STScI | SPACE TELESCOPE SCIENCE INSTITUTE

EXPANDING THE FRONTIERS OF SPACE ASTRONOMY

ONERA
THE FRENCH AEROSPACE LAB

Multi-aperture telescope alignment: PSF stacking with ELASTIC

Iva Laginja

Marseille, November 8, 2018

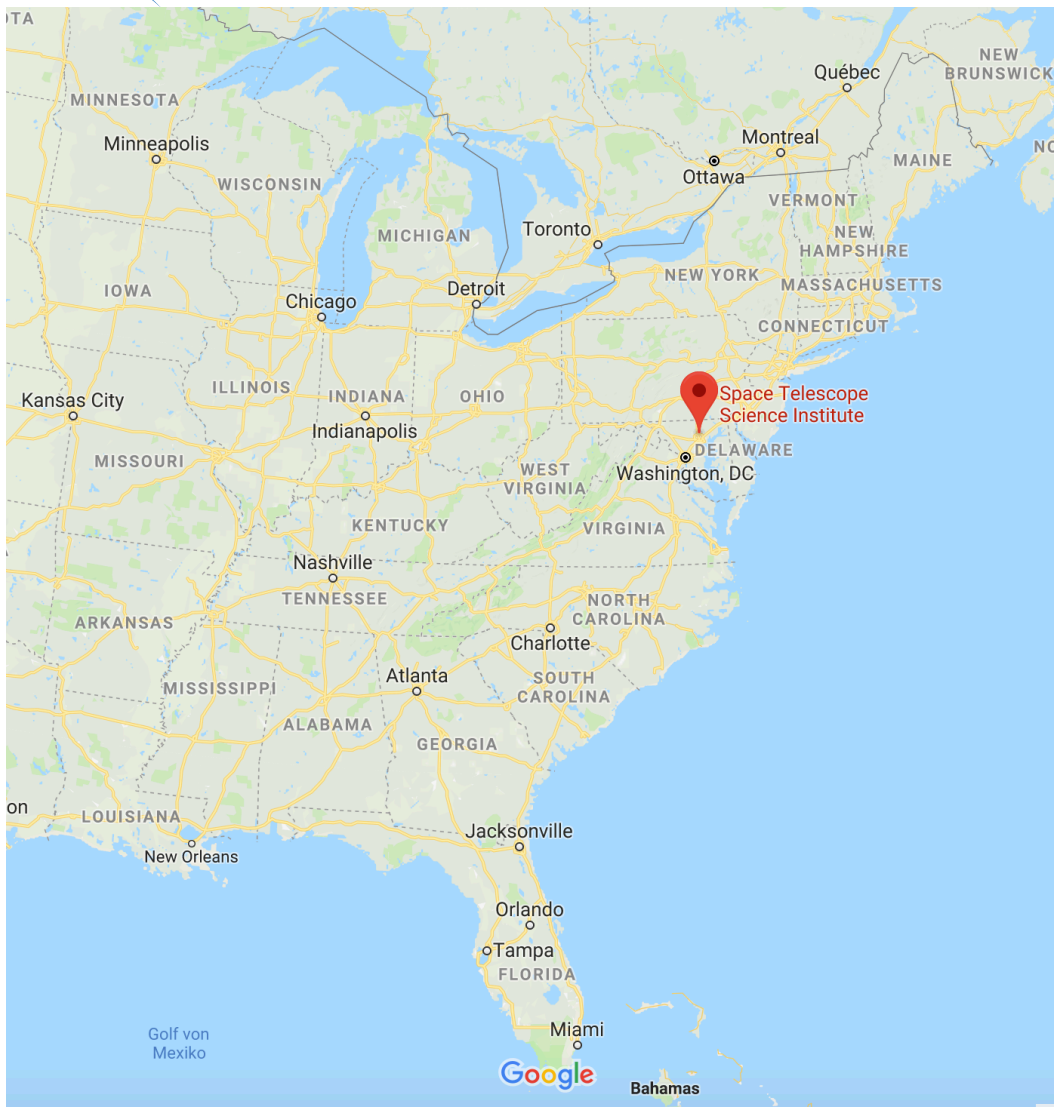
Supervisors: Rémi Soummer (STScI), Jean-Francois Sauvage (ONERA/LAM), Laurent Mugnier (ONERA)

Overview

- The Makidon lab:
  - Who are we and what do we do
- High Contrast imager for complex Aperture Telescopes→ HiCAT
  - Coronagraphy and WFS&C for LUVOIR
- JWST Optical Simulation Testbed → JOST
  - Wavefront sensing and control for segmented apertures
- Estimation of Large Amplitude Subaperture Tip-tilt by Image Correlation: ELASTIC


