SPIE Astronomical Telescopes + Instrumentation, Yokohama 2024

Active coronagraphy and coherence differential imaging in unpolarized light with the Swiss Wideband Active Testbed for Coronagraphic High-Contrast Imaging (SWATCHi) 2.0

Axel Potier[1], Audrey Baur[2], Liurong Lin[1], Ruben Tandon[1], Jonas Kühn[1]

[1]University of Bern

[2]Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud

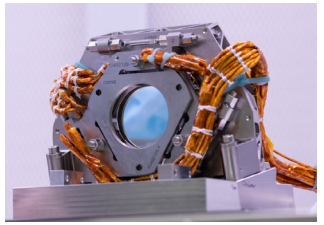
UNIVERSITÄT BERN

RACE GO

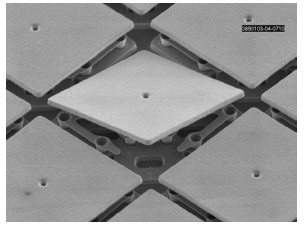
Concepts of active/adaptive coronagraphy

- **Definition**: Any component whose properties can be actively modified to increase the SNR of any astrophysical source.

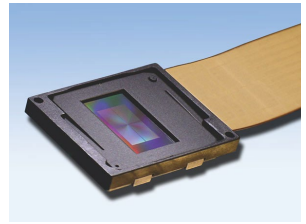
- Could use reflective or transmissive components in any plane: Pupil, Focal, non conjugate.. Modulation of phase, amplitude or polarization.



Moving/Deformable mirrors



Digital Micromirror Devices



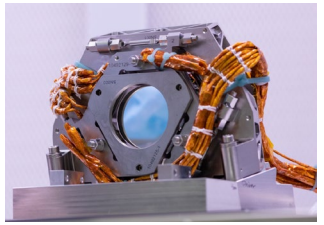
Spatial Light Modulators

Concepts of active/adaptive coronagraphy

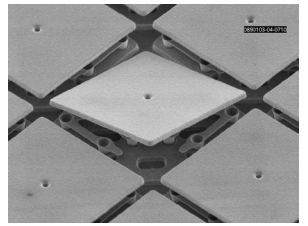
- **Definition**: Any component whose properties can be actively modified to increase the SNR of any astrophysical source.

- Could use reflective or transmissive components in any plane: Pupil, Focal, non conjugate.. Modulation of phase, amplitude or polarization.

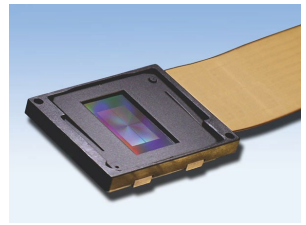
- **Adapting the coronagraph to environmental constrains:**
  - Changing atmosphere turbulence
  - Upcoming extremely large telescope facilities (ground- or space-based) will rely on large segmented primary mirrors, which merit function may evolve in time (i.e. dead/missing/defective segments)
  - Micrometeorites



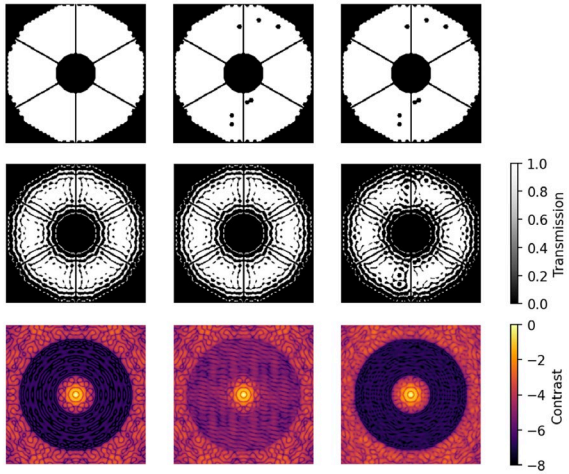
Moving/Deformable mirrors



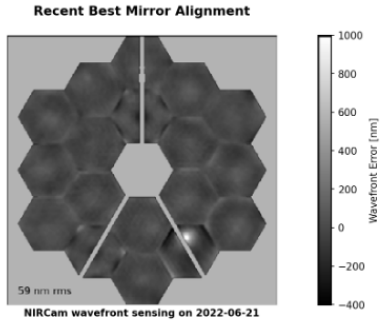
Digital Micromirror Devices



Spatial Light Modulators



Leboulleux et al. 2022



Rigby et al. 2022

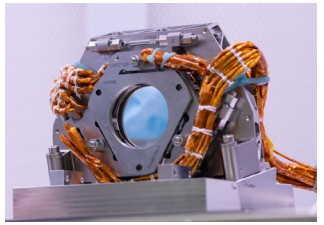
Concepts of active/adaptive coronagraphy

- **Definition**: Any component whose properties can be actively modified to increase the SNR of any astrophysical source.

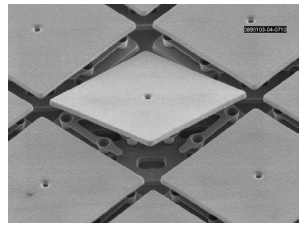
- Could use reflective or transmissive components in any plane: Pupil, Focal, non conjugate.. Modulation of phase, amplitude or polarization.

- **Adapting the coronagraph to environmental constrains:**
  - Changing atmosphere turbulence
  - Upcoming extremely large telescope facilities (ground- or space-based) will rely on large segmented primary mirrors, which merit function may evolve in time (i.e. dead/missing/defective segments)
  - Micrometeorites

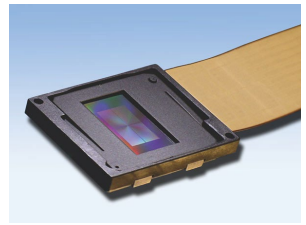
- **Adapting the coronagraph to science cases constrains:**
  - binary/multiple stars systems
  - resolved stars
  - circumstellar disks
  - Infinite number of observing modes (discovery vs. follow-up/characterization).



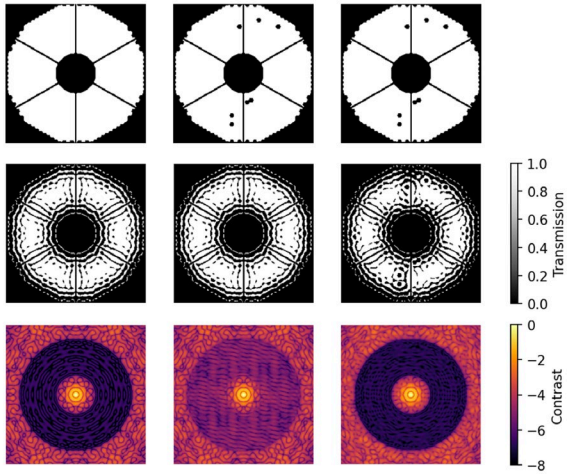
Moving/Deformable mirrors



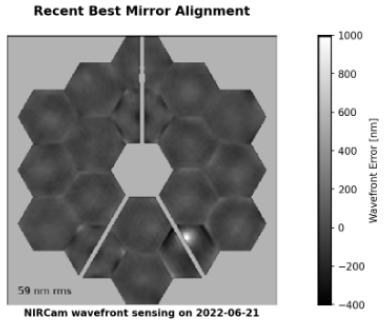
Digital Micromirror Devices



Spatial Light Modulators



Leboulleux et al. 2022

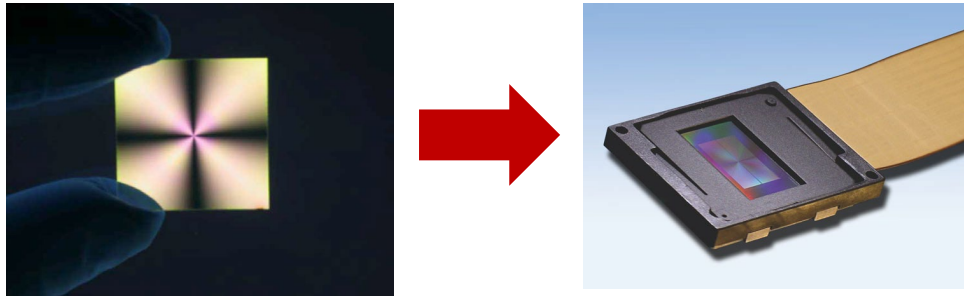


Rigby et al. 2022

NASA/JPL-Caltech/T. Pyle

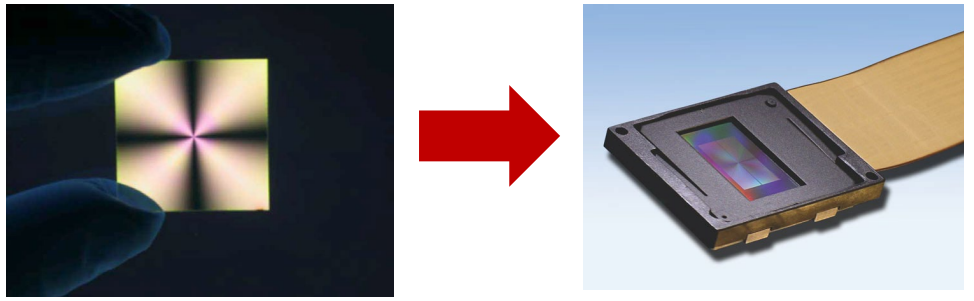
Active/adaptive coronagraphy with SLMs

- We want to **get rid of pre-manufactured phase masks** and use programmable liquid crystal spatial light modulators (SLMs) instead:
  - > 2π phase retardance devices are commercially available up to H/K-band

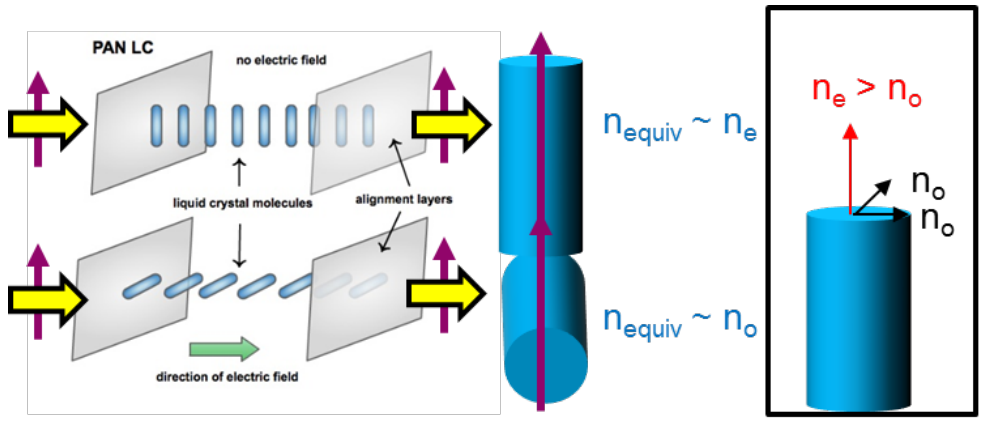


Active/adaptive coronagraphy with SLMs

- We want to **get rid of pre-manufactured phase masks** and use programmable liquid crystal spatial light modulators (SLMs) instead:
  - > 2π phase retardance devices are commercially available up to H/K-band

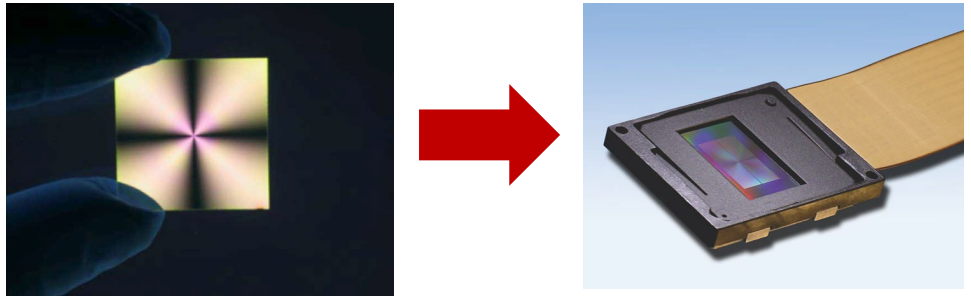


- **Each pixel of a SLM can locally delay the optical path** (phase) of incoming light:
  - Video-rate adjustable birefringence
  - Requirement: linearly-polarized light !

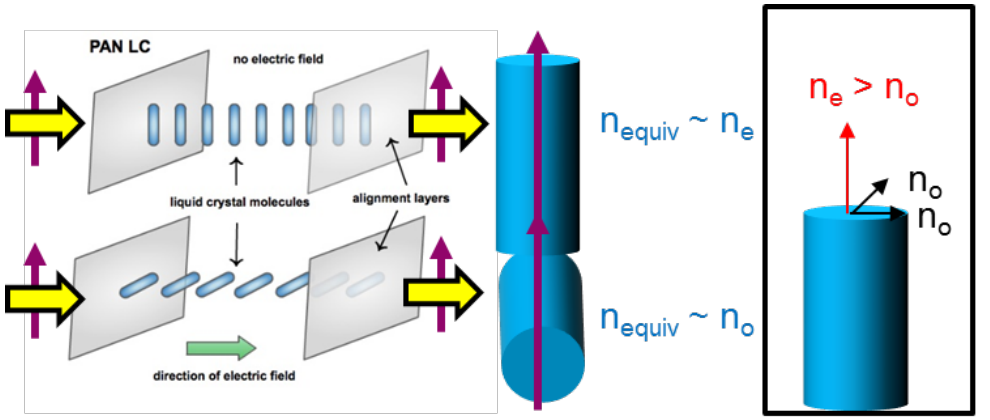


Active/adaptive coronagraphy with SLMs

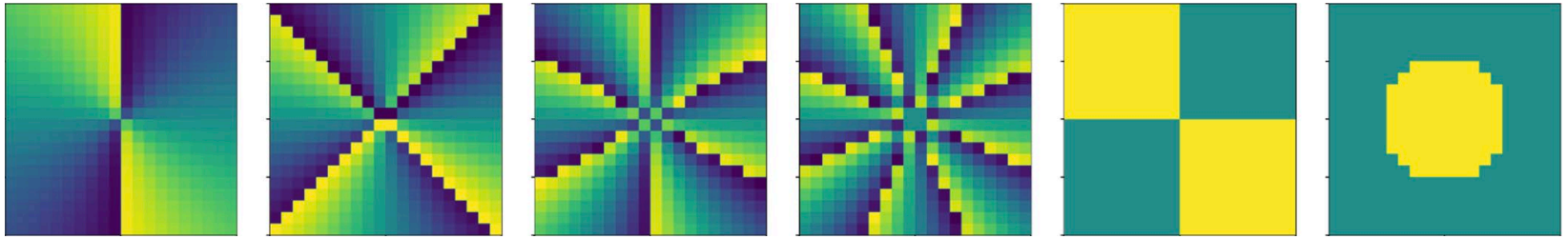
- We want to **get rid of pre-manufactured phase masks** and use programmable liquid crystal spatial light modulators (SLMs) instead:
  - > 2π phase retardance devices are commercially available up to H/K-band



- **Each pixel of a SLM can locally delay the optical path** (phase) of incoming light:
  - Video-rate adjustable birefringence
  - Requirement: linearly-polarized light !



