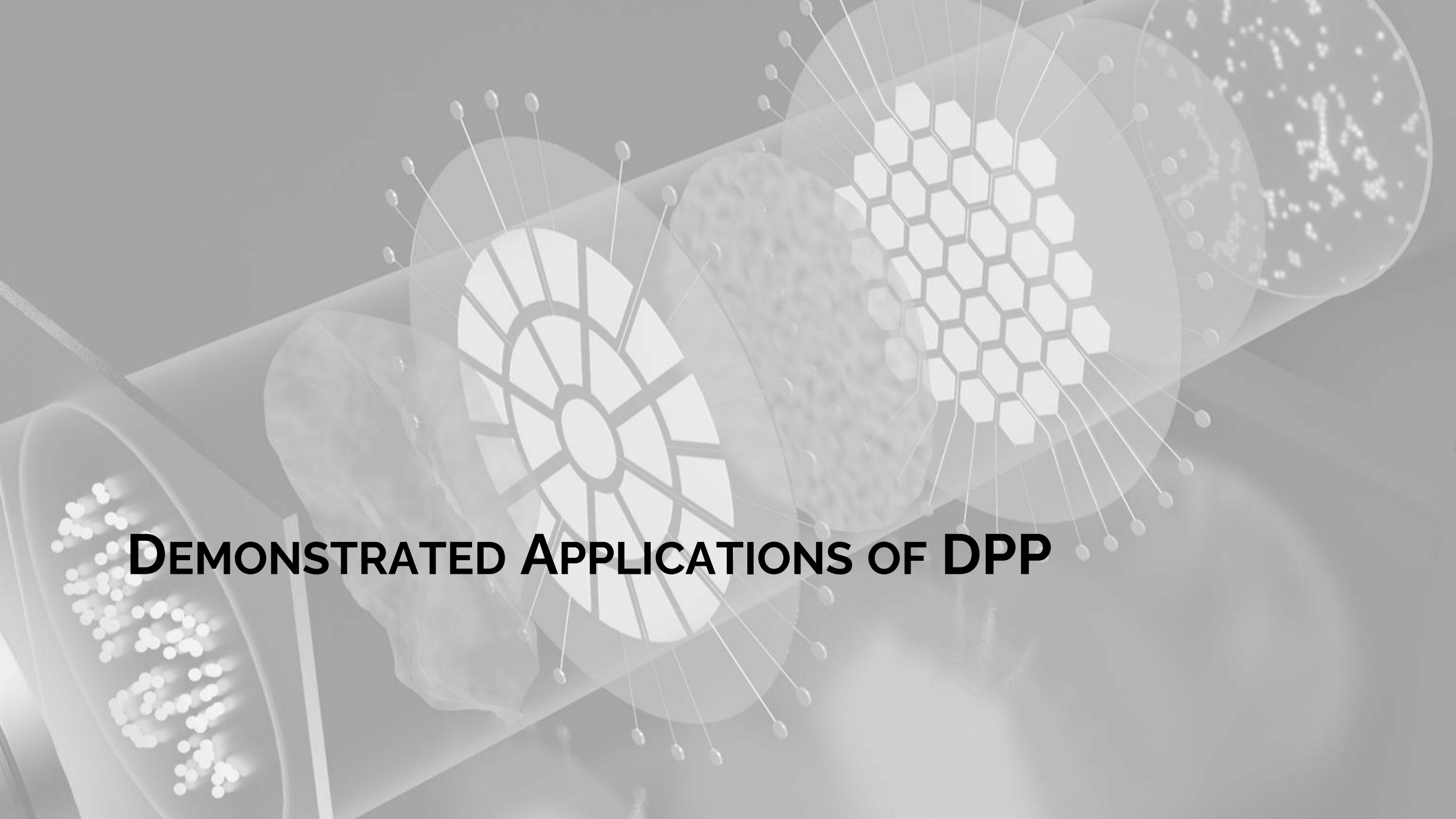
Captured image



Phase modulator status

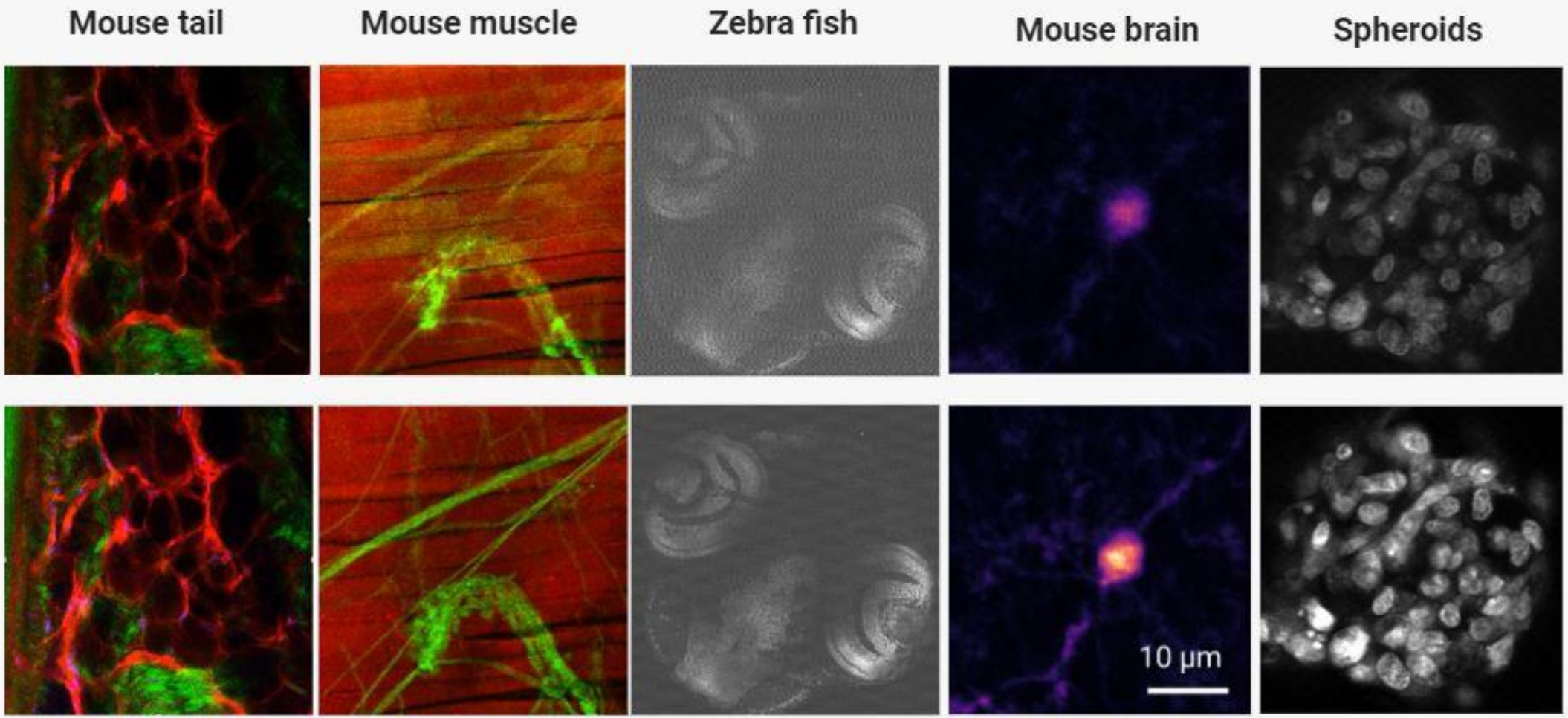


- ✓ Refractive phase modulator
- ✓ Open-loop control system
- ✓ Wavefront error estimation