The Russel B. Makidon Optics Laboratory

Space Telescope Science Institute



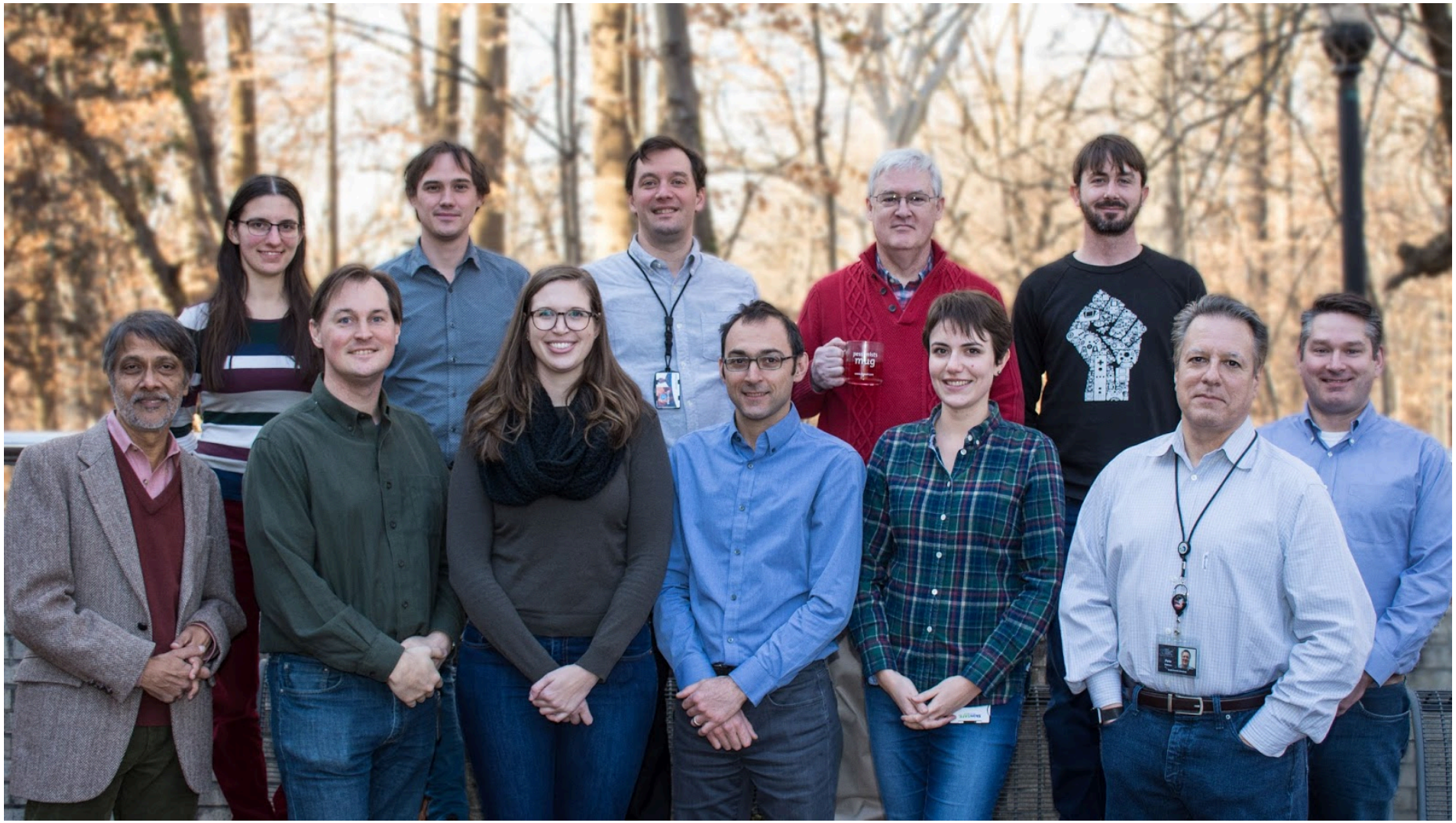
- Science Operations Center for Hubble
- Science and Mission Operations Center for James Webb Space Telescope
- MAST – Mikulski Archive for Space Telescopes
  - Hubble, JWST, Kepler, K2 and others

The team

Rémi Soummer (PI)
Iva Laginja
Kathryn St Laurent
Peter Petrone
Greg Brady
Tom Comeau
Marshall Perrin
Laurent Pueyo
Anand Sivaramakrishnan