- In principle, **any phase pattern can be programmed.**
  - μm-sized pixels provide exquisite sampling, also in the focal-plane



The DAG telescope

East Anatolia Observatory (DAG) is the new national observatory of Turkey

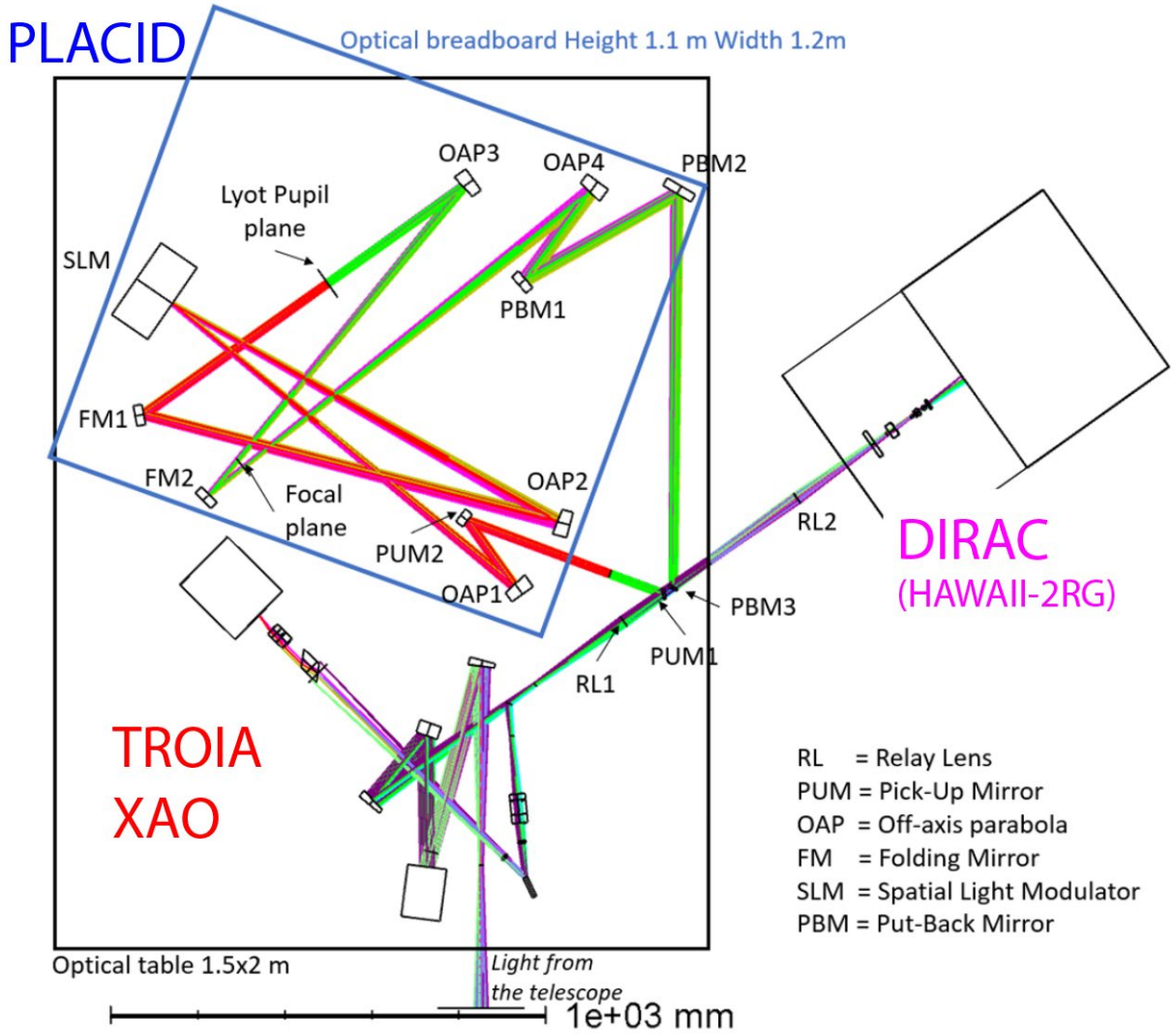
- Ritchey-Chrétien architecture **4-m primary mirror** and two Nasmyth foci
- VIS and NIR (up to 3um)
- Established near Erzurum
- Altitude: 3100m, 260 clear nights, median seeing 0.9’’
- Under leadership of ATASAM

DAG/PLACID in a nutshell

- PLACID stands for “Programmable Liquid-crystal Active Coronagraphic Imager for the DAG telescope”
  - **World’s first SLM-based active high-contrast instrument**
  - H-band (1.65 μm) and Ks-band (2.2 μm)
  - Versatile instrument ideal for prototyping and mentoring
  - Final Design Review (FDR) passed in Dec 2021
  - **First light by end of 2024**

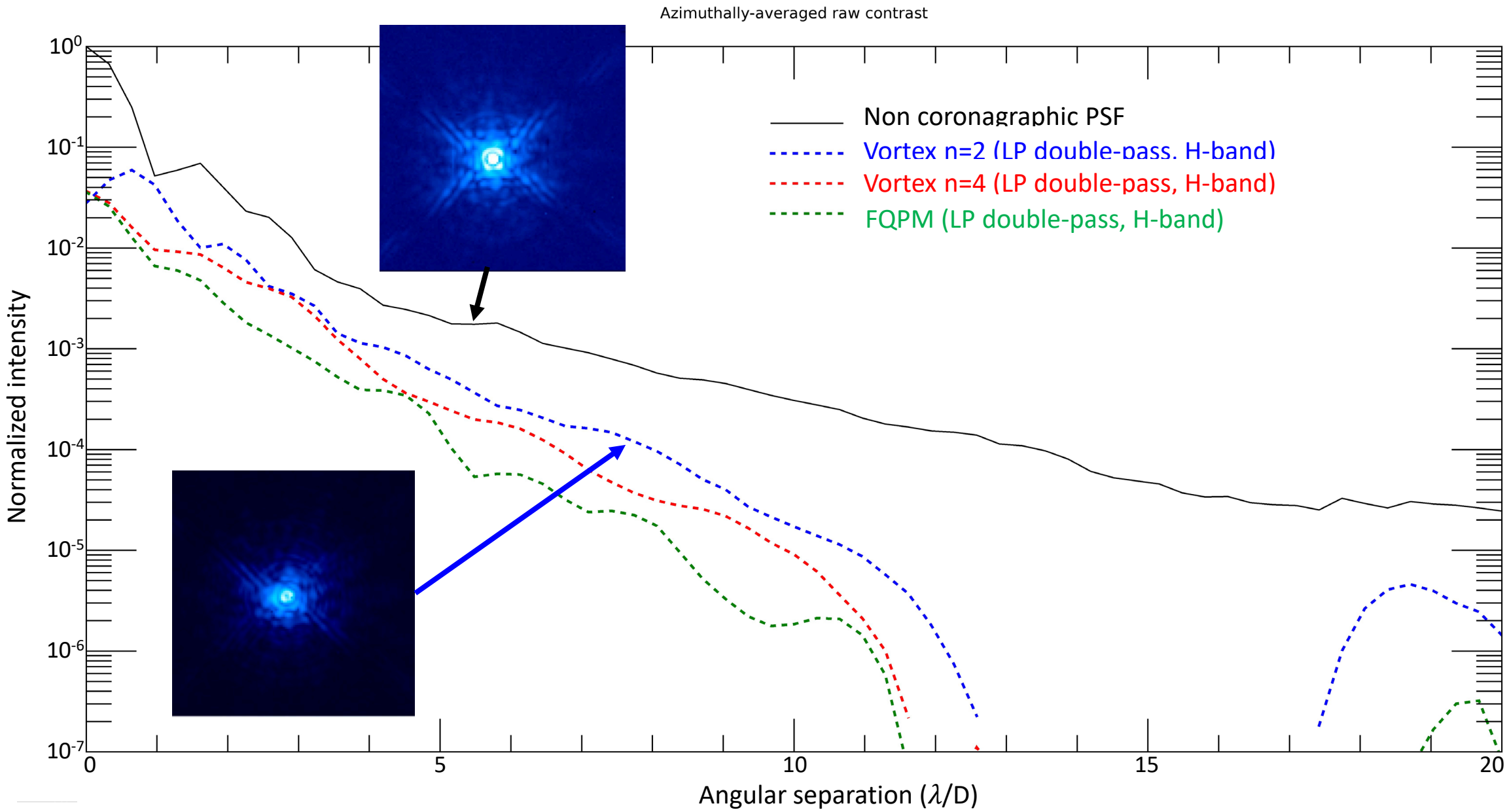
- PLACID will operate downstream of TROIA
  - «TuRkish adaptive Optics system for Infrared Astronomy»
  - **Extreme AO with pyWSF and 468-DM from AlpAO**

- … and upstream of DIRAC
  - «DAG InfRAed Camera»
  - **HAWAII-2RG detector**

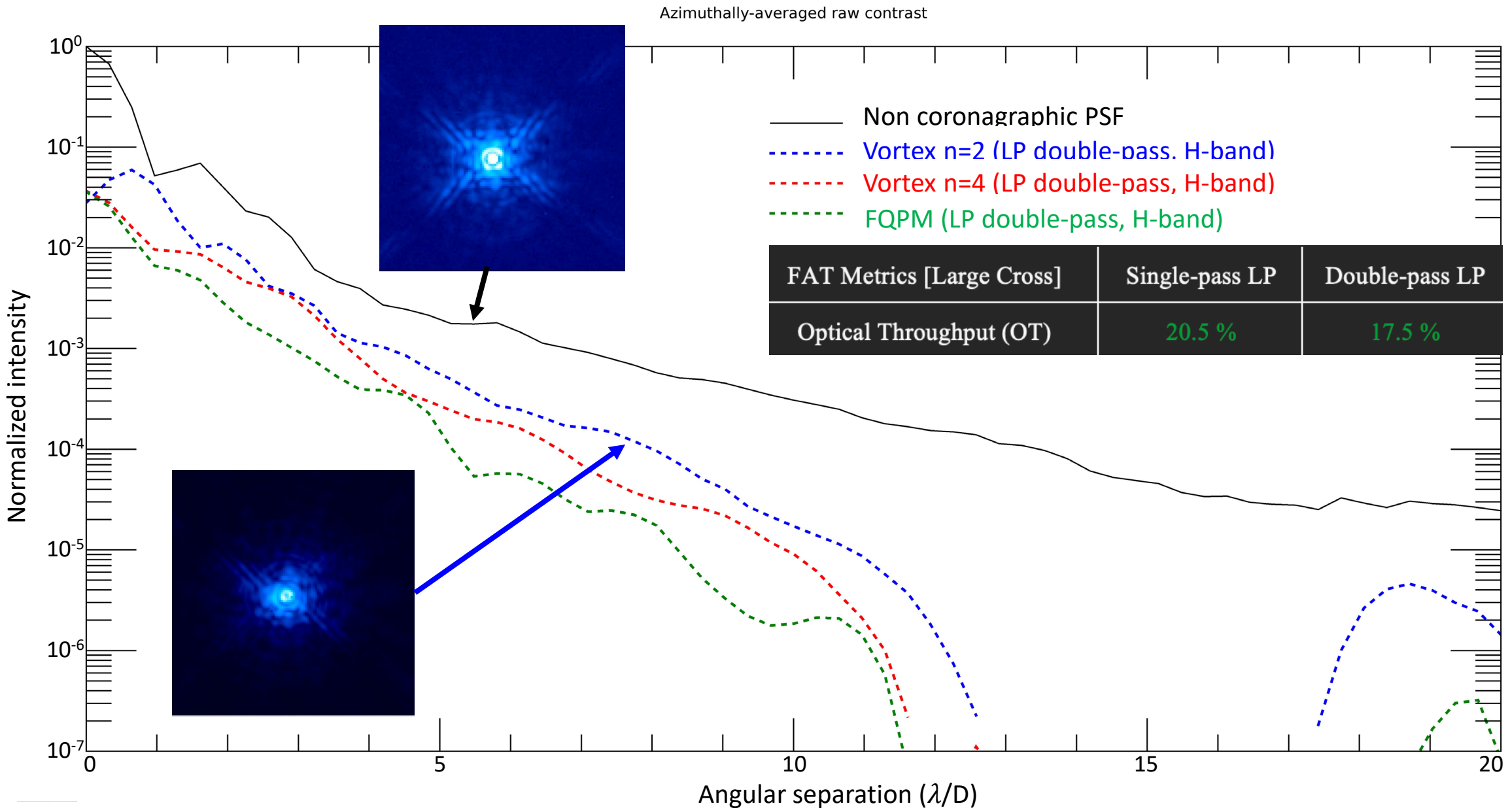


FDR optical design of PLACID, with its interfaces with TROIA and DIRAC

DAG/PLACID performance at Factory Acceptance Review



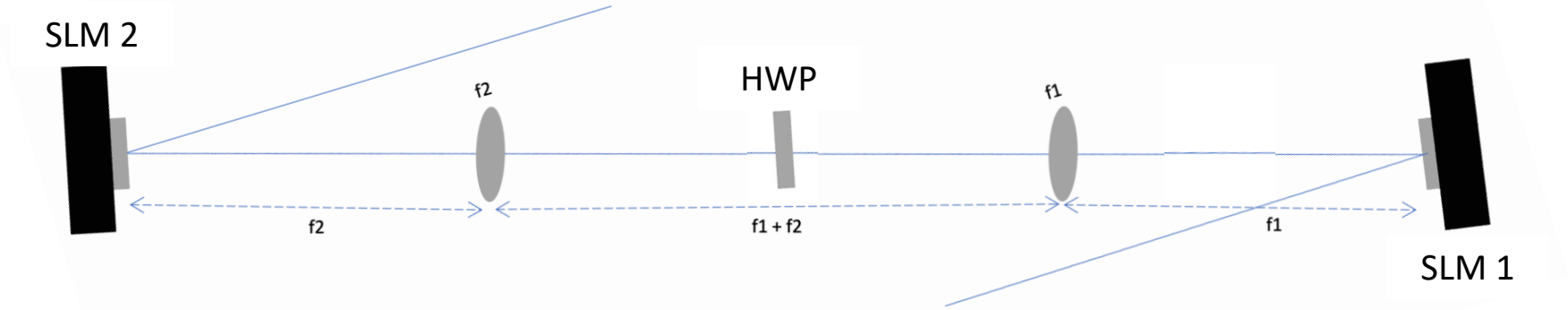
DAG/PLACID performance at Factory Acceptance Review