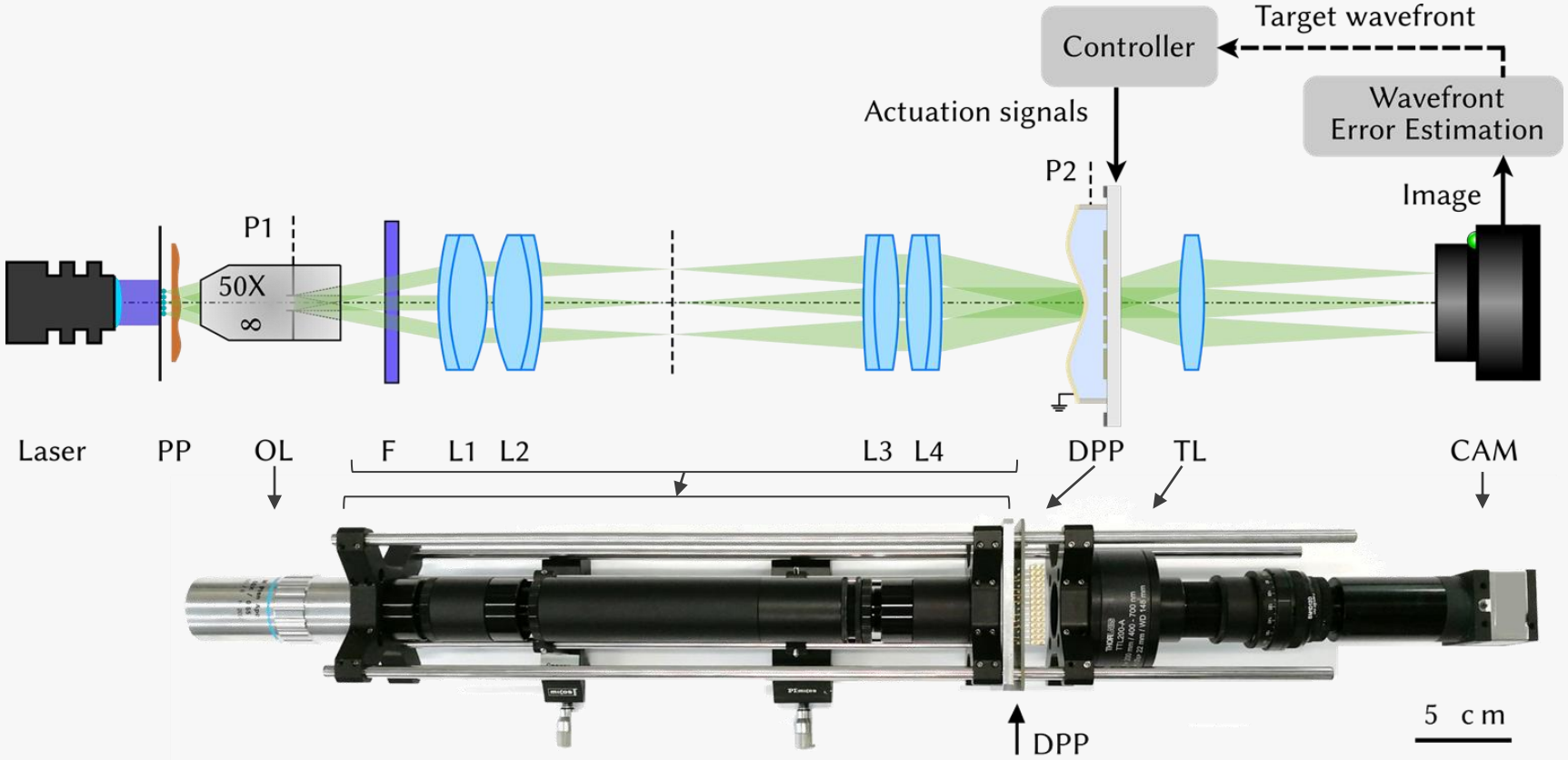
Demonstrated Applications of DPP

Customer installations – 2P microscopes

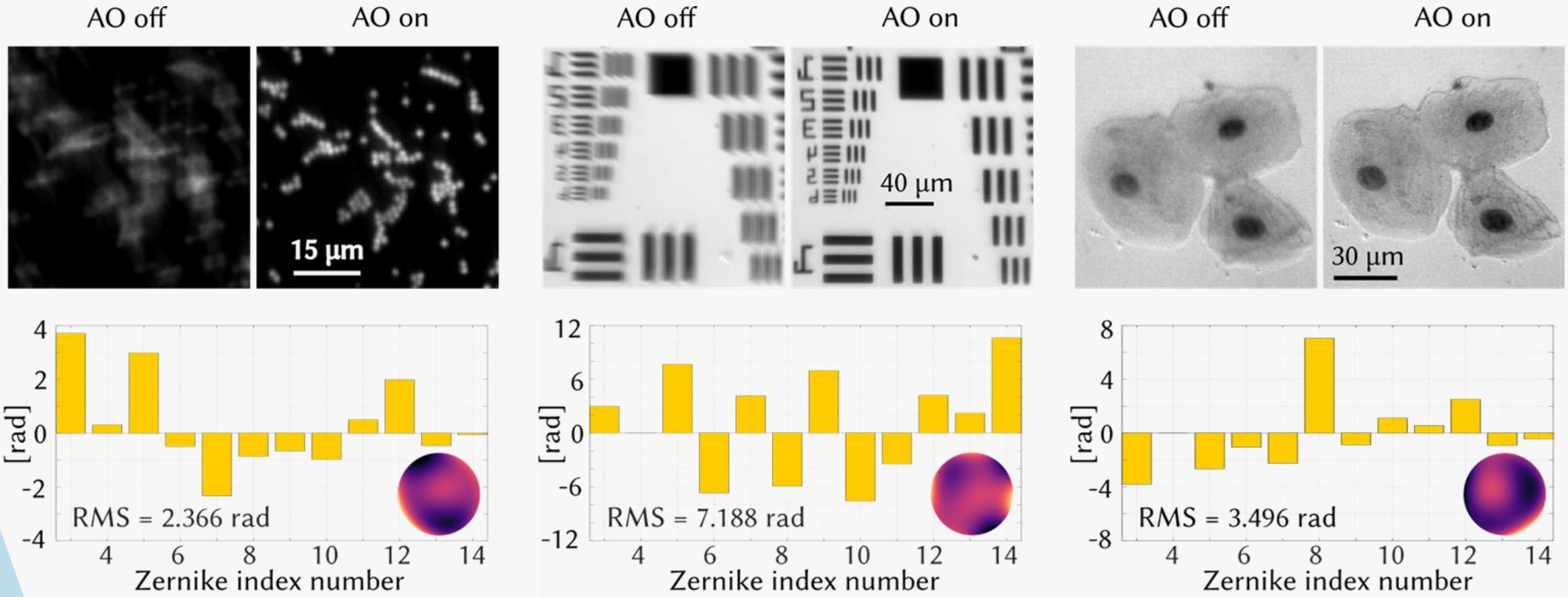


Fully refractive AO widefield microscope

- Example: correcting for a single aberration mode

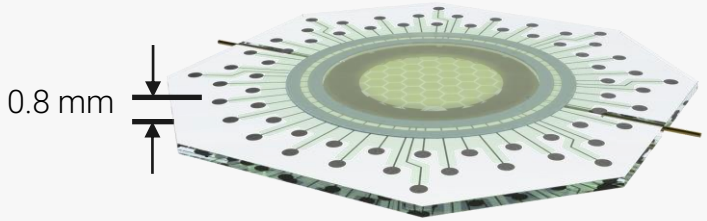


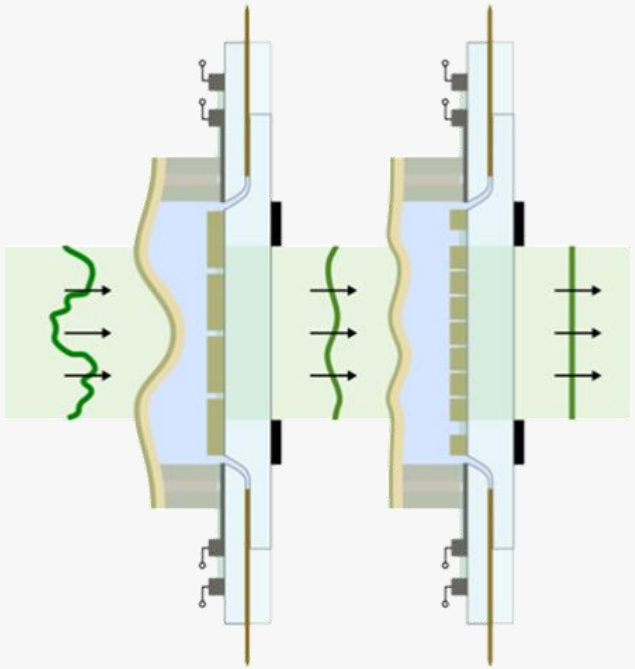
Fully refractive AO widefield microscope



Cascading multiple DPPs

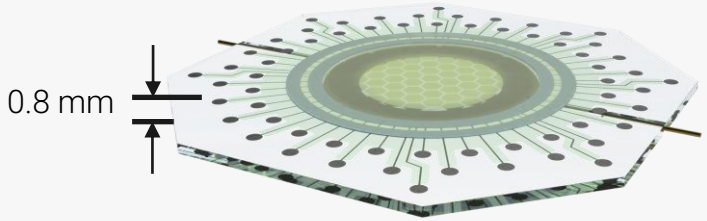
- Enhancing performance
  - Improved range
  - Improved fidelity
- Dedicated control strategy
- Applications
  - Woofer-tweeter AO systems
  - Multi-conjugate AO

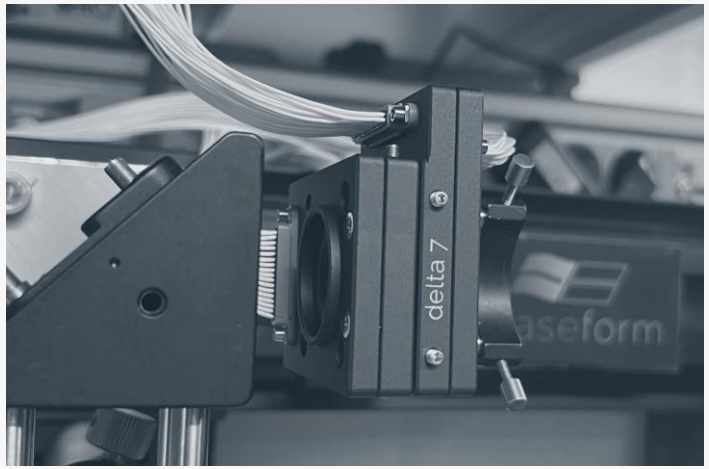




Cascading multiple DPPs

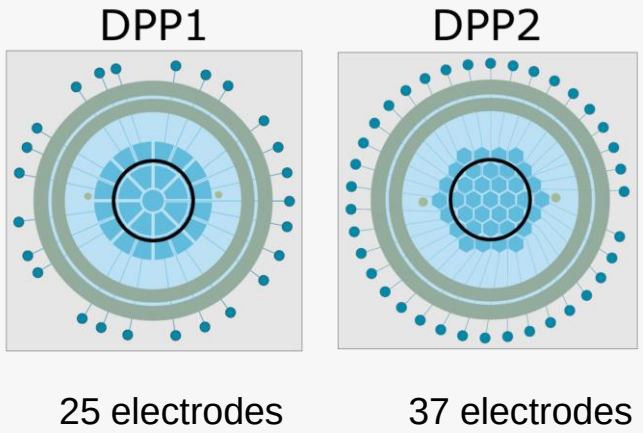
- Enhancing performance
  - Improved range
  - Improved fidelity
- Dedicated control strategy
- Applications
  - Woofer-tweeter AO systems
  - Multi-conjugate AO