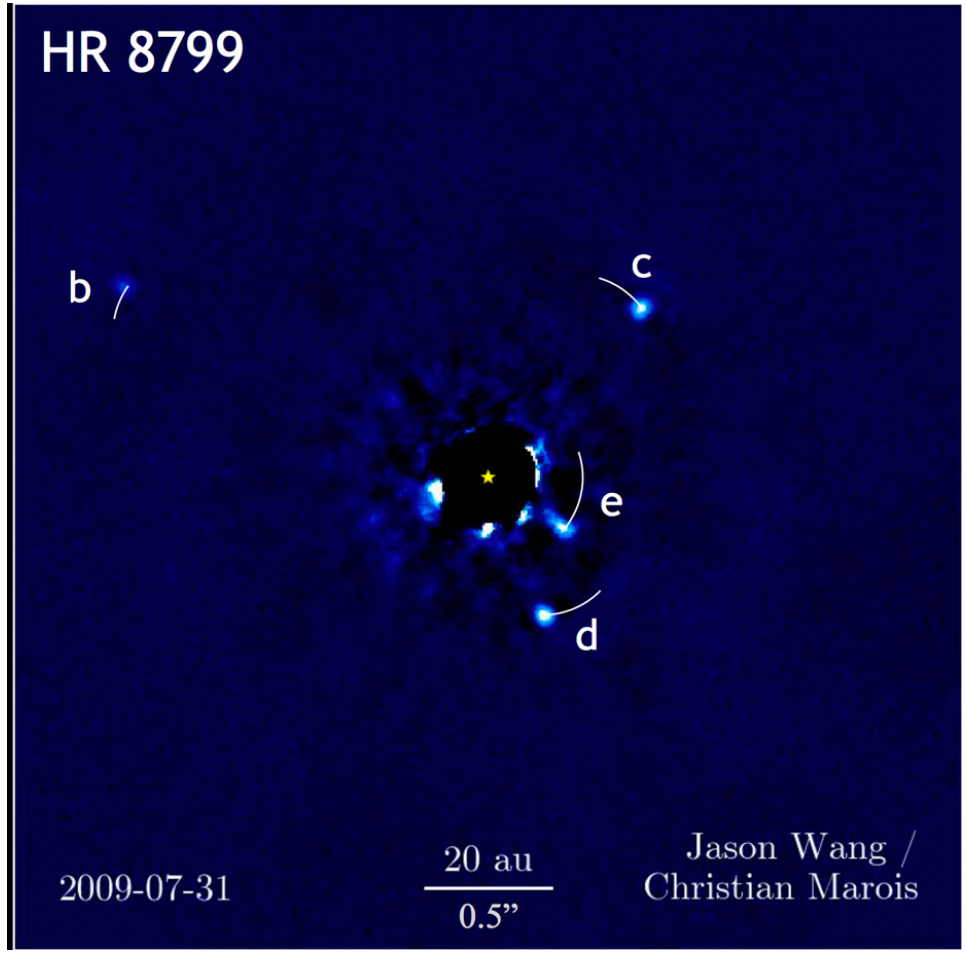
Have left:
Christopher Moriarty
Lucie Leboulleux
Keira Brooks
Johan Mazoyer
Kevin Fogarty

New:
Jules Fowler



Wide range of skills: scientists, software engineers, technical support, IT, admin, …

Ultimate goal: imaging of terrestrial exoplanets from **space**



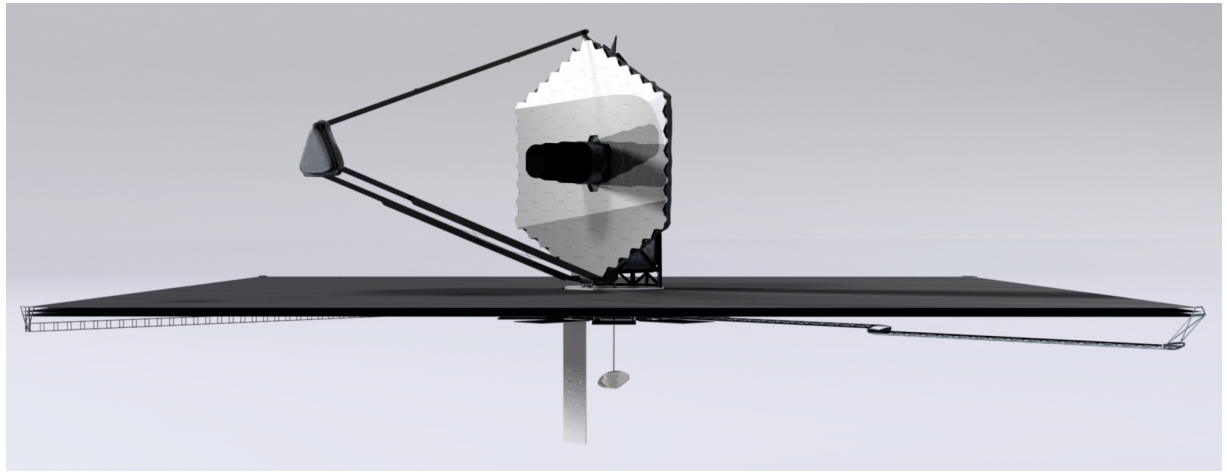
- Small angular separation requires big primary mirrors → **segmentation**
- Deal with **aberrations** stemming from segmentation – JOST testbed
- Segmentation introduces complexity in **high contrast imaging** system
- Need to work around those complexities while trying to reach **contrast of 10^{-10}** – HiCAT testbed