FAT Metrics [Large Cross]	Single-pass LP	Double-pass LP
Optical Throughput (OT)	20.5 %	17.5 %

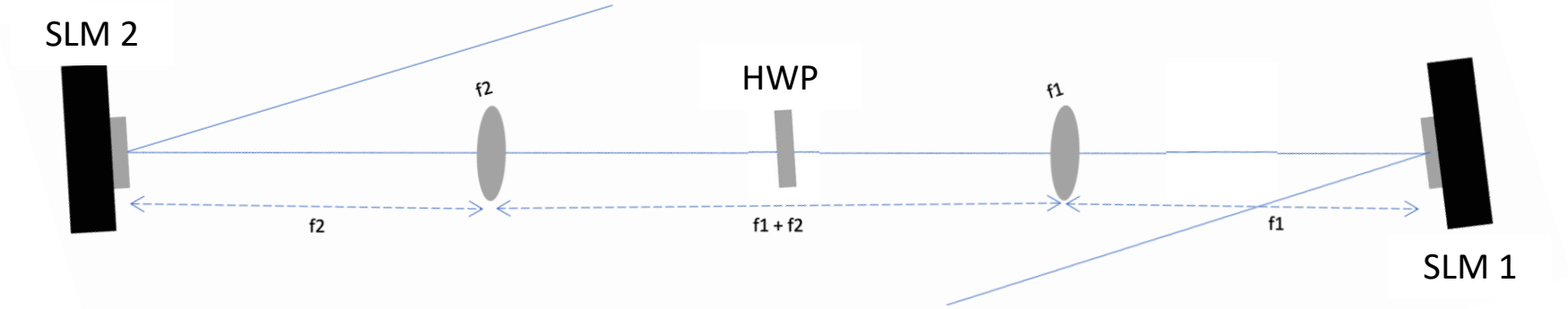
PLACID upgrade first goal: Beat polarization -> Increase throughput

- Use 2 off the shelf LCOS SLMs in cascade, half-wave plate in between

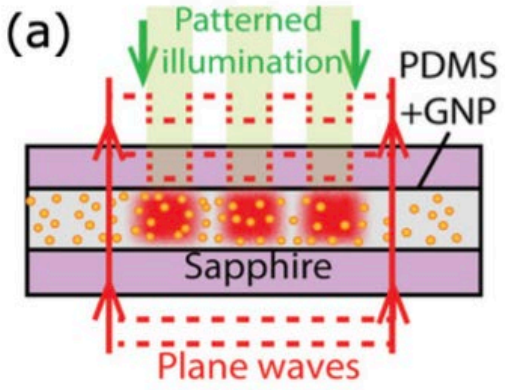


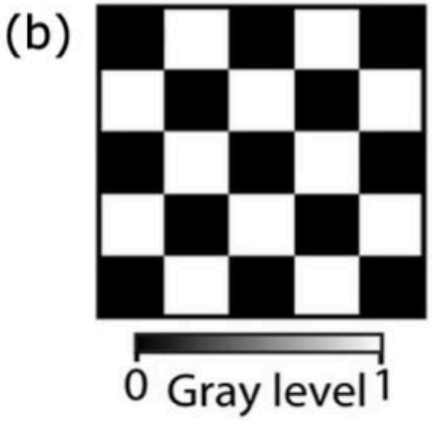
PLACID upgrade first goal: Beat polarization -> Increase throughput

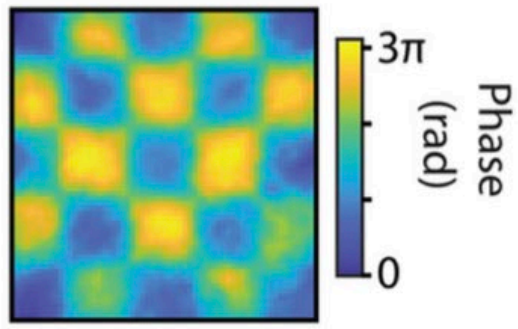
- Use 2 off the shelf LCOS SLMs in cascade, half-wave plate in between

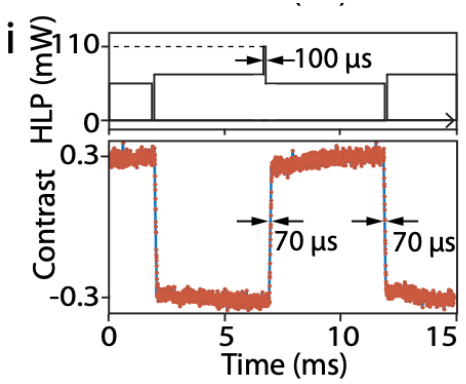


- Use 1 photothermal SLM prototype: active material whose index of refraction is changed by a local temperature gradient









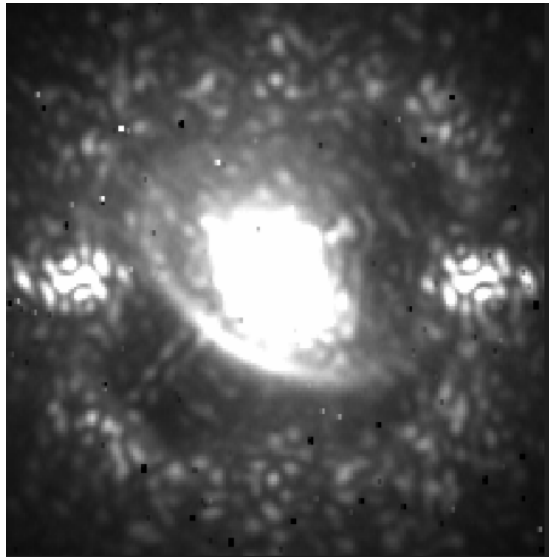
Robert et al. 2021

See SPIE paper #13097-150

PLACID upgrade second goal: coherent differential imaging

Results recently obtained with VLT/SPHERE. To be optimized.

Total intensity



Composed of:

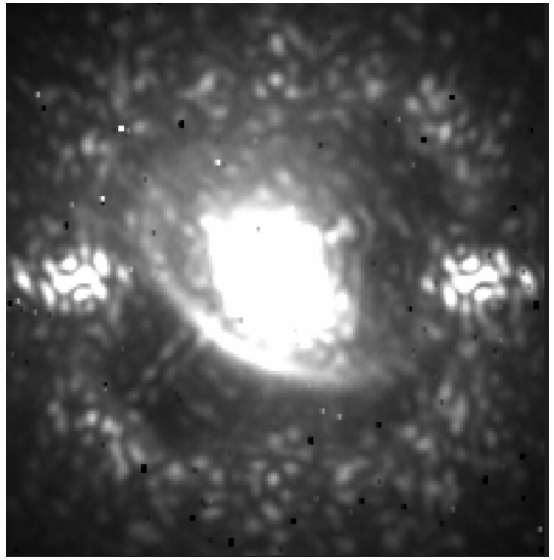
- HD 163296 disk
- Static speckles
- Turbulent speckles forming a halo

PLACID upgrade second goal: coherent differential imaging

- The residual stellar speckles are incoherent with the off-axis source

Results recently obtained with VLT/SPHERE. To be optimized.

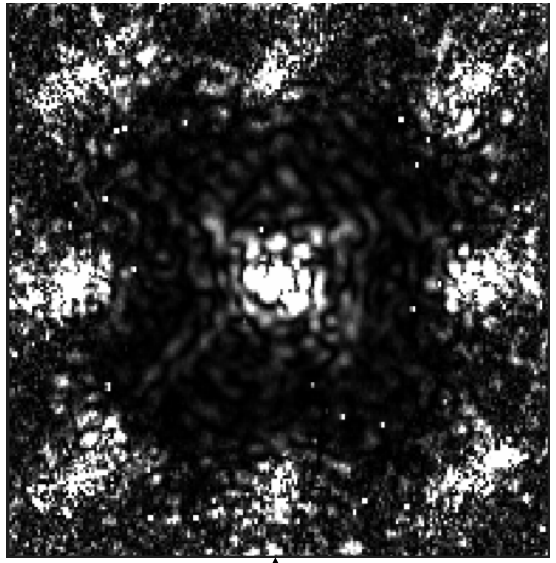
Total intensity



Composed of:

- HD 163296 disk
- Static speckles
- Turbulent speckles forming a halo

Coherent intensity



Calibration of the static speckles

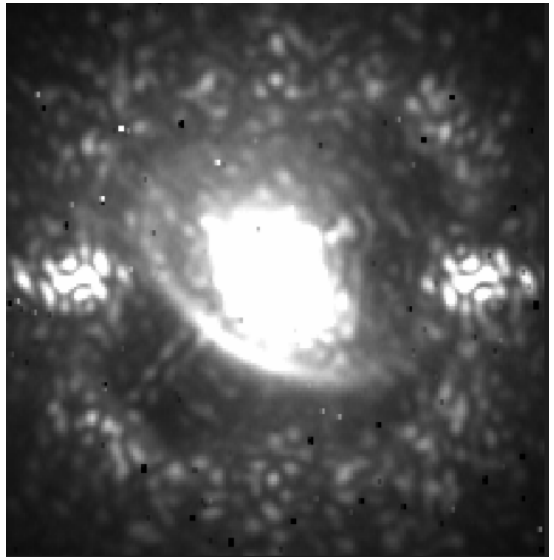
Temporal modulation of the speckle through phase diversity

PLACID upgrade second goal: coherent differential imaging

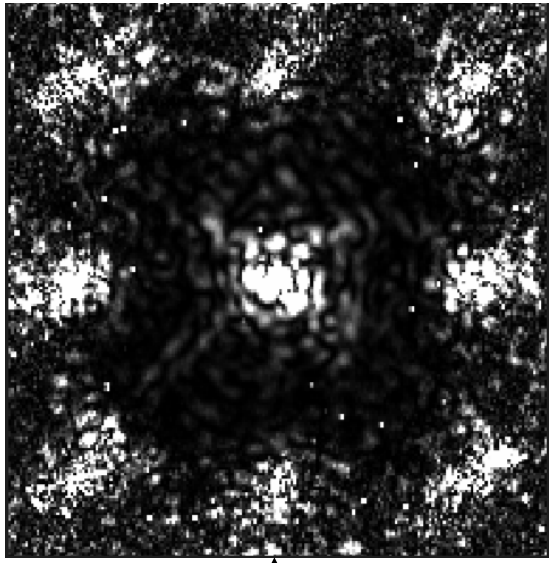
- The residual stellar speckles are incoherent with the off-axis source
- Creating coherence and incoherence maps

Results recently obtained with VLT/SPHERE. To be optimized.