Cascading multiple DPPs

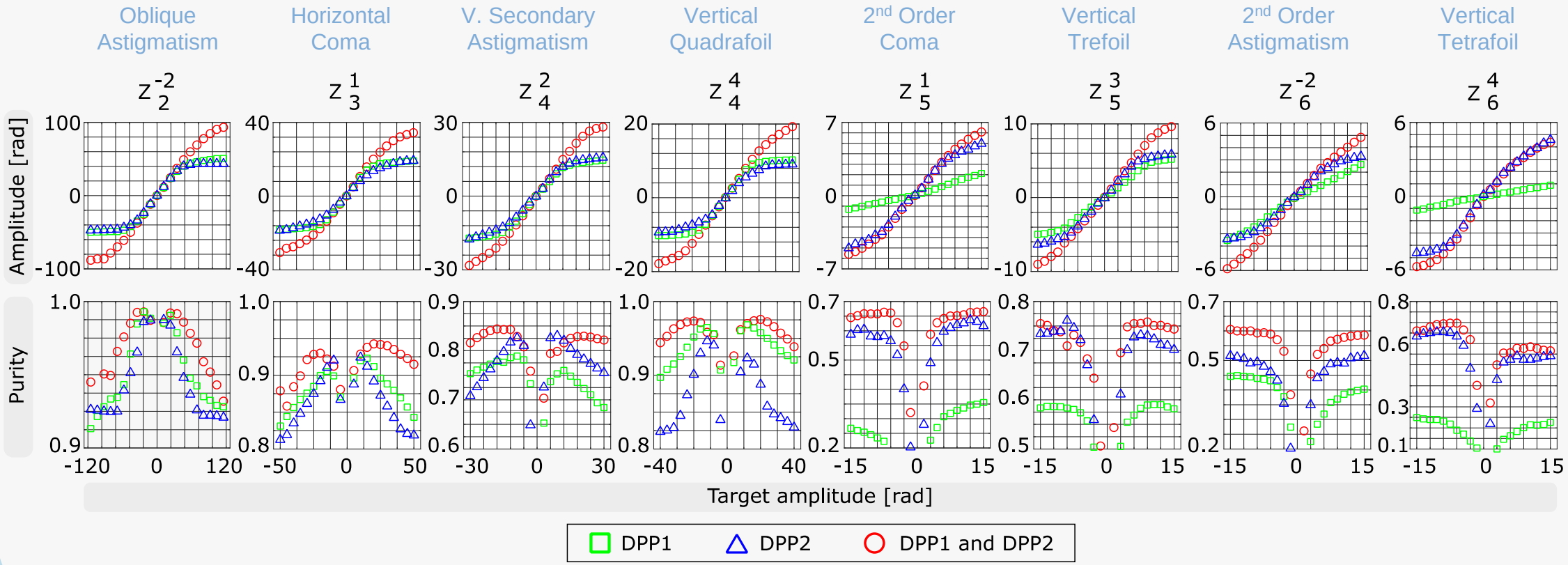
- Performance enhancement in a woofer-tweeter configuration



Advanced Photonics 2.6 (2021)

Cascading multiple DPPs

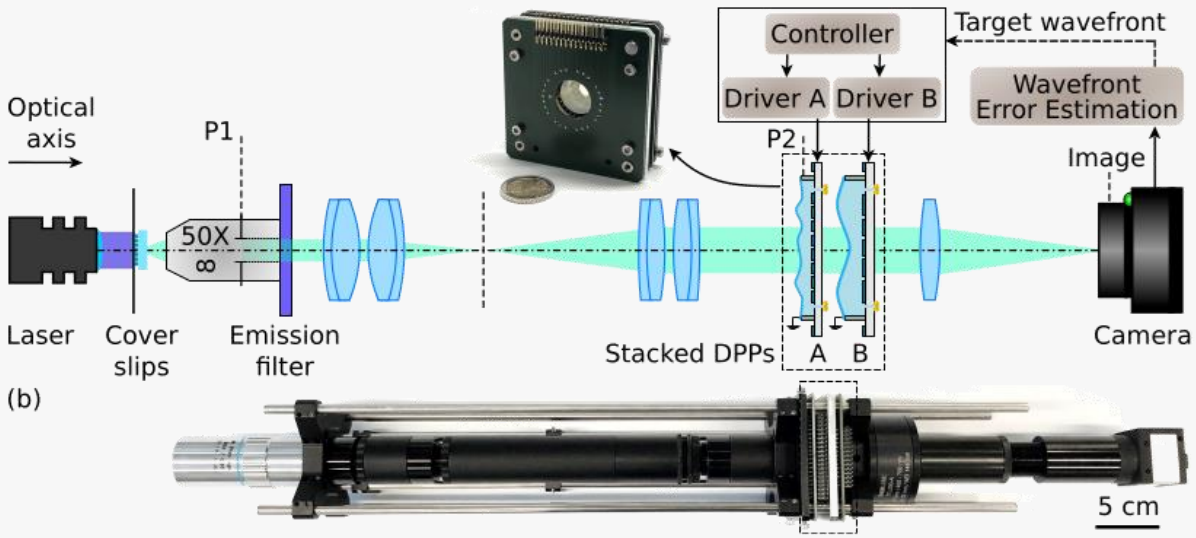
- Performance enhancement in a woofer-tweeter configuration

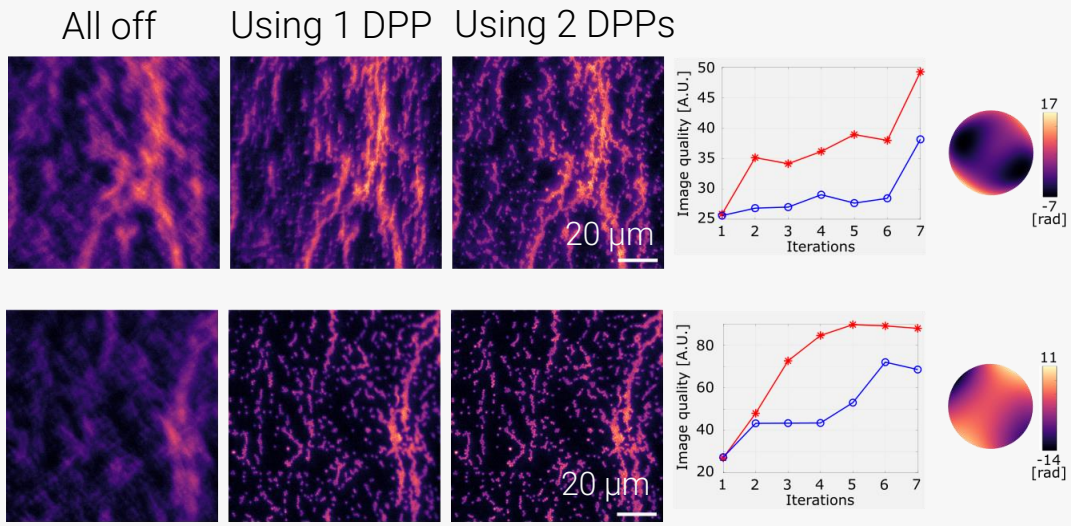


Advanced Photonics 2.6 (2021)