High contrast imager for Complex Aperture Telescopes
HiCAT

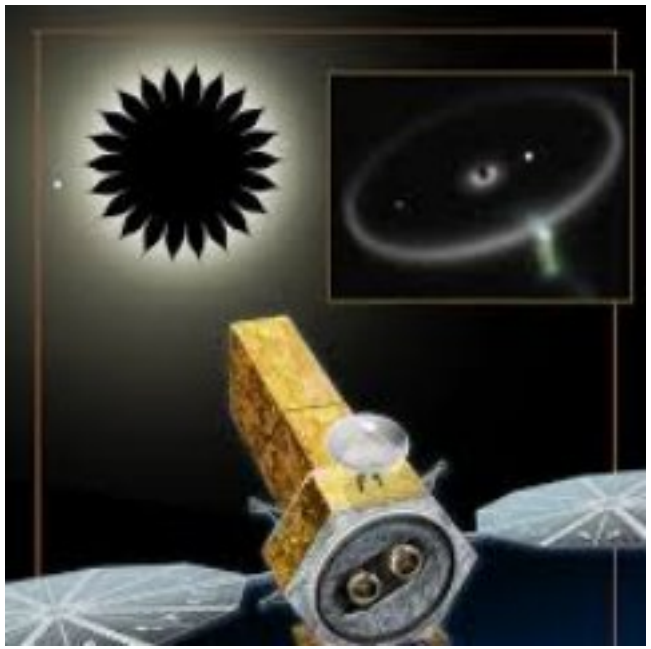
High contrast imager for Complex Aperture Telescopes (HiCAT)

HiCAT is specifically for space telescopes that will have segments, secondary mirrors supports and other complex apertures

- Currently being built for LUVOIR architectures but could also be used for some HABEX architectures
- Includes a **Apodized Pupil Lyot Coronagraph (APLC)**
- Uses a variety of **Deformable Mirrors (DMs)** to actively control the suppression of light and wavefront variations