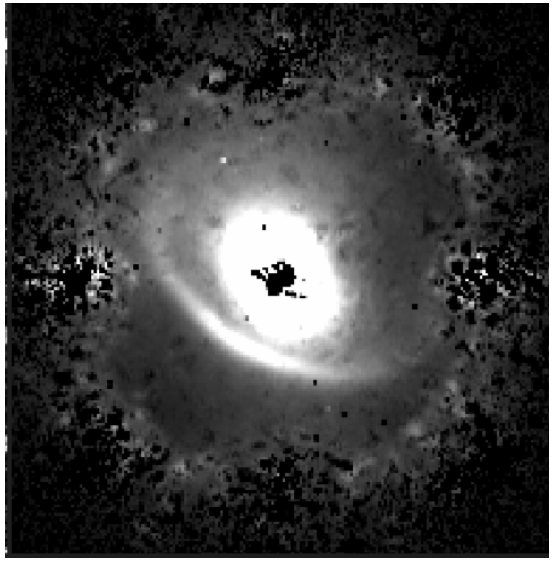
Total intensity



Coherent intensity



Incoherent intensity



Composed of:
- HD 163296 disk
- Static speckles
- Turbulent speckles forming a halo

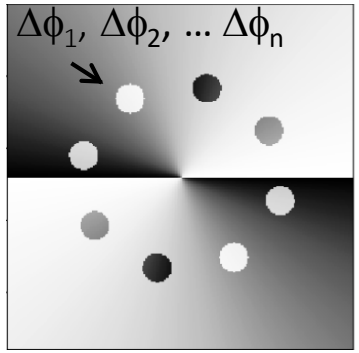
Calibration of the static speckles

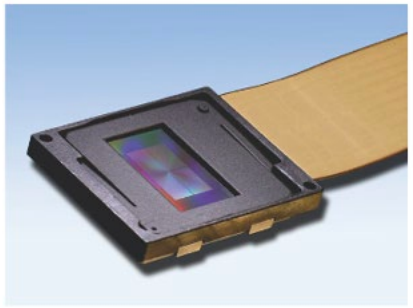
Temporal modulation of the speckle through phase diversity

Composed of:
- HD 163296 disk
- Turbulent speckles forming a halo

PLACID upgrade second goal: coherent differential imaging

- The residual stellar speckles are incoherent with the off-axis source
- Creating coherence and incoherence maps

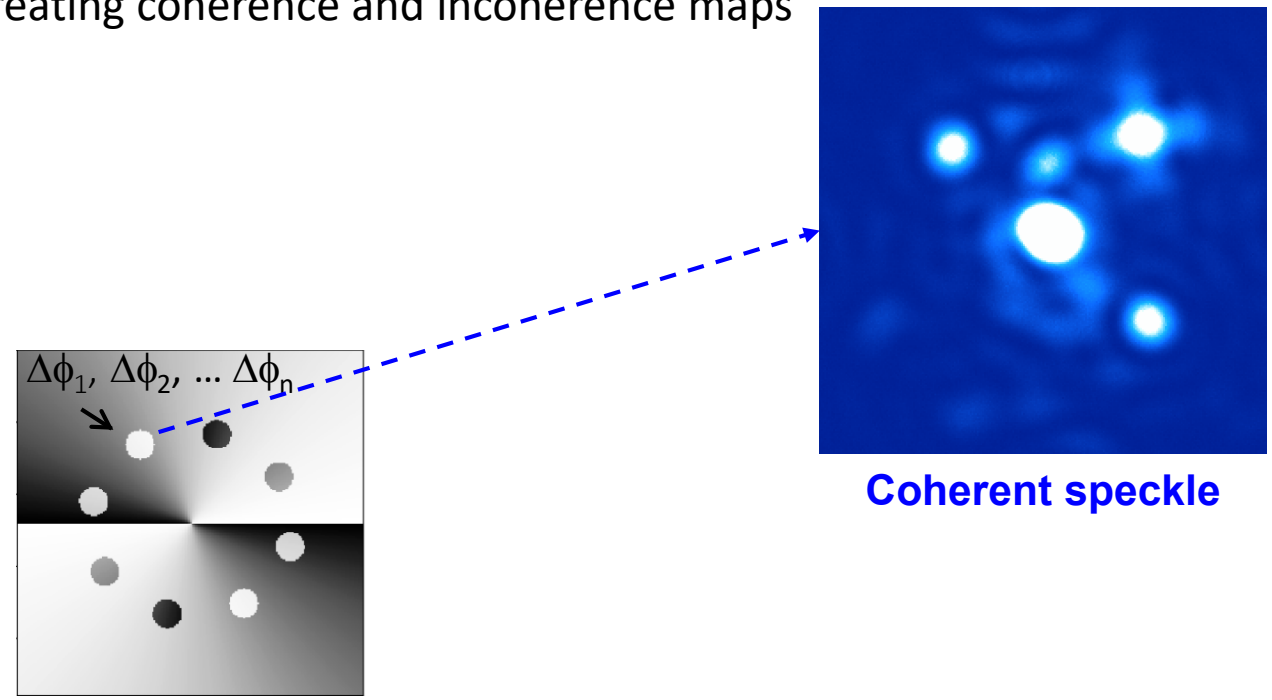


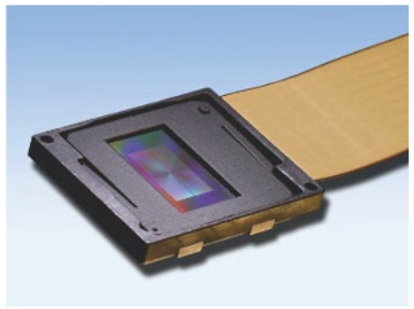


Kuhn et al. 2018

PLACID upgrade second goal: coherent differential imaging

- The residual stellar speckles are incoherent with the off-axis source
- Creating coherence and incoherence maps

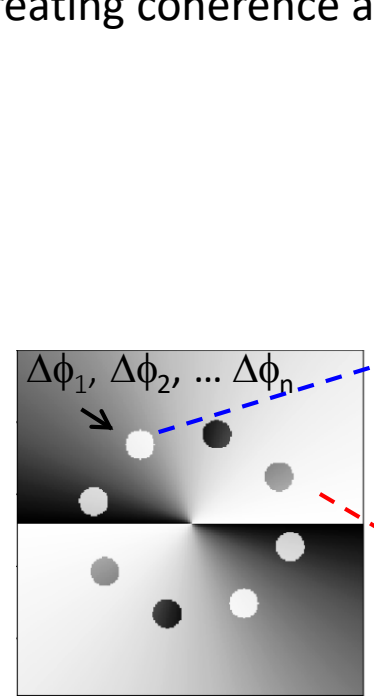


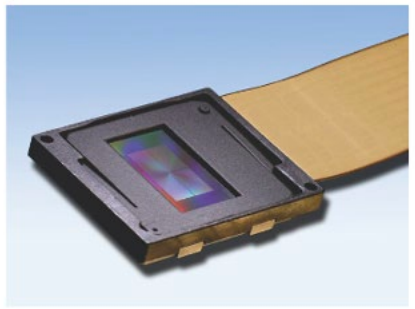


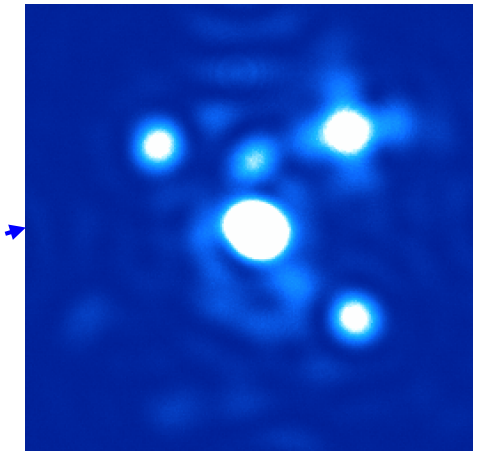
Kuhn et al. 2018

PLACID upgrade second goal: coherent differential imaging

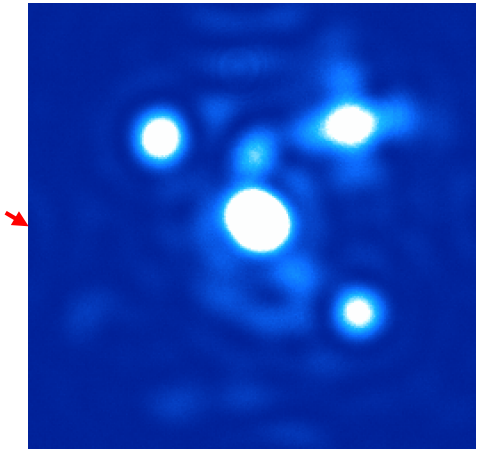
- The residual stellar speckles are incoherent with the off-axis source
- Creating coherence and incoherence maps







Coherent speckle

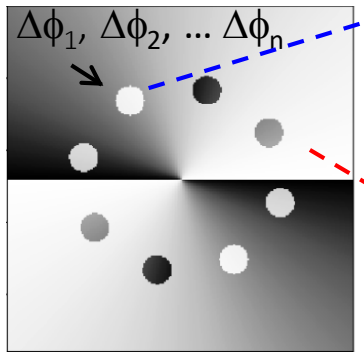


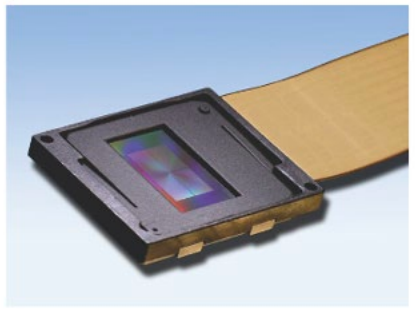
Incoherent off-axis point source

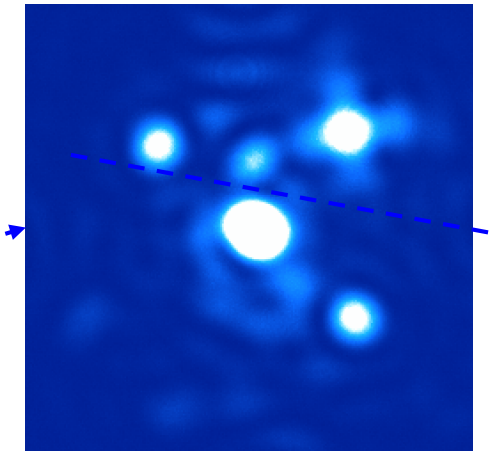
Kuhn et al. 2018

PLACID upgrade second goal: coherent differential imaging

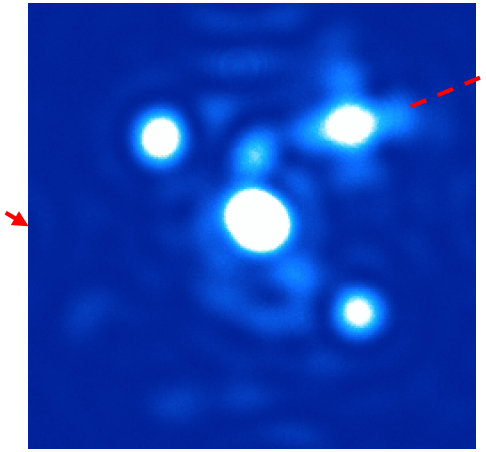
- The residual stellar speckles are incoherent with the off-axis source
- Creating coherence and incoherence maps



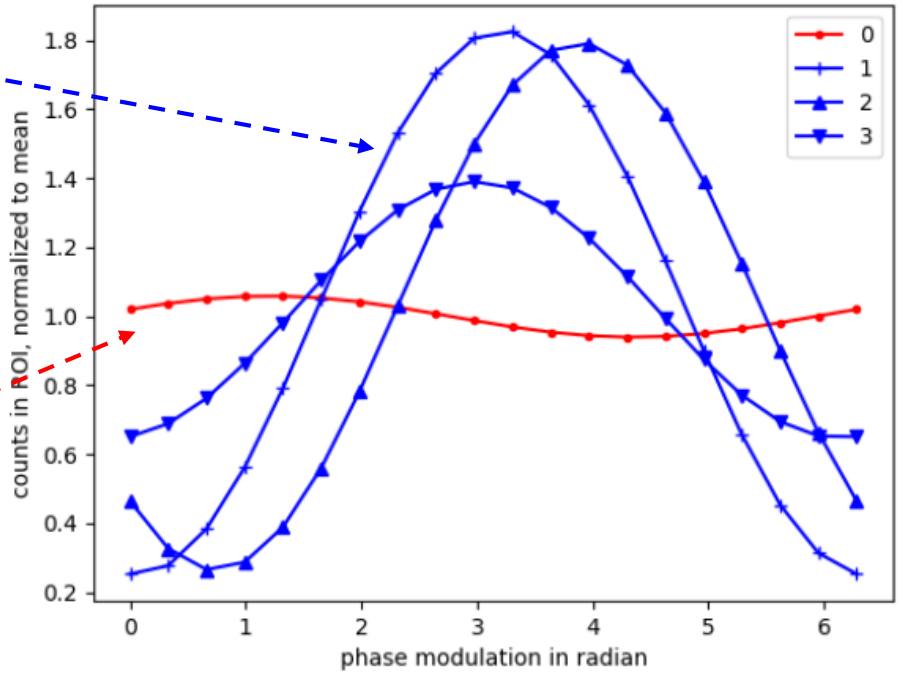




Coherent speckle



Incoherent off-axis point source

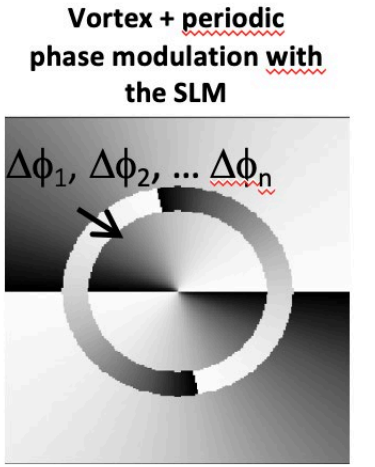


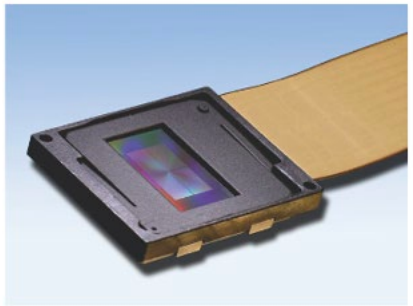
Kuhn et al. 2018

PLACID upgrade second goal: coherent differential imaging

- The residual stellar speckles are incoherent with the off-axis source
- Creating coherence and incoherence maps

Naive implementation: synchronous noise detection in the temporal Fourier domain:



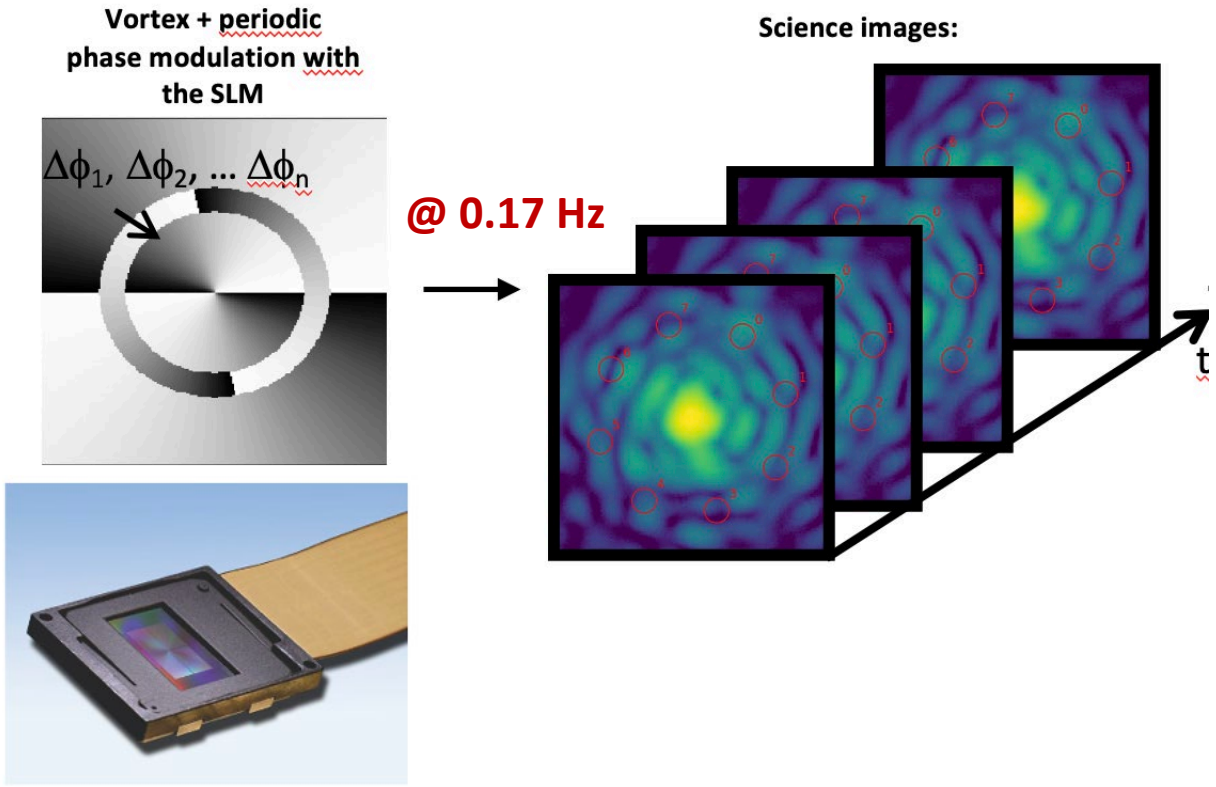


Kuhn et al. 2018

PLACID upgrade second goal: coherent differential imaging

- The residual stellar speckles are incoherent with the off-axis source
- Creating coherence and incoherence maps

Naive implementation: synchronous noise detection in the temporal Fourier domain:

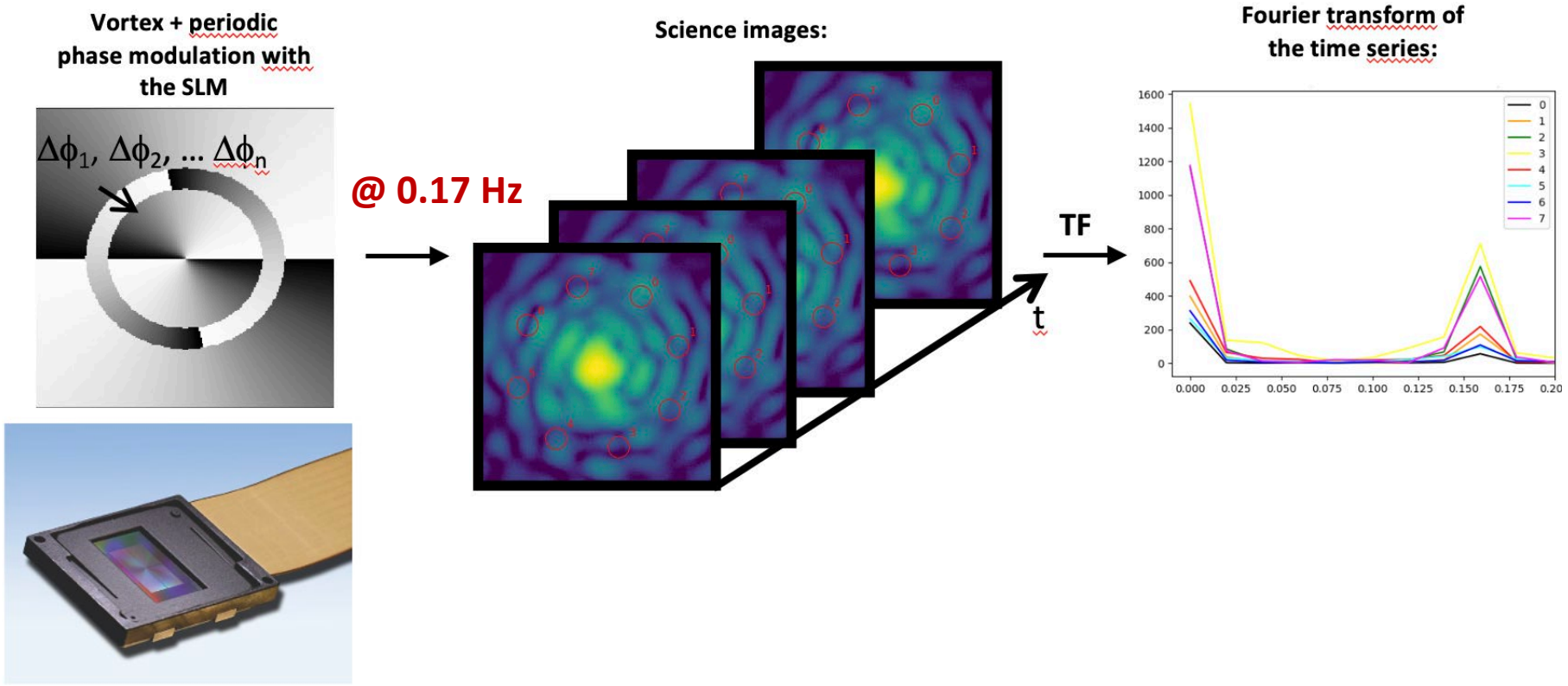


Kuhn et al. 2018

PLACID upgrade second goal: coherent differential imaging

- The residual stellar speckles are incoherent with the off-axis source
- Creating coherence and incoherence maps

Naive implementation: synchronous noise detection in the temporal Fourier domain:

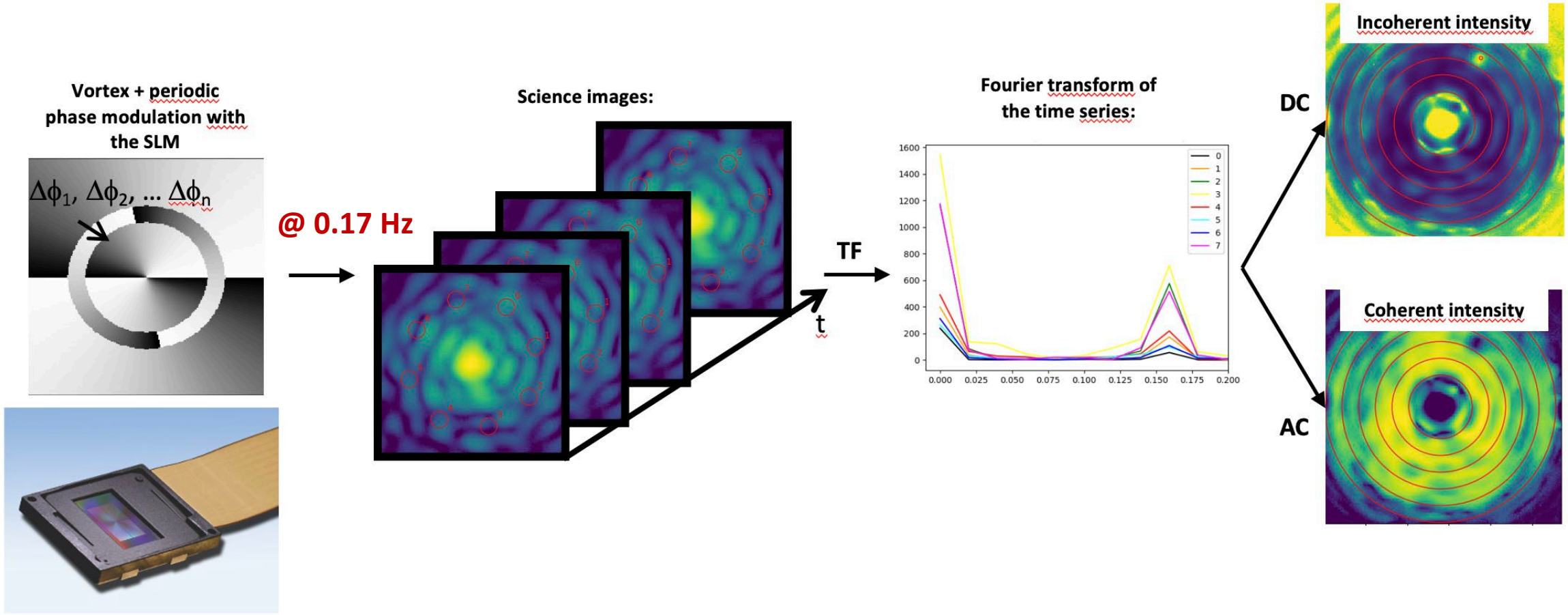


Kuhn et al. 2018

PLACID upgrade second goal: coherent differential imaging

- The residual stellar speckles are incoherent with the off-axis source
- Creating coherence and incoherence maps

Naive implementation: synchronous noise detection in the temporal Fourier domain:

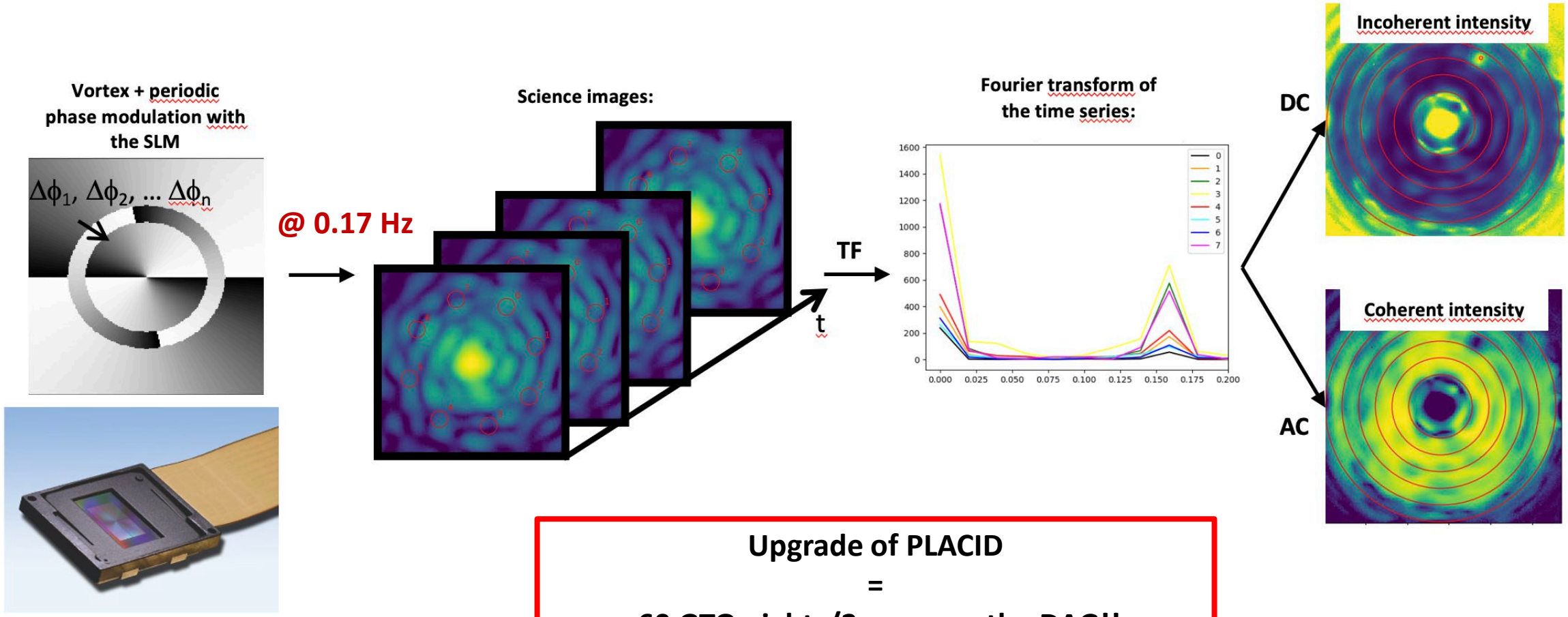


Kuhn et al. 2018

PLACID upgrade second goal: coherent differential imaging

- The residual stellar speckles are incoherent with the off-axis source
- Creating coherence and incoherence maps

Naive implementation: synchronous noise detection in the temporal Fourier domain:



Upgrade of PLACID

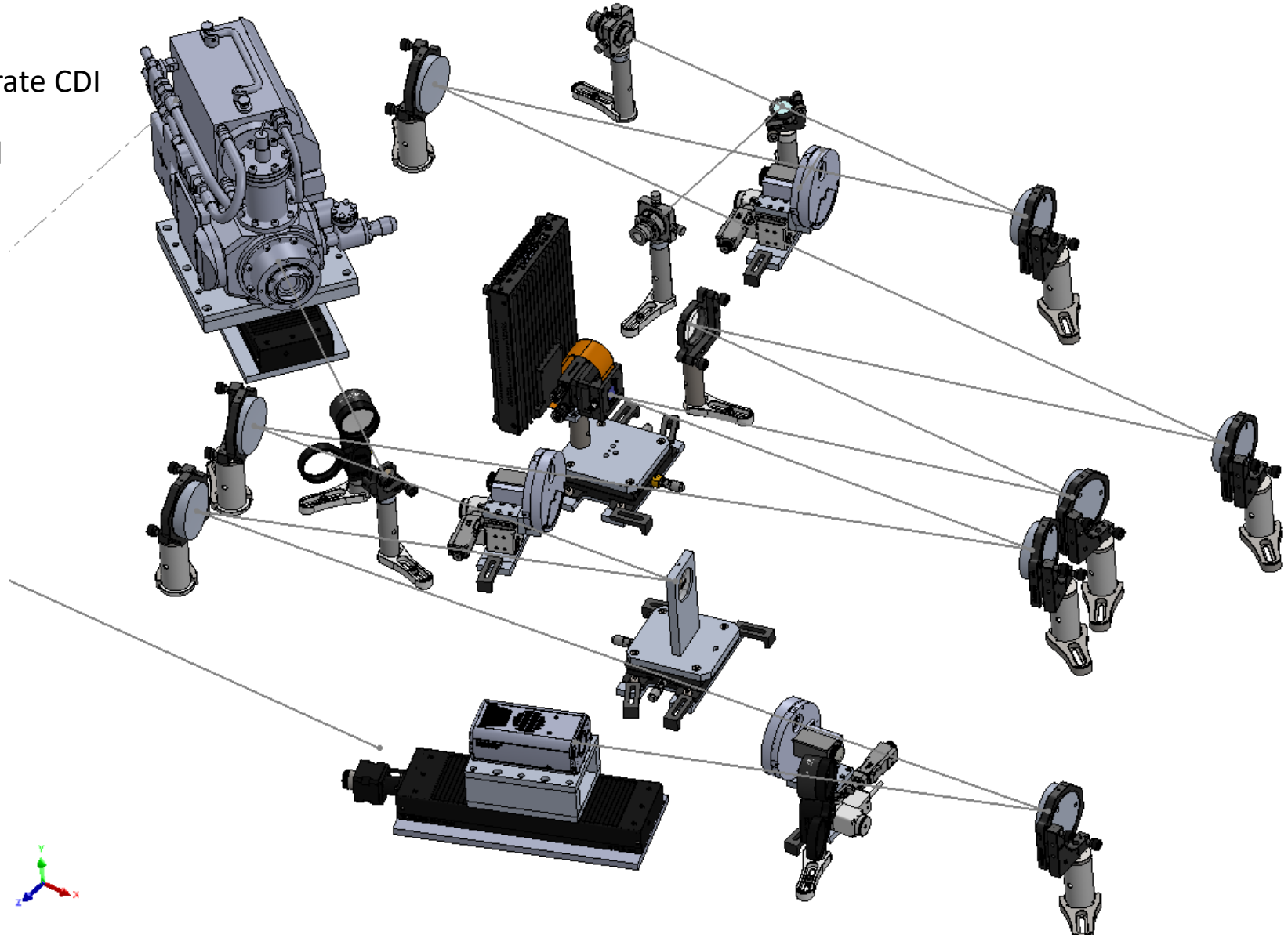
=

60 GTO nights/2 years on the DAG!!

Kuhn et al. 2018

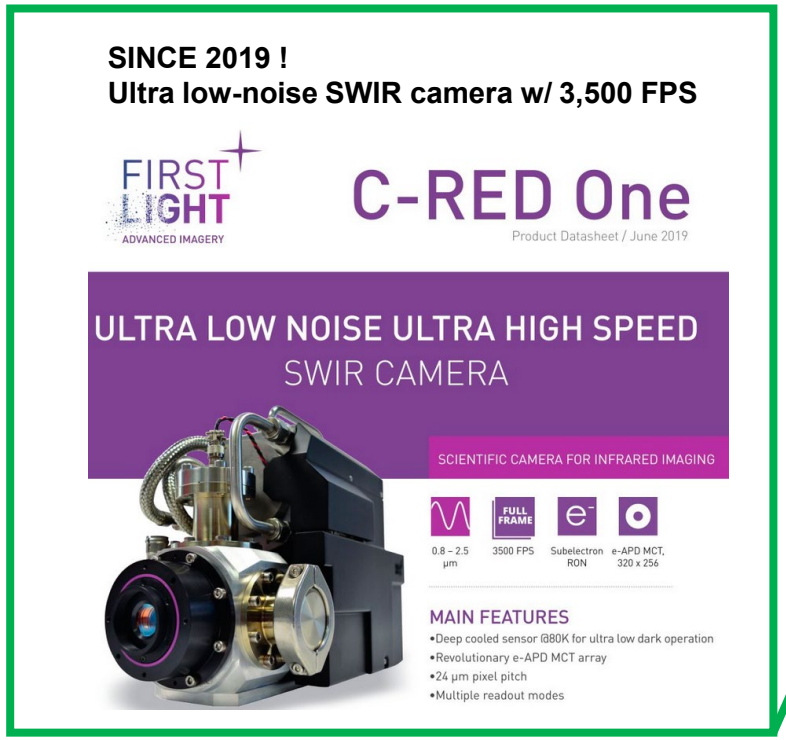
Design of SWATCHi 2.0 (University of Bern)

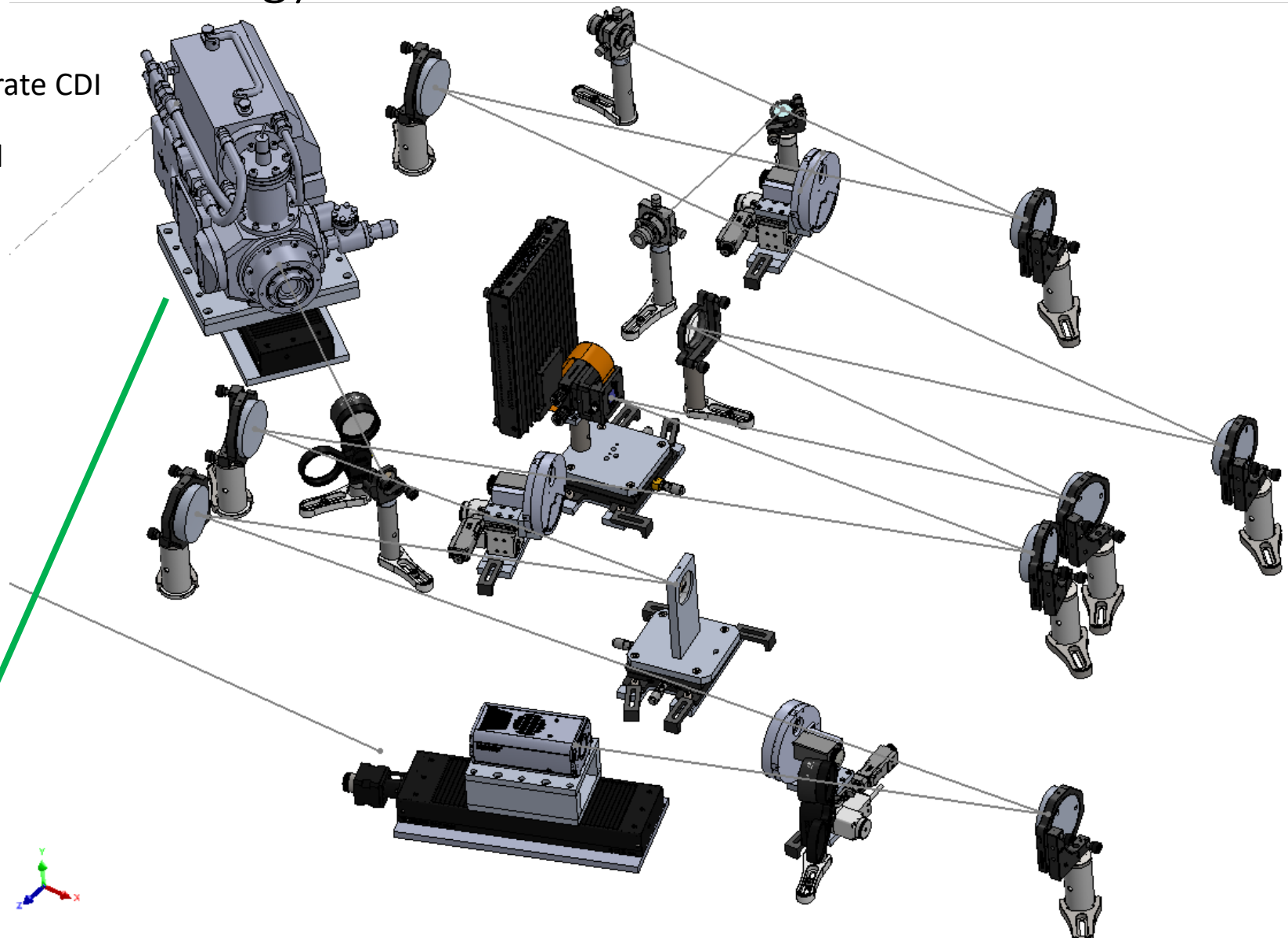
- Broadband (H-band)
- One Off-axis incoherent source to demonstrate CDI
- Motorized filter wheels
- 1 Multi-3.5 BMC DM -> 4mm entrance pupil
- F# = 160



Design of SWATCHi 2.0: latest technology for millisecond CDI

- Broadband (H-band)
- One Off-axis incoherent source to demonstrate CDI
- Motorized filter wheels
- 1 Multi-3.5 BMC DM -> 4mm entrance pupil
- F# = 160





- 11 pixels/resol
- 23 λ/D FoV

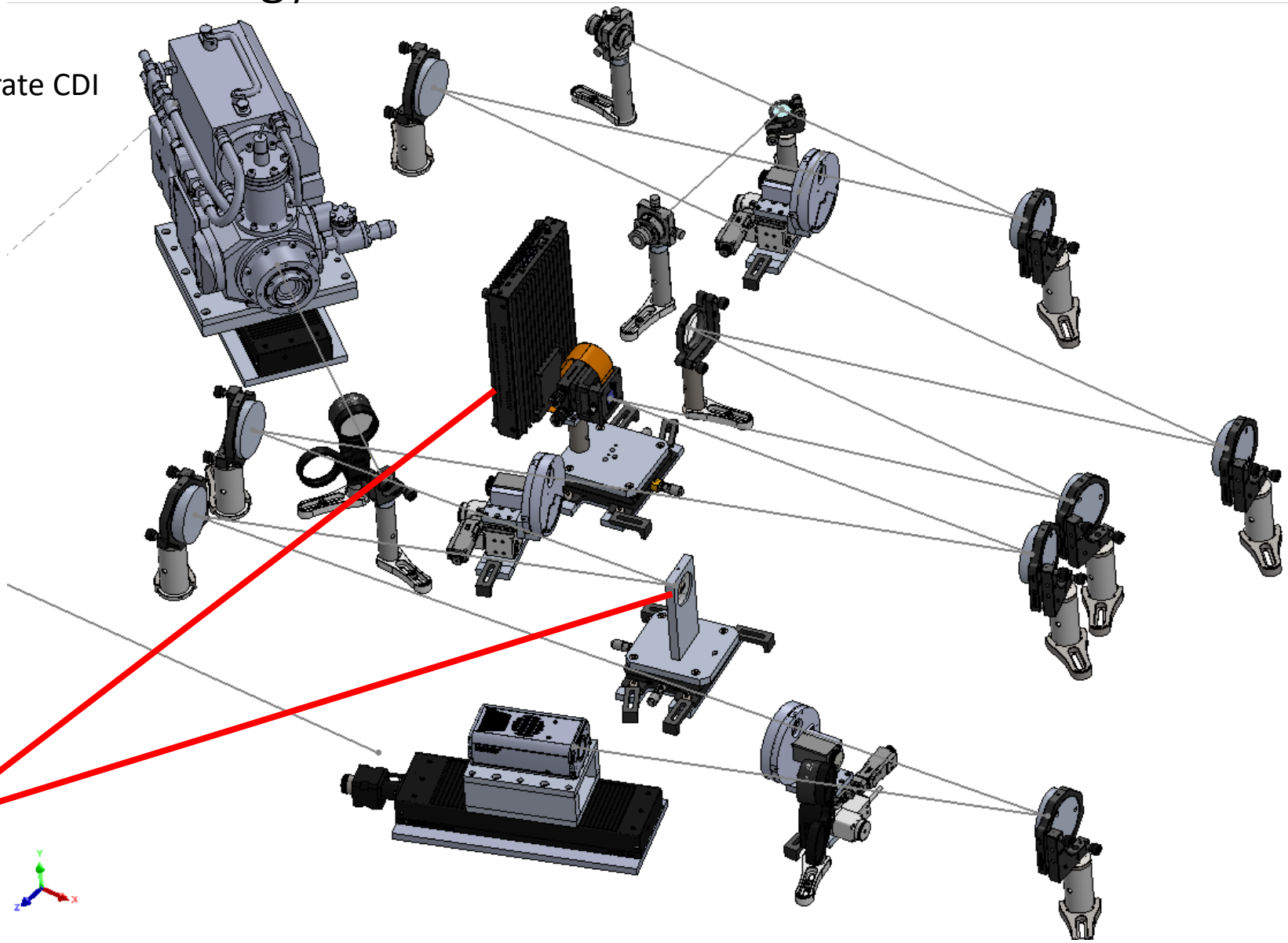
Design of SWATCHi 2.0: latest technology for millisecond CDI

- Broadband (H-band)
- One Off-axis incoherent source to demonstrate CDI
- Motorized filter wheels
- 1 Multi-3.5 BMC DM -> 4mm entrance pupil
- F# = 160