Cascading multiple DPPs

- Performance enhancement in a woofer-tweeter configuration

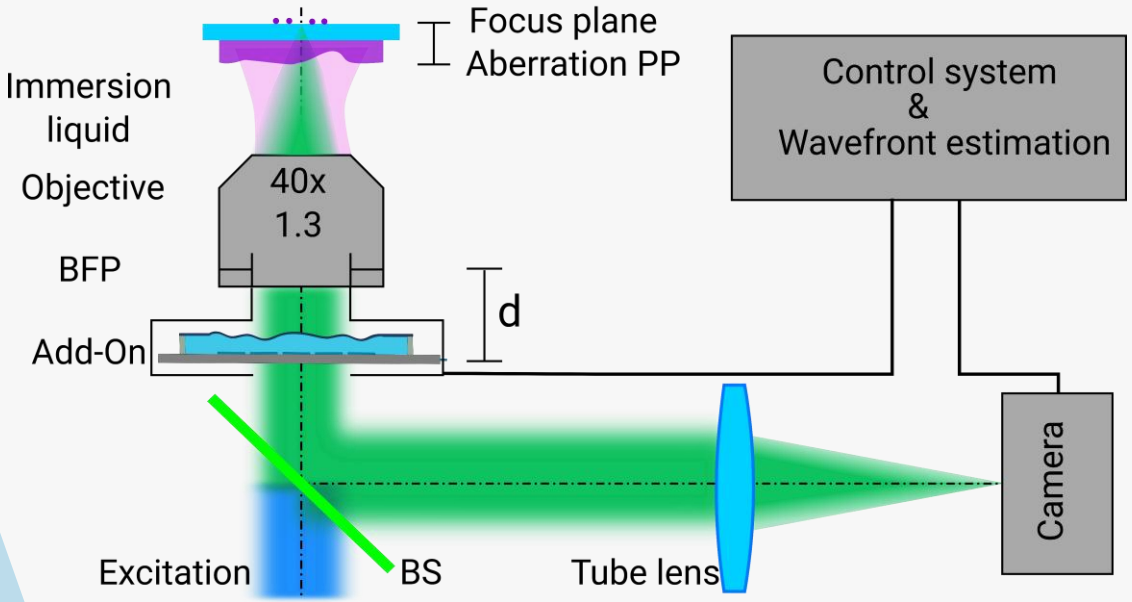


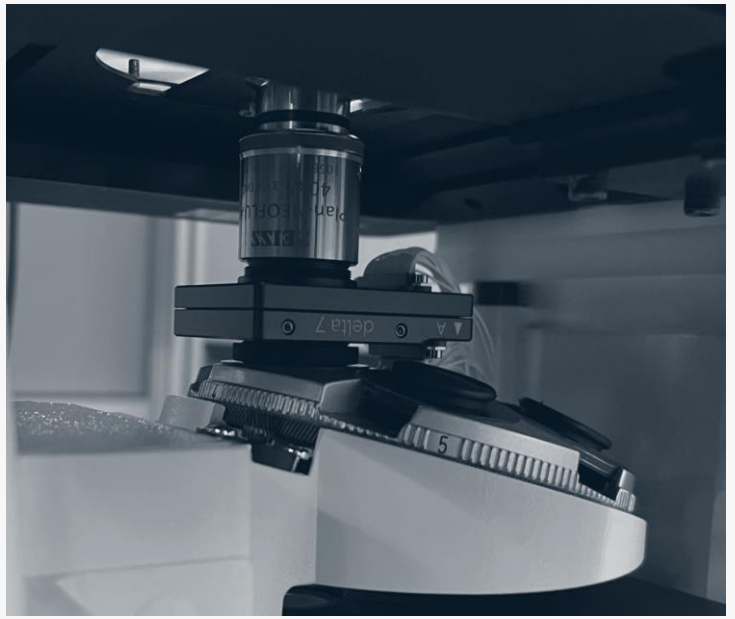


Advanced Photonics 2.6 (2021)

Refractive Objective Add-on

- Inserting DPP between the microscope objective and torret
- Sensorless aberration measurement and correction



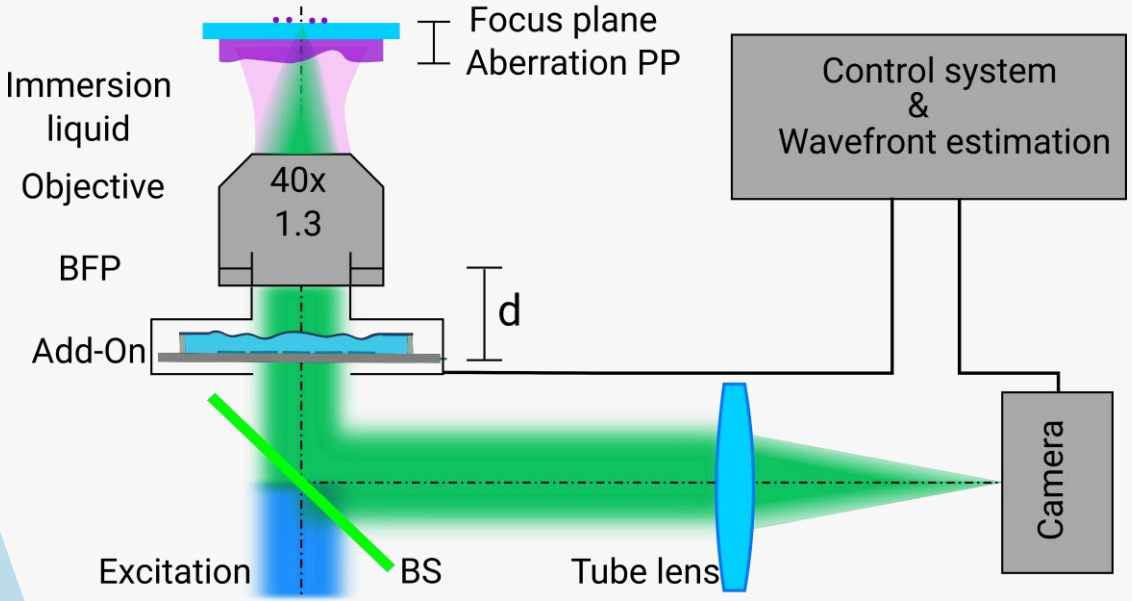


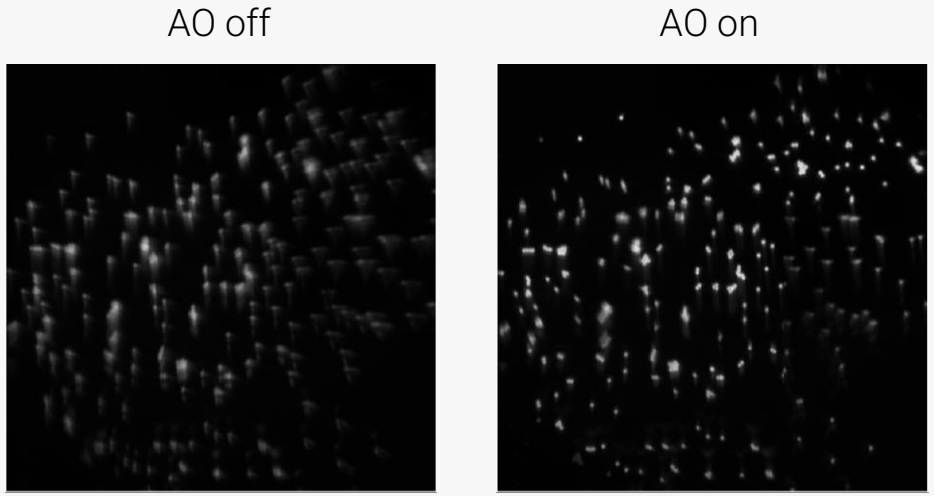
DPP installed in a commercial Zeiss Axiovert microscope in collaboration with the University of Freiburg.

Courtesy of Alex Dorn & Dr. Çağlar Ataman

Refractive Objective Add-on

- Inserting DPP between the microscope objective and torret
- Sensorless aberration measurement and correction





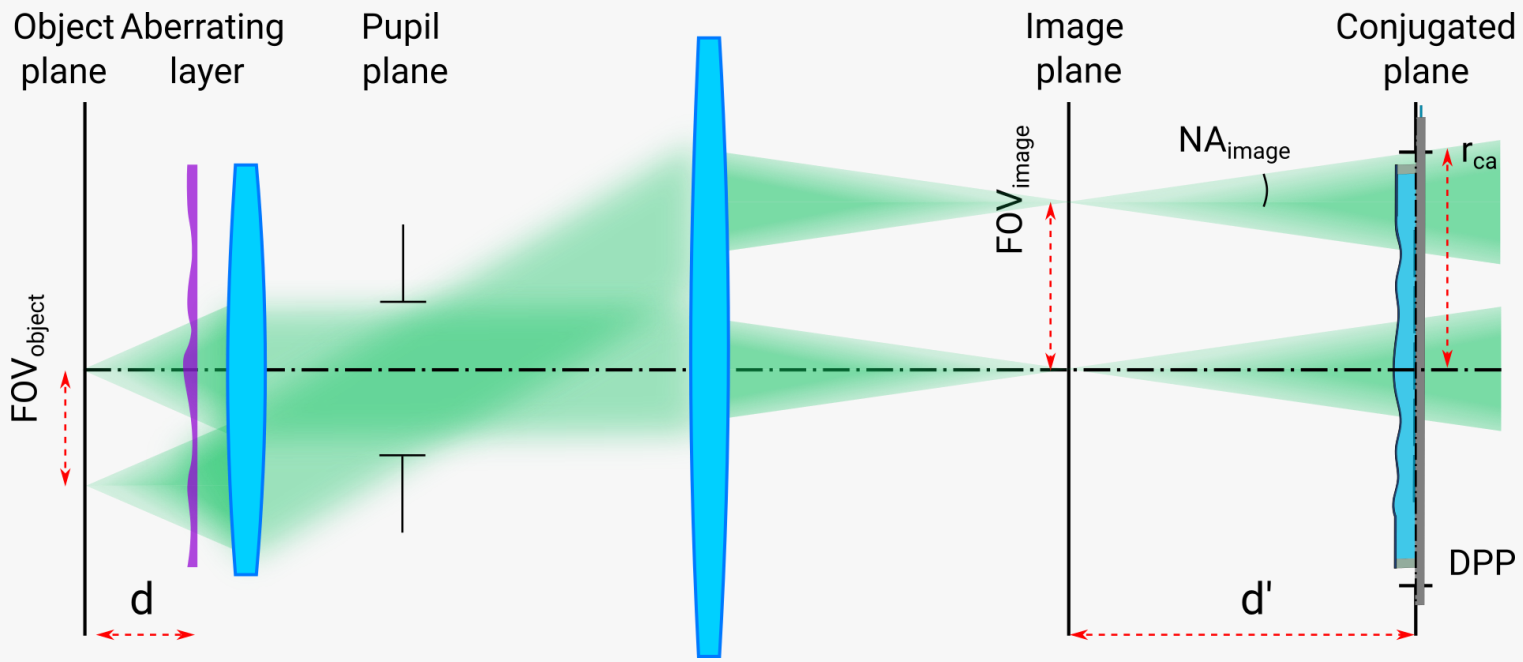
- 750 nm beads imaged with 40x objective
- 3x3 Segment recorded

DPP installed in a commercial Zeiss Axiovert microscope in collaboration with the University of Freiburg.