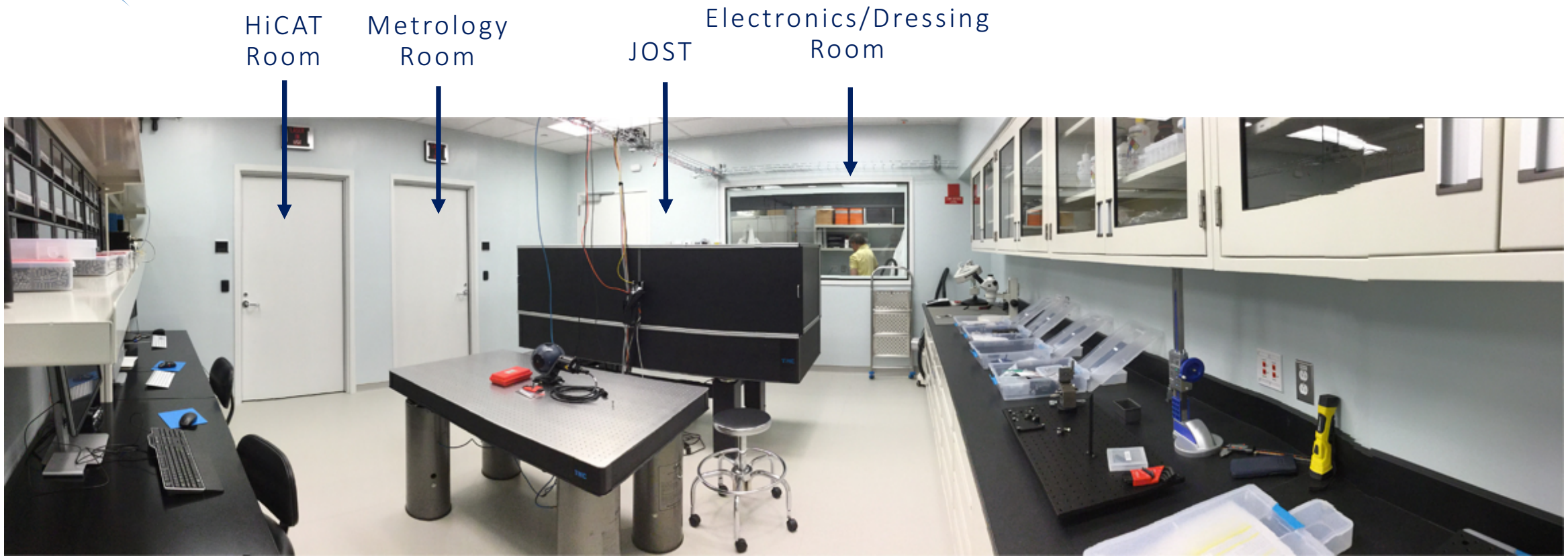


NASA



NASA

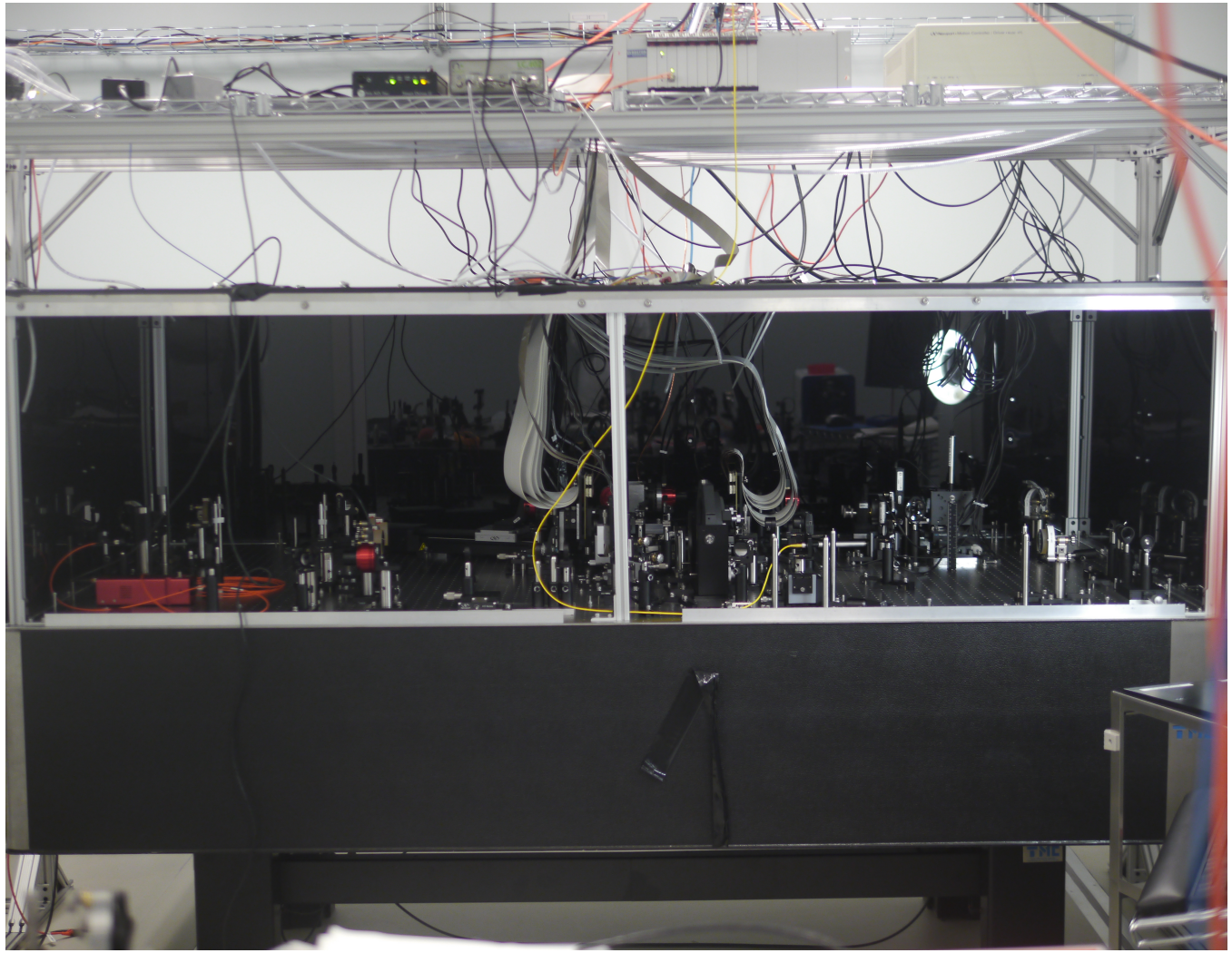
Lab Facilities