NEW SINCE 2021 !
High-speed > 200 Hz SLMs

1920 x 1152 Spatial Light Modulator
- High Resolution
- High Speed

With PCIe Controller
supporting frame rates up to 422 Hz



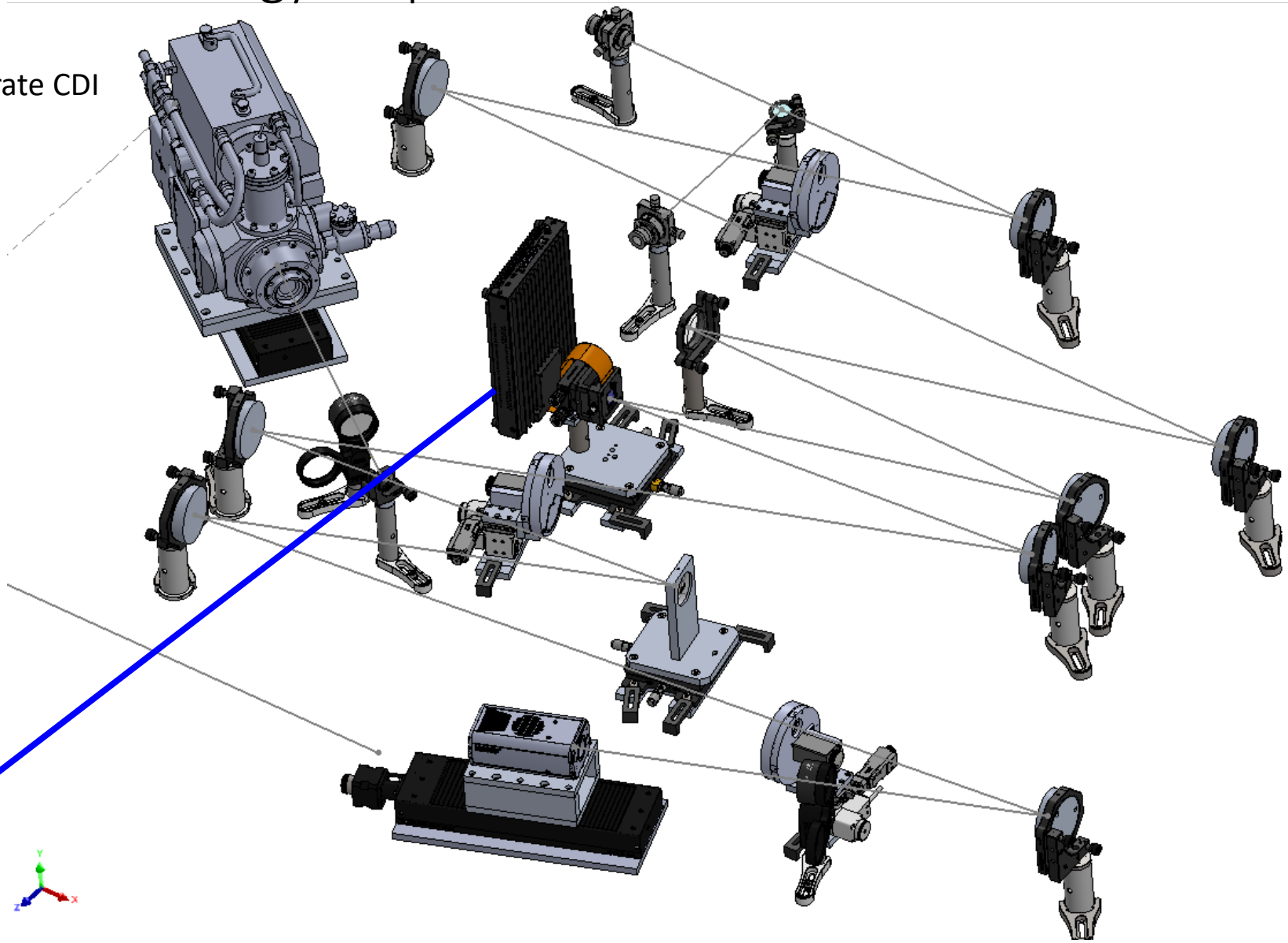
- Pixel size = 9.2um -> 28.5 spixel/resol

Design of SWATCHi 2.0: latest technology for polarization-insensitive SLM solution

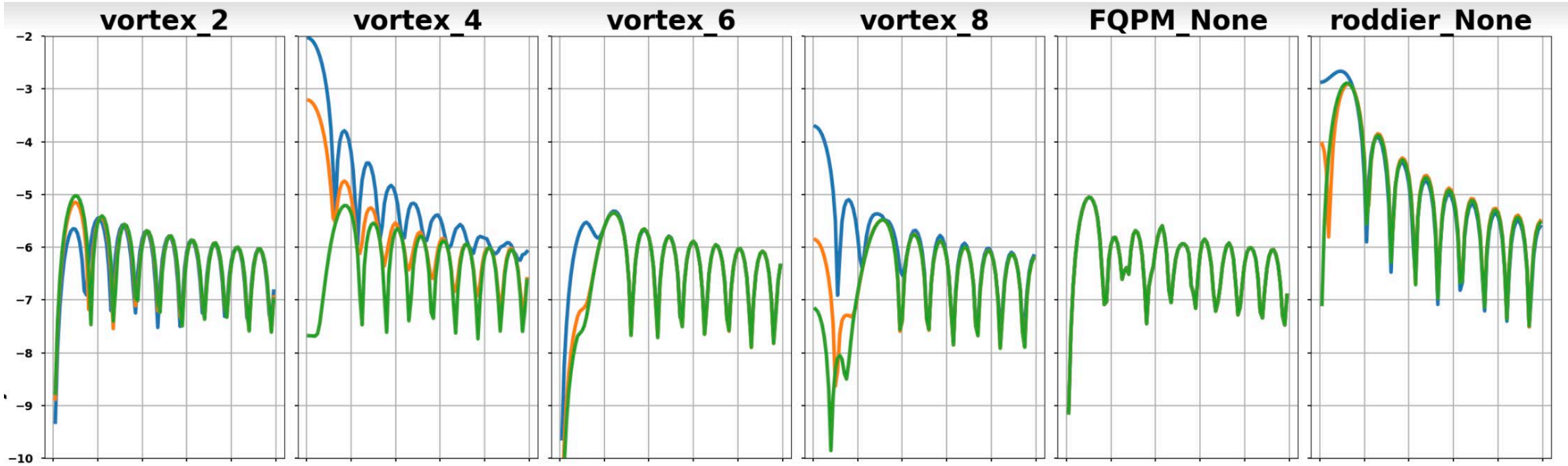
- Broadband (H-band)
- One Off-axis incoherent source to demonstrate CDI
- Motorized filter wheels
- 1 Multi-3.5 BMC DM -> 4mm entrance pupil
- F# = 160

NEW SINCE 2024!

- Pixel size < 50um -> 5.2 spixel/resol



Design of SWATCHi 2.0: Testbed simulations for spatial sampling at the SLM



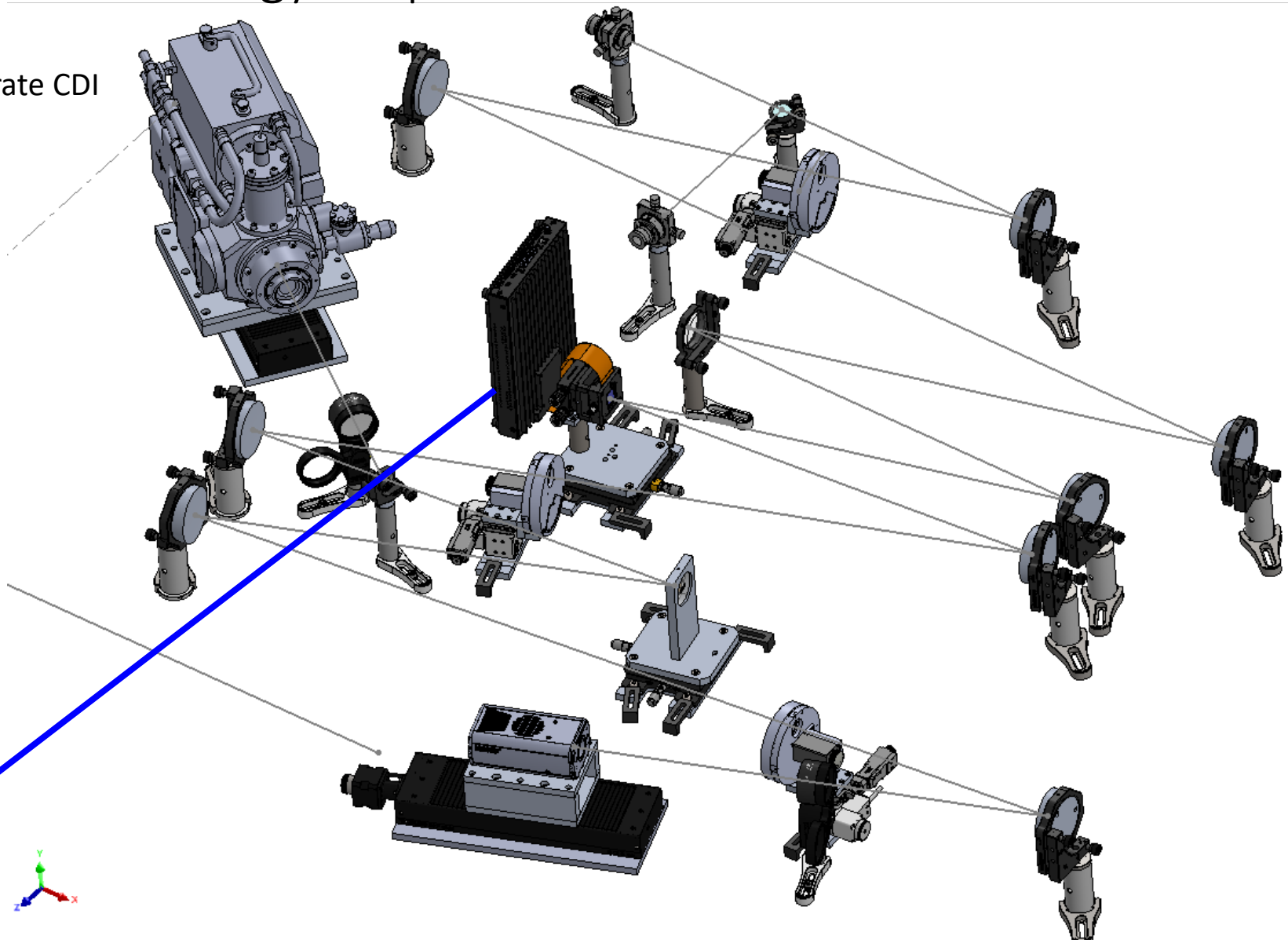
See Liurong Lin's poster !
SPIE paper #13096-128

Design of SWATCHi 2.0: latest technology for polarization-insensitive SLM solution

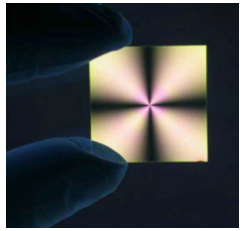
- Broadband (H-band)
- One Off-axis incoherent source to demonstrate CDI
- Motorized filter wheels
- 1 Multi-3.5 BMC DM -> 4mm entrance pupil
- F# = 160

NEW SINCE 2024!

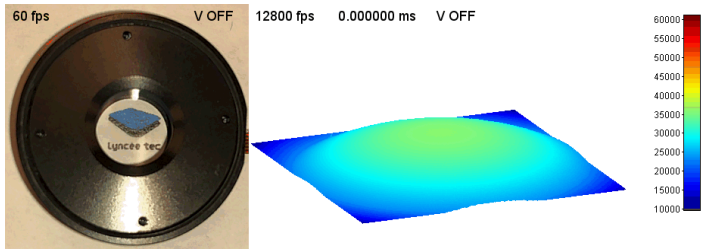
- Pixel size < 50um -> 5.2 spixel/resol



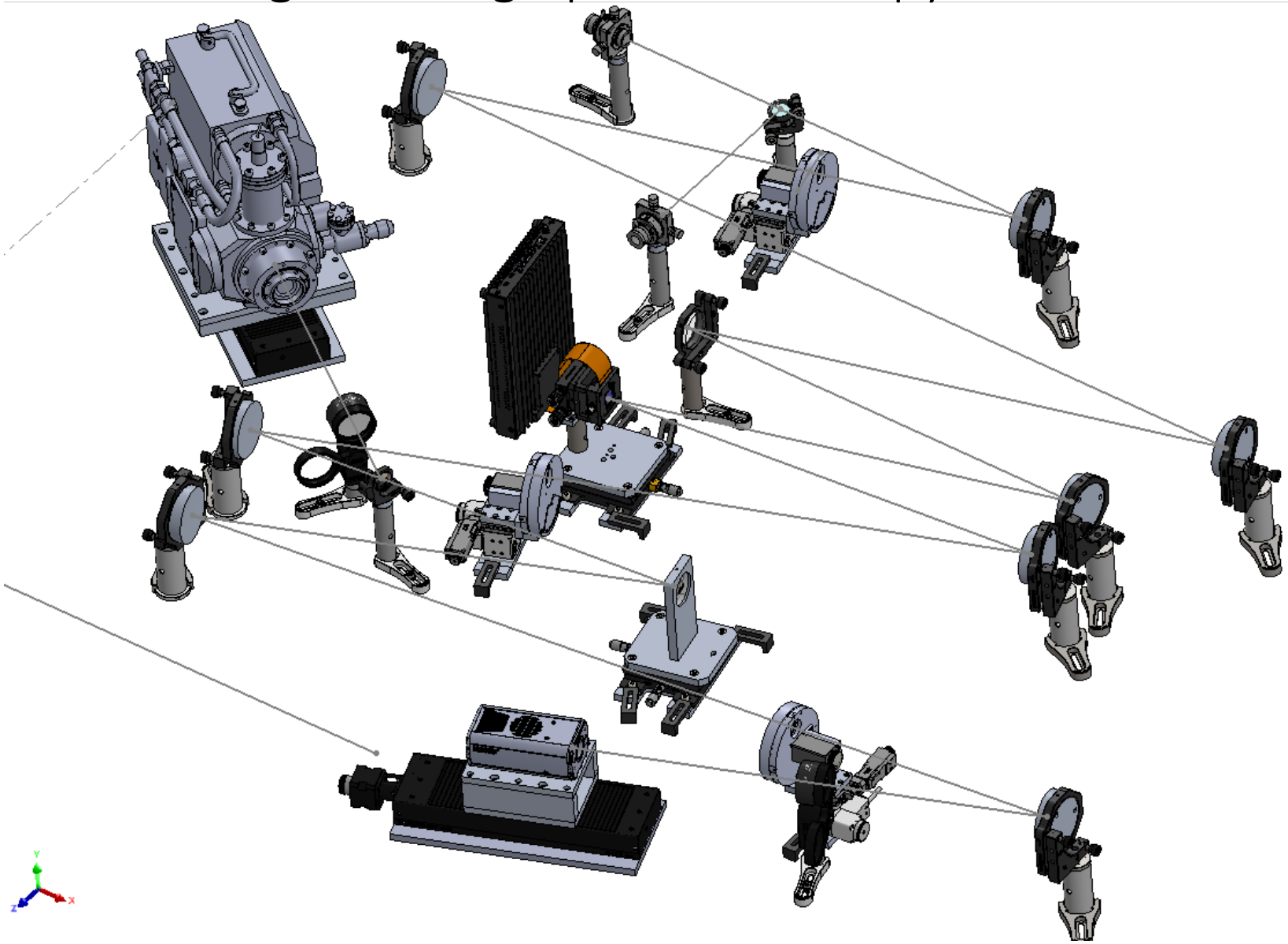
Side project: caracterizing SLMs with Digital Holographic Microscopy