Courtesy of Alex Dorn & Dr. Çağlar Ataman

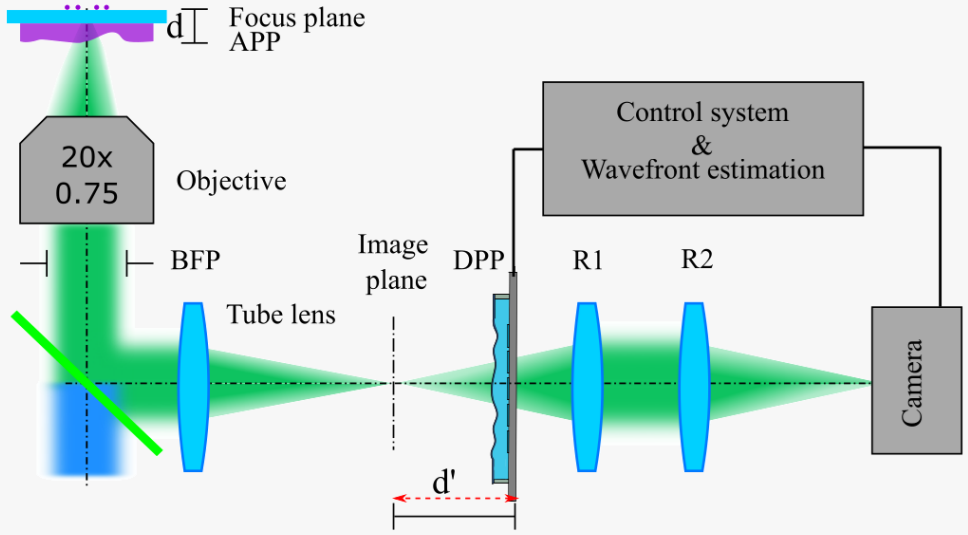
Sample Conjugate Adaptive Optics

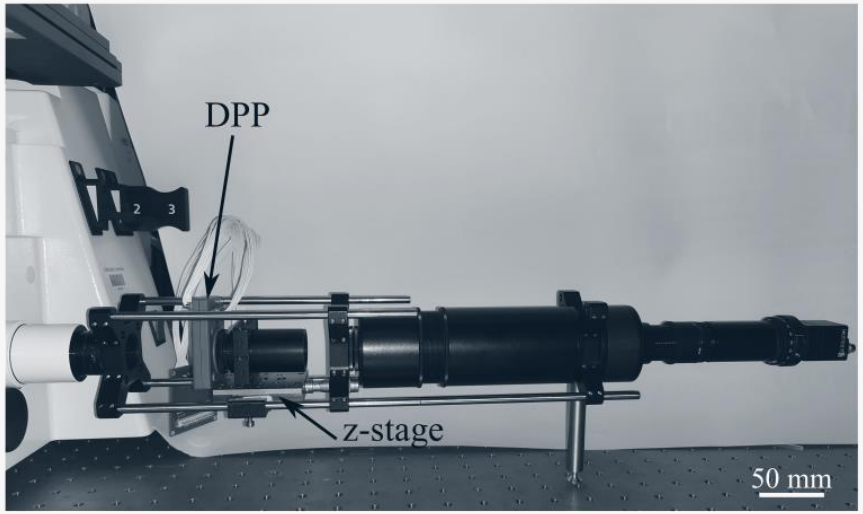
- Placing DPP conjugate to the aberrating layer



Sample Conjugate Adaptive Optics

- Placing DPP conjugate to the aberrating layer





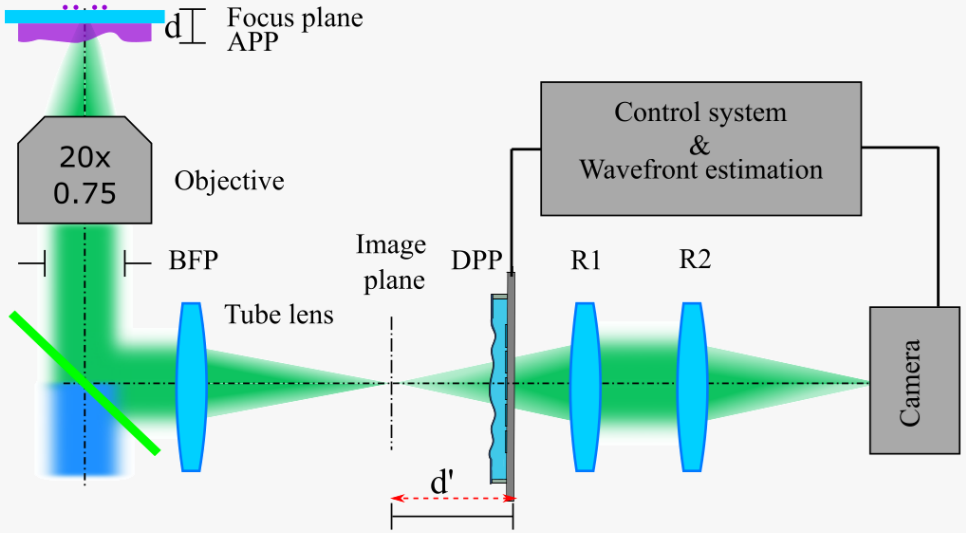
DPP installed in a commercial Zeiss Axiovert microscope in collaboration with the University of Freiburg.

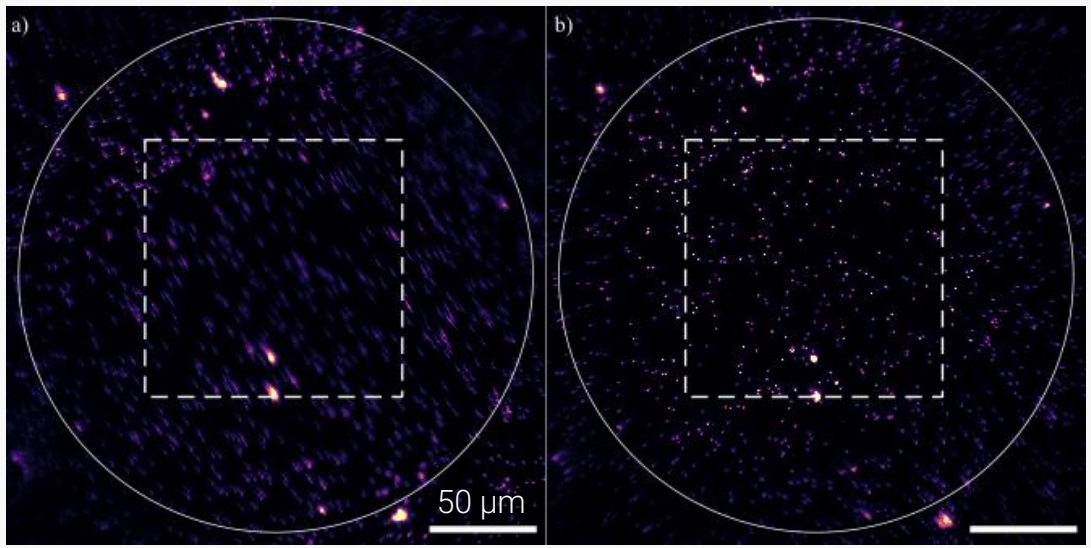
Courtesy of Alex Dorn & Dr. Çağlar Ataman

Dorn et al., *Proc. SPIE,* 11966, 2022.