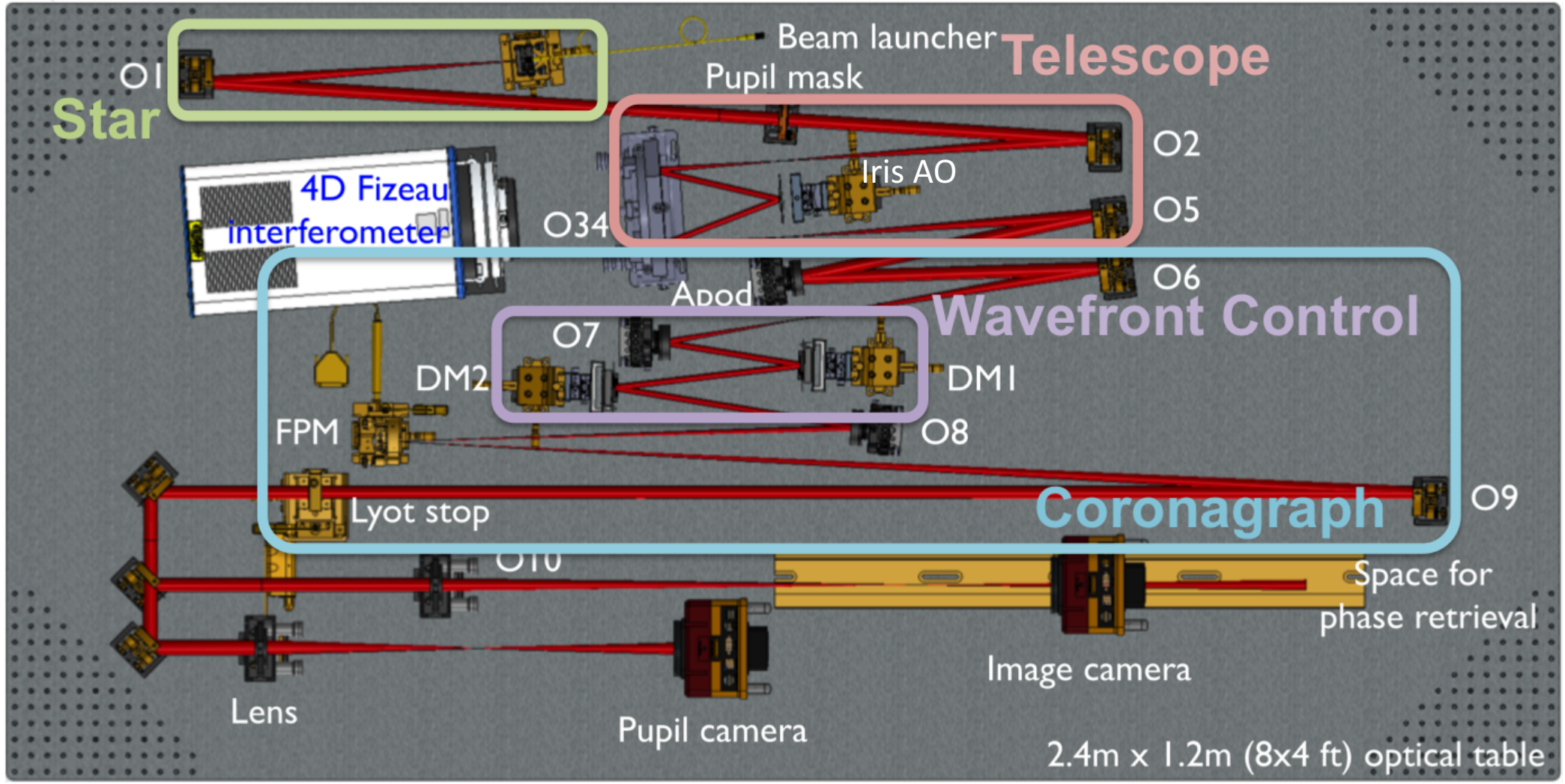
Lab blog: http://stsci-makidon-optics-lab.blogspot.com

Class 10000/1000 cleanrooms → bunny suits!