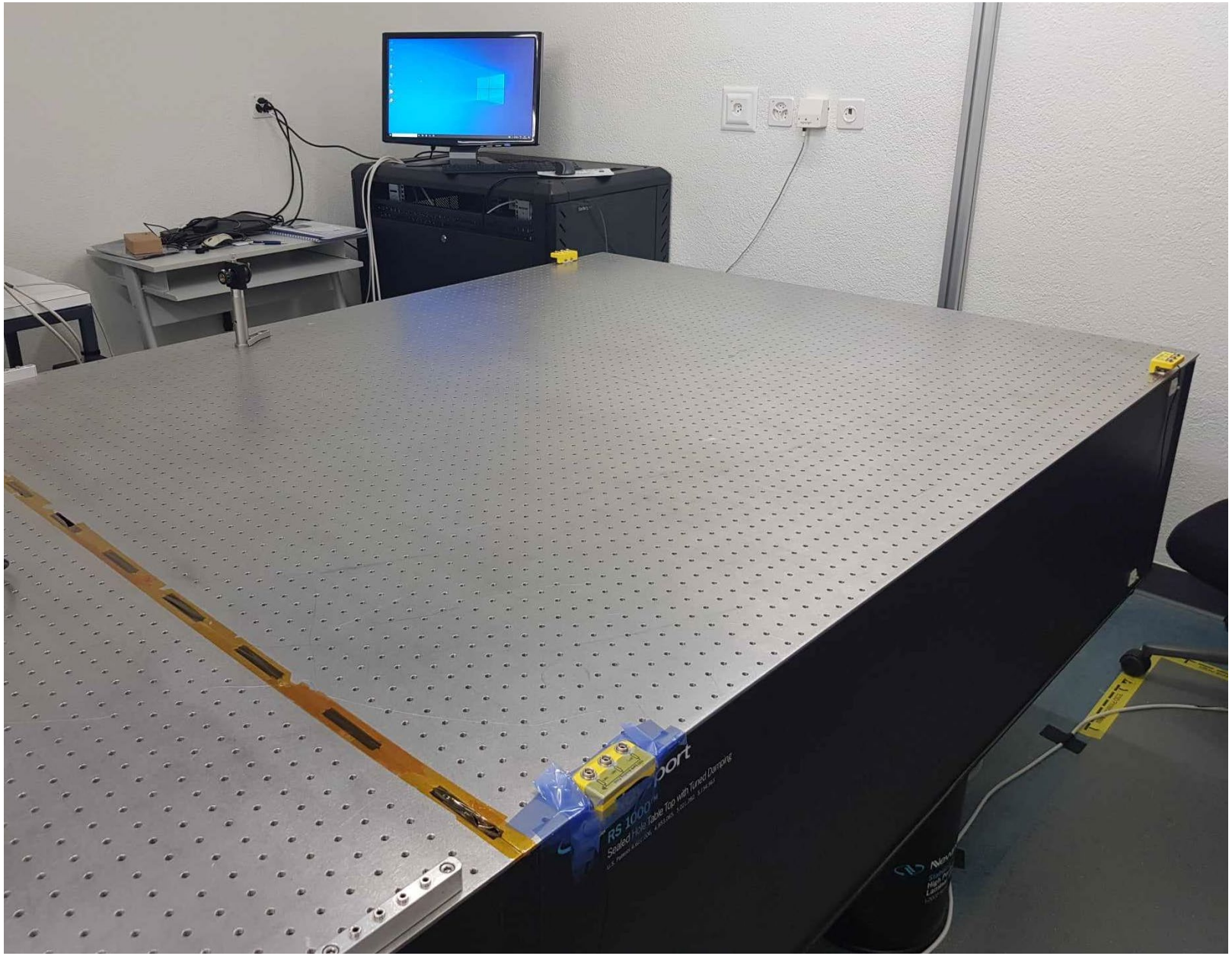
DHM from LyncéeTec (Lausanne)



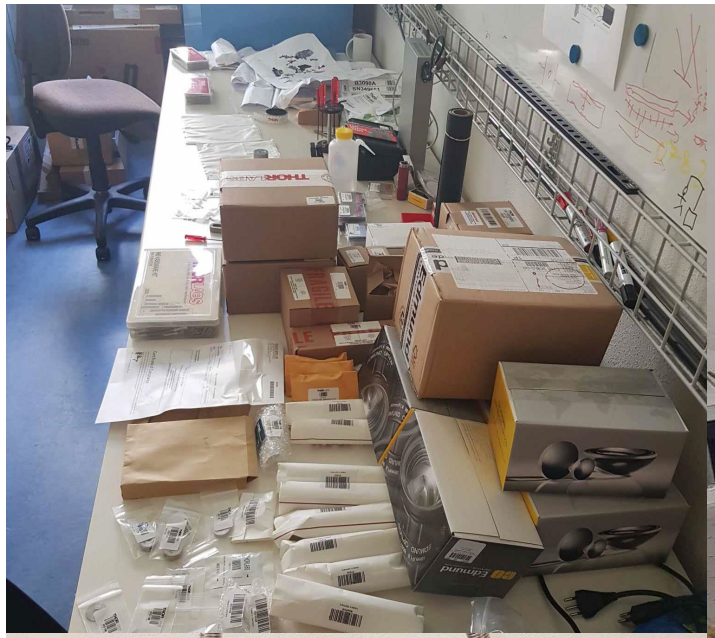
- High 3D spatial resolution
- High temporal resolution

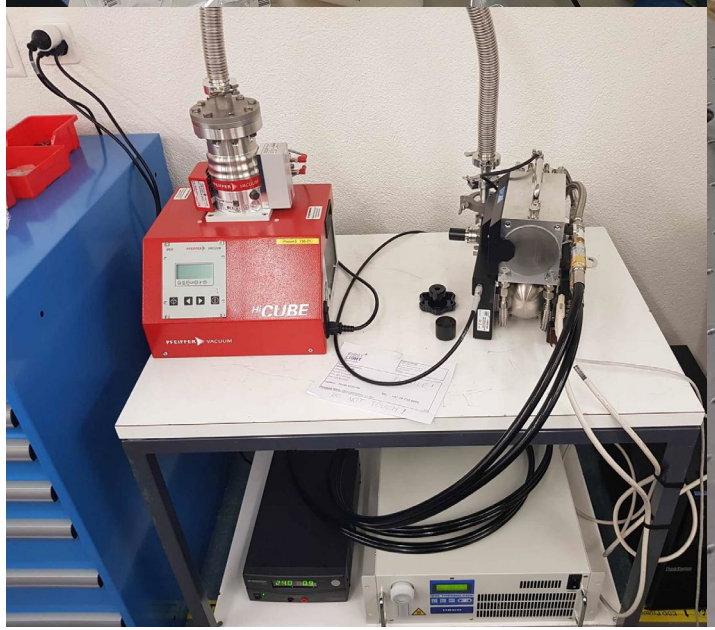


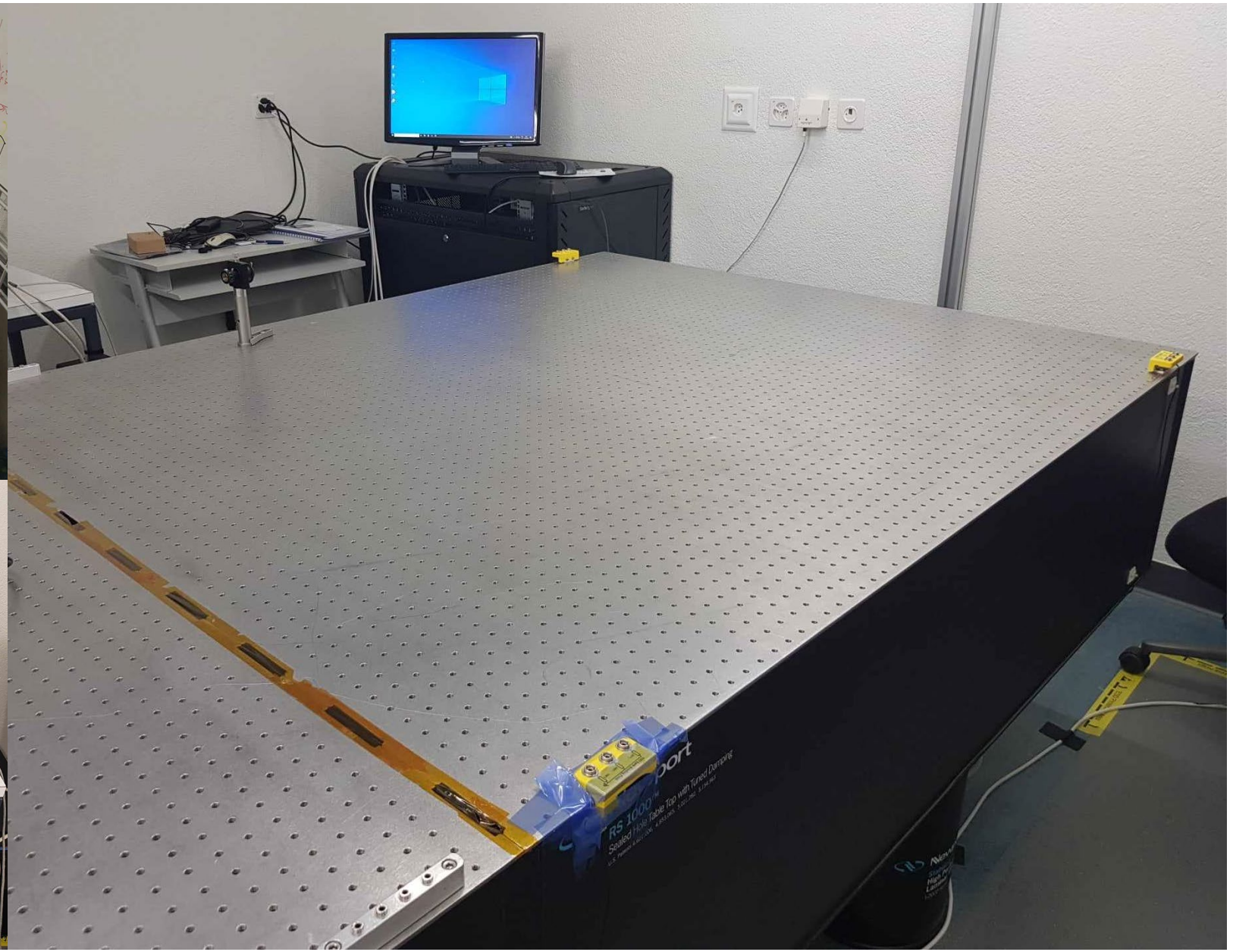
SWATCHi 2.0 current status: alignement to be started!



SWATCHi 2.0 current status: alignement to be started!







RACE-GO team at SPIE'24 and steps forwards

2023

2024

2025

2026

Bern lab

Design of SWATCHi 2.0 and hardware procurement

Alignment/interfacing of SWATCHi 2.0

Broadband tests

Full characterization and comparison of SLM technologies

Developping new algorithms for PLACID

Development a viable scheme for CDI

PLACID

Packing and shipping to Turkey

Target list

Development of PLACID exposure time calculator

Commisionning at DAG

PLACID operations:

- Validation of observing modes on known exoplanets, BD and disks
- High-contrast imaging survey of binaries
- On-sky tests of customized coronagraphs

Data reduction pipeline

PLACID upgrade for CDI application

On-sky validation of the CDI

Simulations

Detailed simulations of high-contra performance with SLMs and PLACID:
- Understand the impact of spatial and electrical resolution on coronagraph null
- Understand PLACID future on-sky results and artifacts

CDI in simulations:
- Deriving the optimal observing strategy with the CDI postprocessing technique

The PI

SPIE poster #13096-129

SPIE poster #13096-128

SPIE talk #13096-58

WE WANT YOU!

Postdoc position at the University of Bern