Sample Conjugate Adaptive Optics

- Placing DPP conjugate to the aberrating layer





450 nm beads imaged with 20x objective

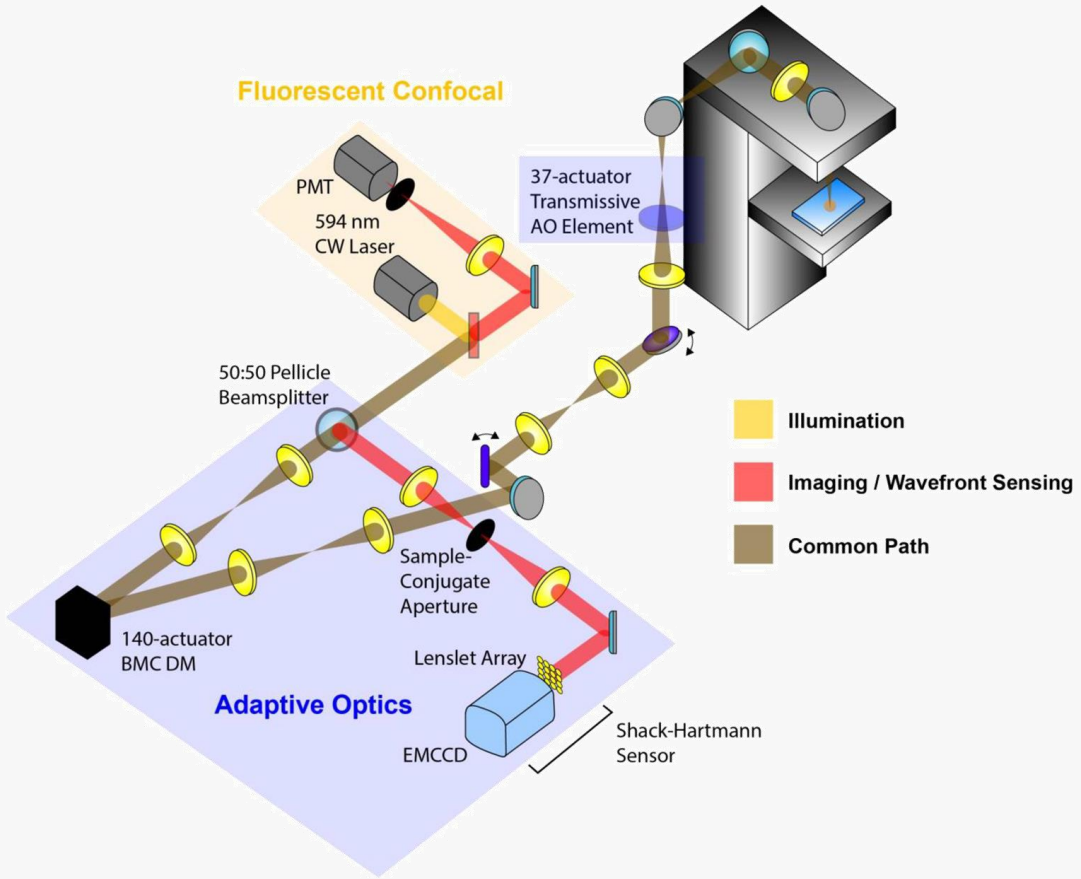
DPP installed in a commercial Zeiss Axiovert microscope in collaboration with the University of Freiburg.

Courtesy of Alex Dorn & Dr. Çağlar Ataman

Dorn et al., *Proc. SPIE,* 11966, 2022.

Multi Conjugate Adaptive Optics

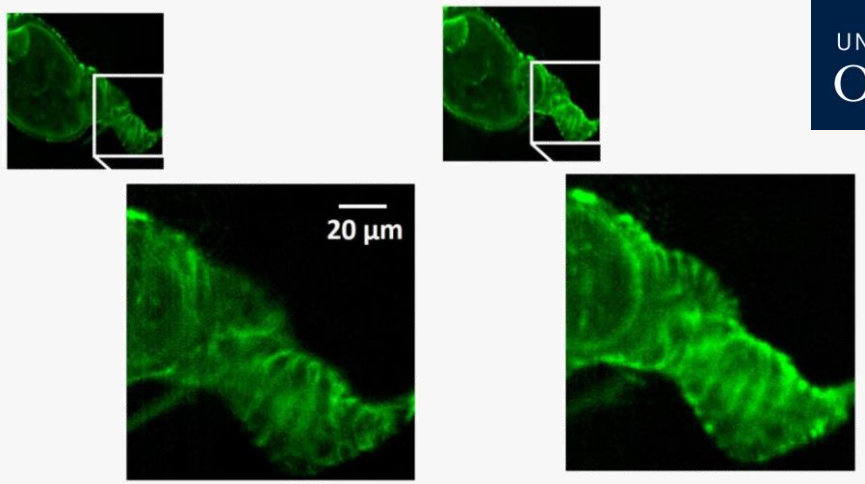
- Placing DPP conjugate to the aberrating layer and a DM conjugate to the Pupil plane



Hampson et al., *Proc. SPIE,* 11248, 2020.

Before correction

After correction

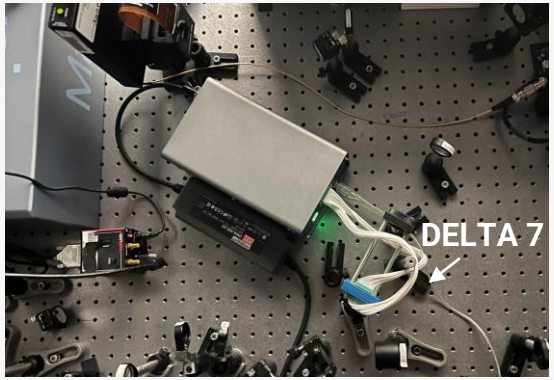


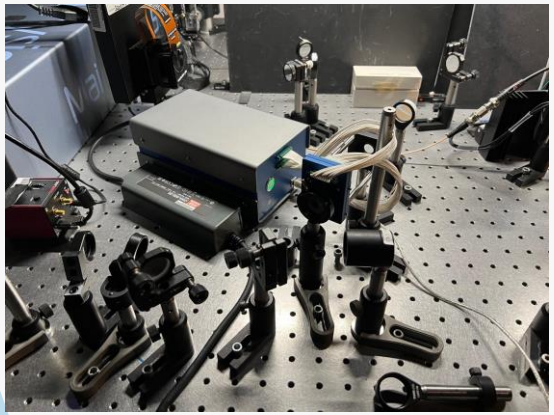
Confocal fluorescence images from a Drosophila ovary stained with Alex Fluor 594 obtained at a 12 µm depth

Experiments performed using a custom confocal fluorescence microscope in collaboration with the Univeristy of Oxford, Group of Prof. Martin Booth

DPP for Two-photon Microscopy

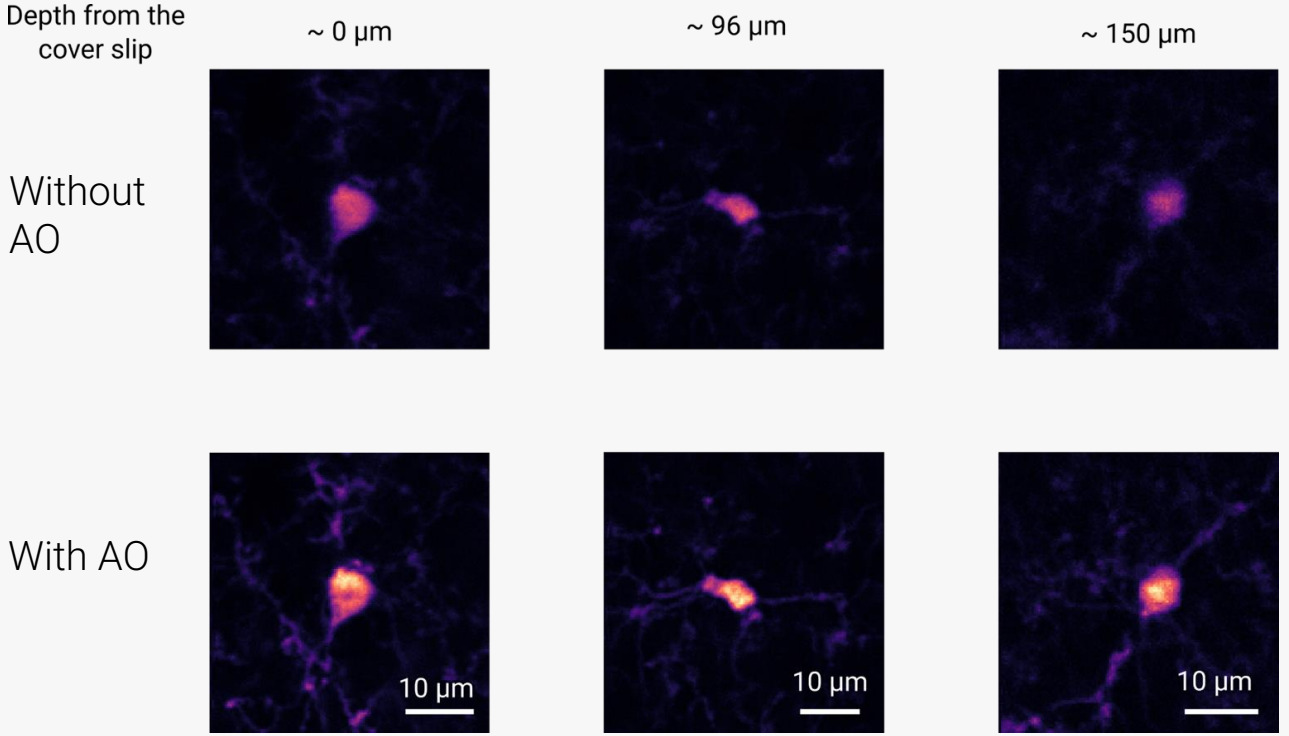
- Plug-and-play AO experiment with an existing custom 2P microscope





Objective lens:
XLUMPLFLN20XW, NA = 1,
water immersion, Olympus Corp.