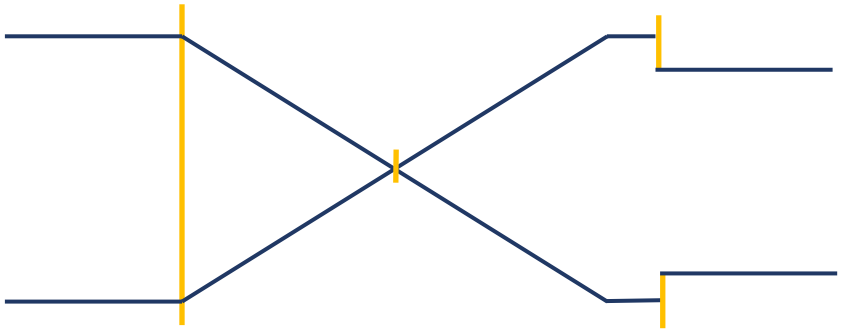
High contrast imager for Complex Aperture Telescopes (HiCAT)



HiCAT

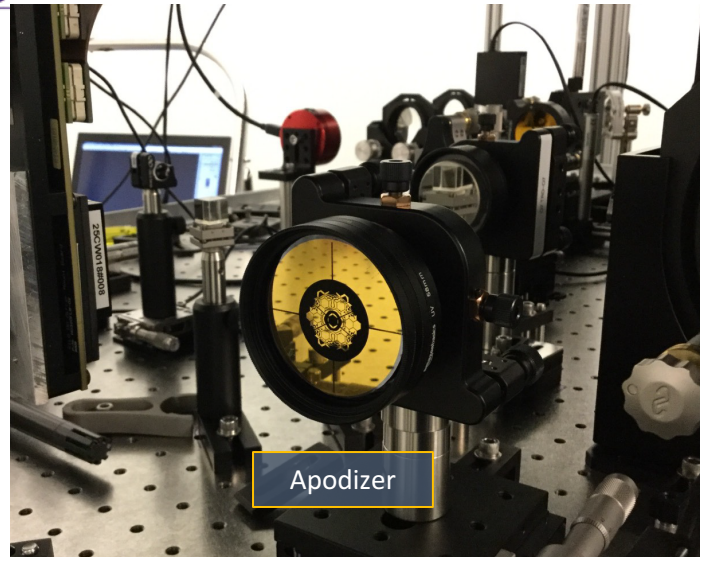

Beam launcher
Telescope
Pupil mask
O1
Star
O2
Iris AO
4D Fizeau
interferometer
O34
O5
O6
Apod
Wavefront Control
O7
DM2
DM1
FPM
O8
Lyot stop
Coronagraph
O9
O10
Space for
phase retrieval
Image camera
Lens
Pupil camera
2.4m x 1.2m (8x4 ft) optical table

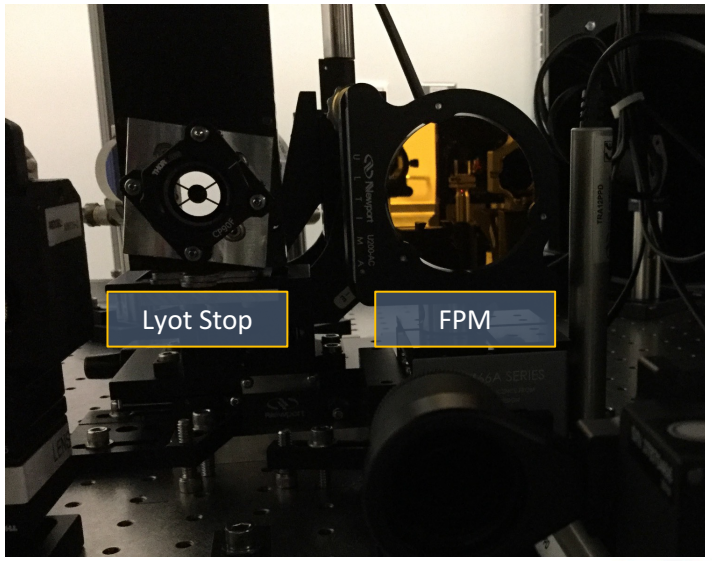
HiCAT – The Coronagraph: APLC



"… the solution is the pupil apodization which produces the most concentrated star light behind a given focal plane mask (and thus blocked)" – Soummer et al. 2004