Single mouse brain neuronal imaging



- Down to ~150 µm deep into brain tissue
- **Wavefront sensorless measurement** and **active compensation** of system and sample induced optical aberrations by DELTA 7

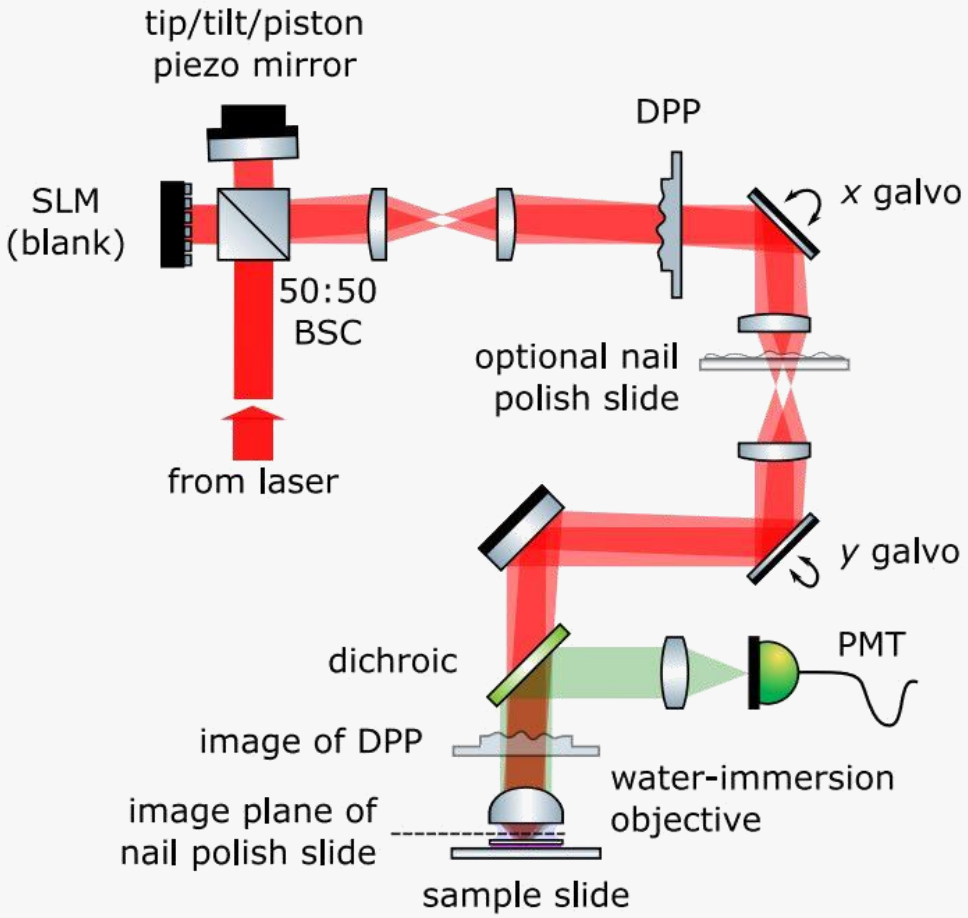
MEDIZINISCHE UNIVERSITÄT INNSBRUCK

DELTA 7 installed in a two-photon microscope setup for biological imaging at Medical University of Innsbruck

Courtesy of Group of Prof. Alexander Jesacher

DPP for Two-photon Microscopy

- DPP combined with F-SHARP technique for fast (~1 sec) aberration measurement



MEDIZINISCHE UNIVERSITÄT INNSBRUCK

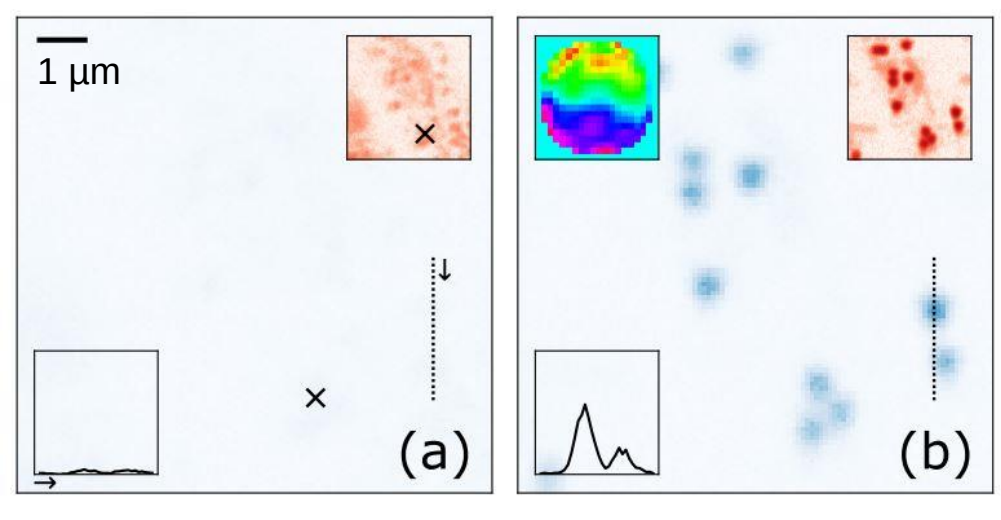
DELTA 7 installed in a two-photon microscope setup for biological imaging at Medical University of Innsbruck

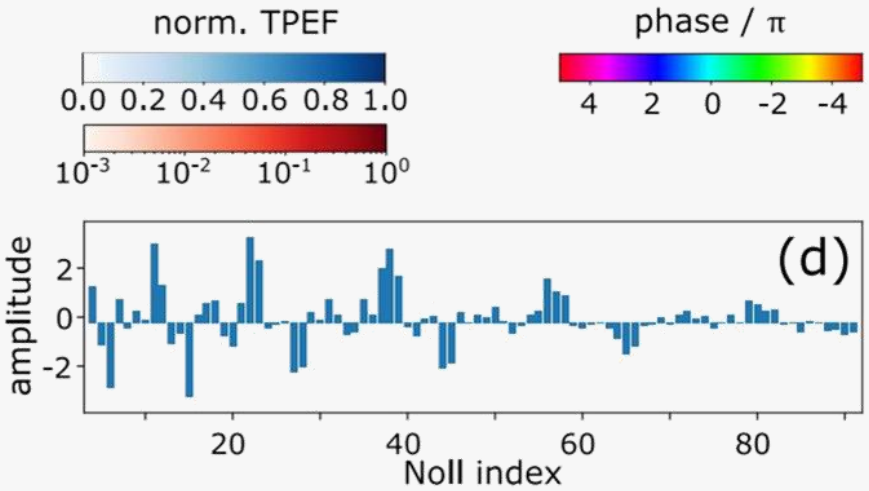
Courtesy of Group of Prof. Alexander Jesacher

Maximilian Sohmen et al.

DPP for Two-photon Microscopy

- DPP combined with F-SHARP technique for fast (~1 sec) aberration measurement
- 500 nm beads aberrated by a nail polished slide





MEDIZINISCHE UNIVERSITÄT INNSBRUCK

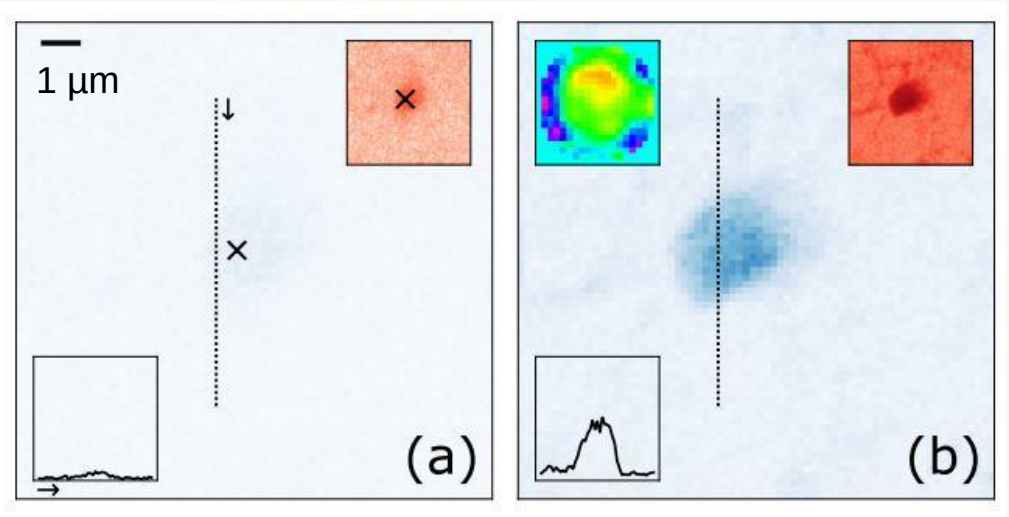
DELTA 7 installed in a two-photon microscope setup for biological imaging at Medical University of Innsbruck

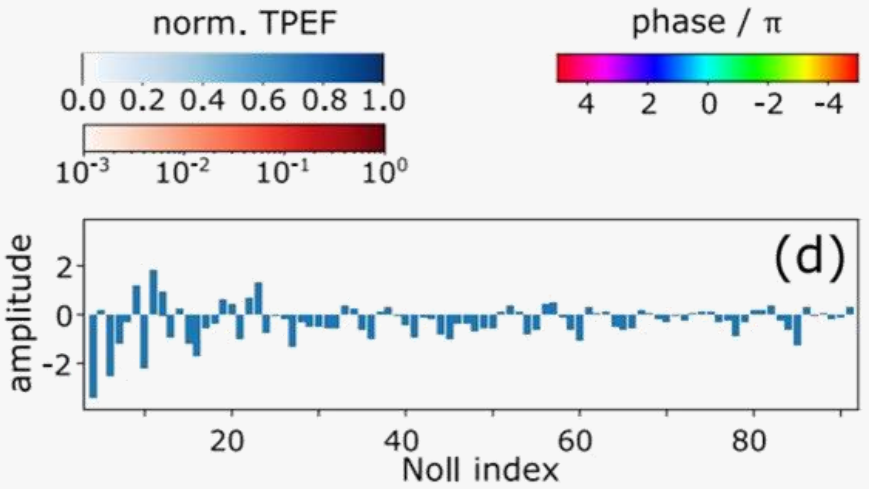
Courtesy of Group of Prof. Alexander Jesacher

Maximilian Sohmen et al

DPP for Two-photon Microscopy

- DPP combined with F-SHARP technique for fast (~1 sec) aberration measurement
- 200 µm deep into mouse brain tissue





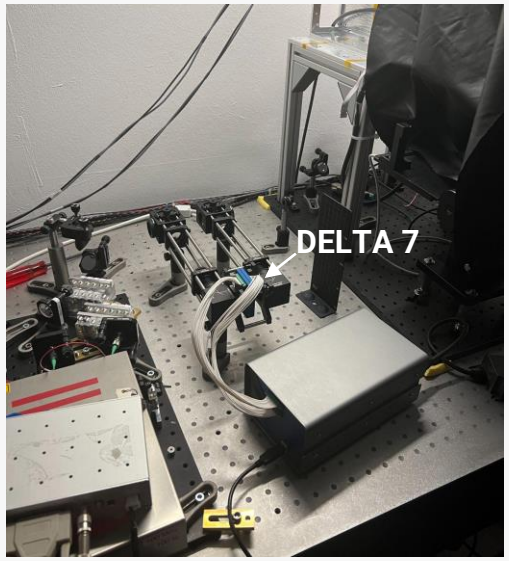
MEDIZINISCHE UNIVERSITÄT INNSBRUCK

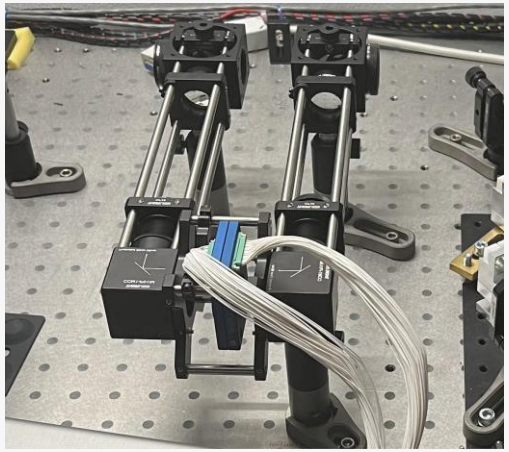
DELTA 7 installed in a two-photon microscope setup for biological imaging at Medical University of Innsbruck

Courtesy of Group of Prof. Alexander Jesacher

Maximilian Sohmen et al.

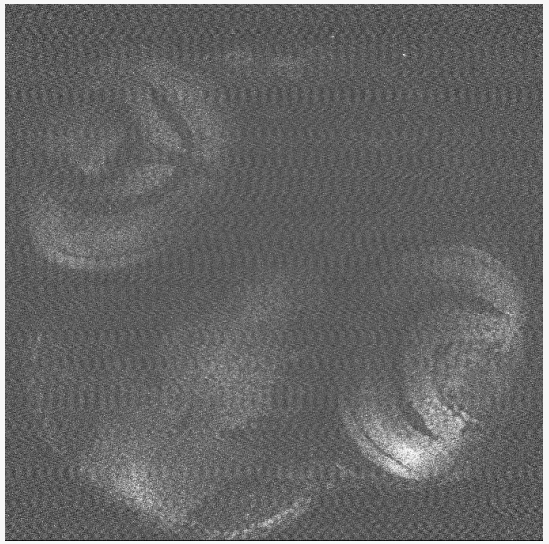
DPP for Two-photon Microscopy



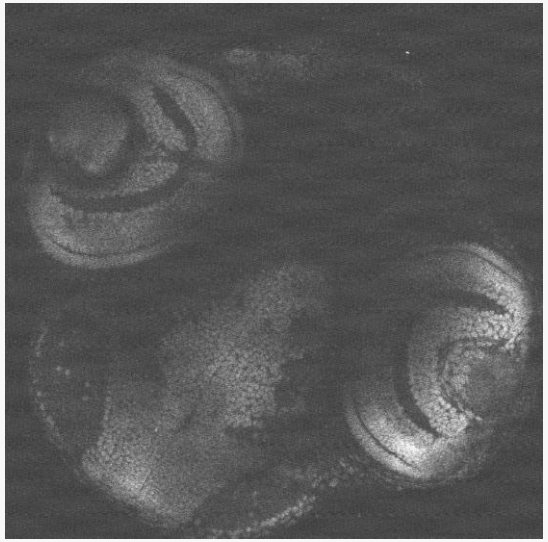


Zebrafish frontal face

Without AO



With AO



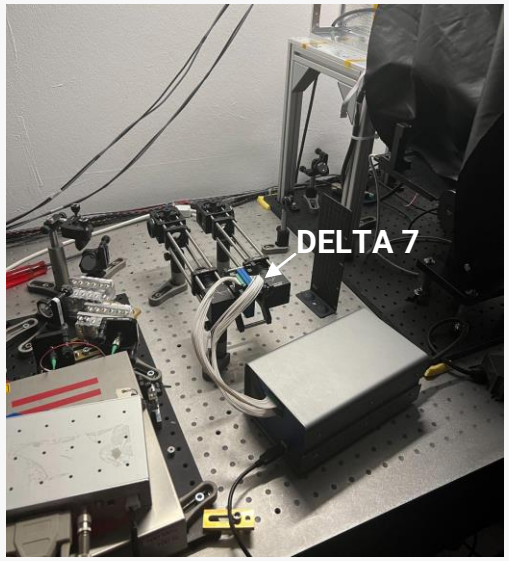
- Down to ~250 µm deep into the Zebrafish eye
- **Wavefront sensorless measurement** and **active compensation** of system and sample induced optical aberrations by DELTA 7

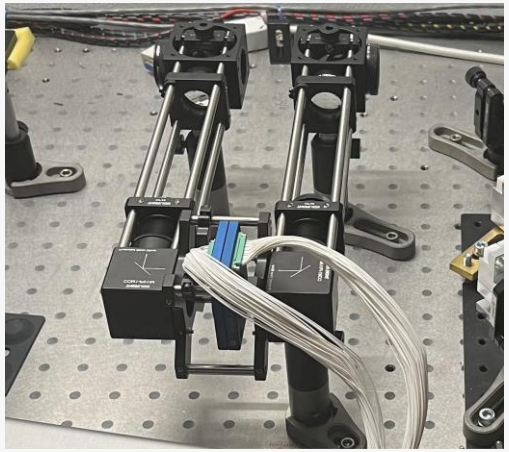
DELTA 7 installed in a two-photon microscope (MPX-1040) in collaboration with Prospective Instruments

Courtesy of Dr. Stefanie Kiderlen & Dr. Lukas Krainer
https://www.p-inst.com/

Objective lens:
Olympus XLPlan N
Magnification: 20x
NA: 1.0
Immersion: water

DPP for Two-photon Microscopy

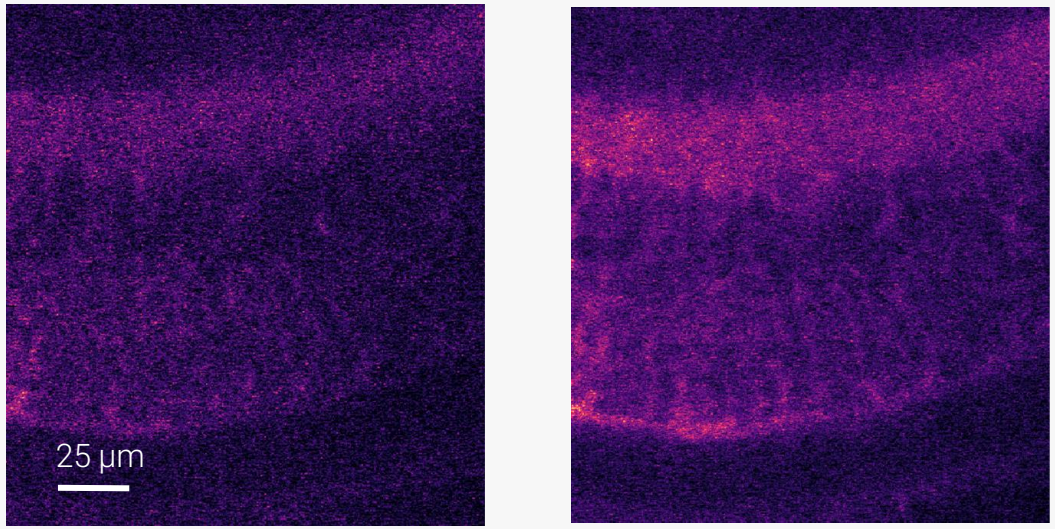




Zebrafish retina

Without AO

With AO



- Down to ~250 µm deep into the Zebrafish eye
- **Wavefront sensorless measurement** and **active compensation** of system and sample induced optical aberrations by DELTA 7

DELTA 7 installed in a two-photon microscope (MPX-1040) in collaboration with Prospective Instruments

Courtesy of Dr. Stefanie Kiderlen & Dr. Lukas Krainer
https://www.p-inst.com/

Objective lens:
Olympus XLPlan N
Magnification: 20x
NA: 1.0
Immersion: water

Concluding Remarks

- DPP; a new addition to the contemporary AO tool-box
- Refractive AO implementations; demonstrating the easy integration and versatility of DPP

Online & social media:

LinkedIn: linkedin.com/company/phaseform
Twitter: @phaseformgmbh
Web: www.phaseform.com
Email: rajaeipour@phaseform.com

phaseform

phaseform

Deformable Phase Plate – a New Technology for Plug-and-Play Adaptive Optics

Pouya Rajaeipour
Phaseform GmbH, Freiburg, Germany