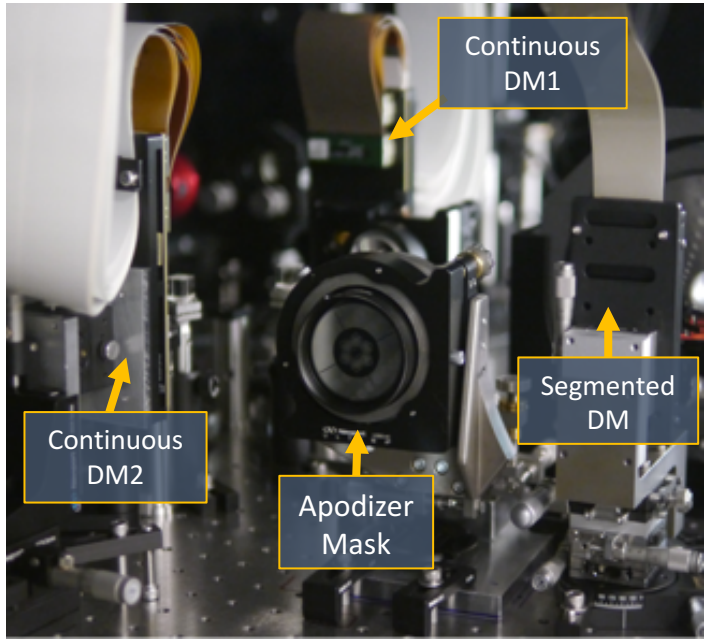
HiCAT – The Coronagraph + Wavefront Control/Speckle Suppression

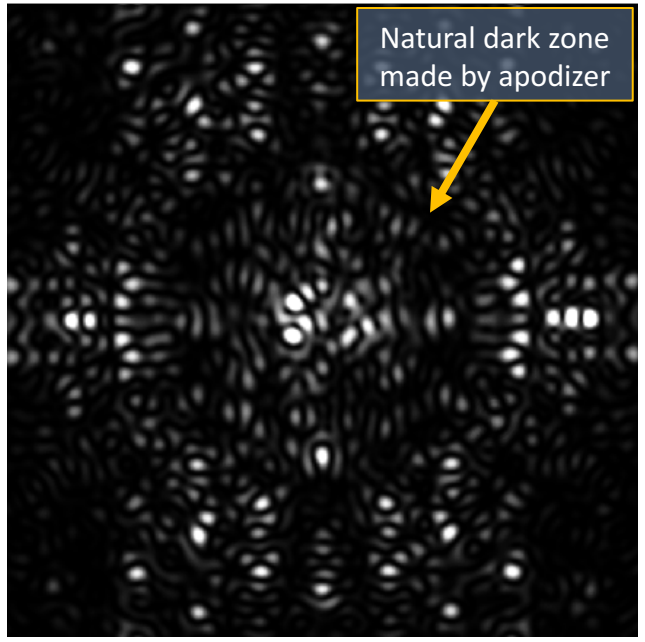


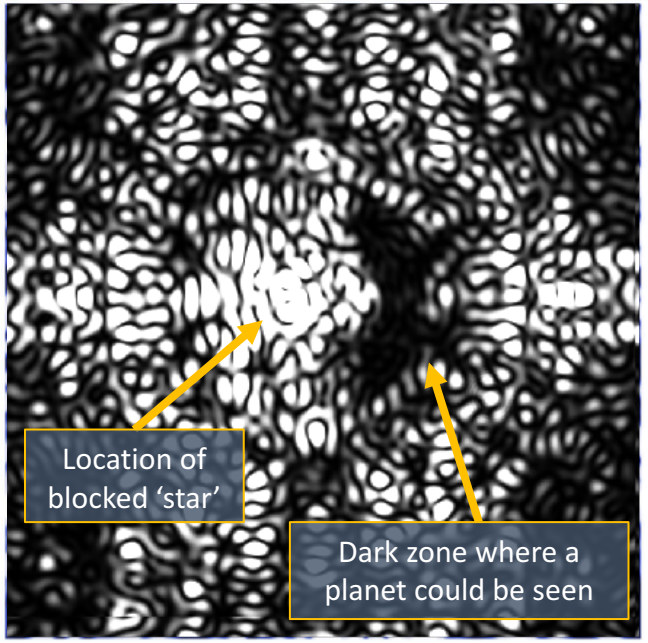


- Flexible swapping of components (apodizer, FMP, DMs) ~1 day with recalibration
- Ready for integration of different dark hole digging techniques: e.g. speckle nulling, EFC
- WFS&C: COFFEE, OPeRA

same view







Current contrast: 10^{-6}

Upcoming work on HiCAT

For 10^{-10} contrast, we need **10-100 pm wavefront residual:**

- Demonstrate **sub-nm phasing of segments** with coronagraphic wavefront sensors: COFFEE, pair-wise

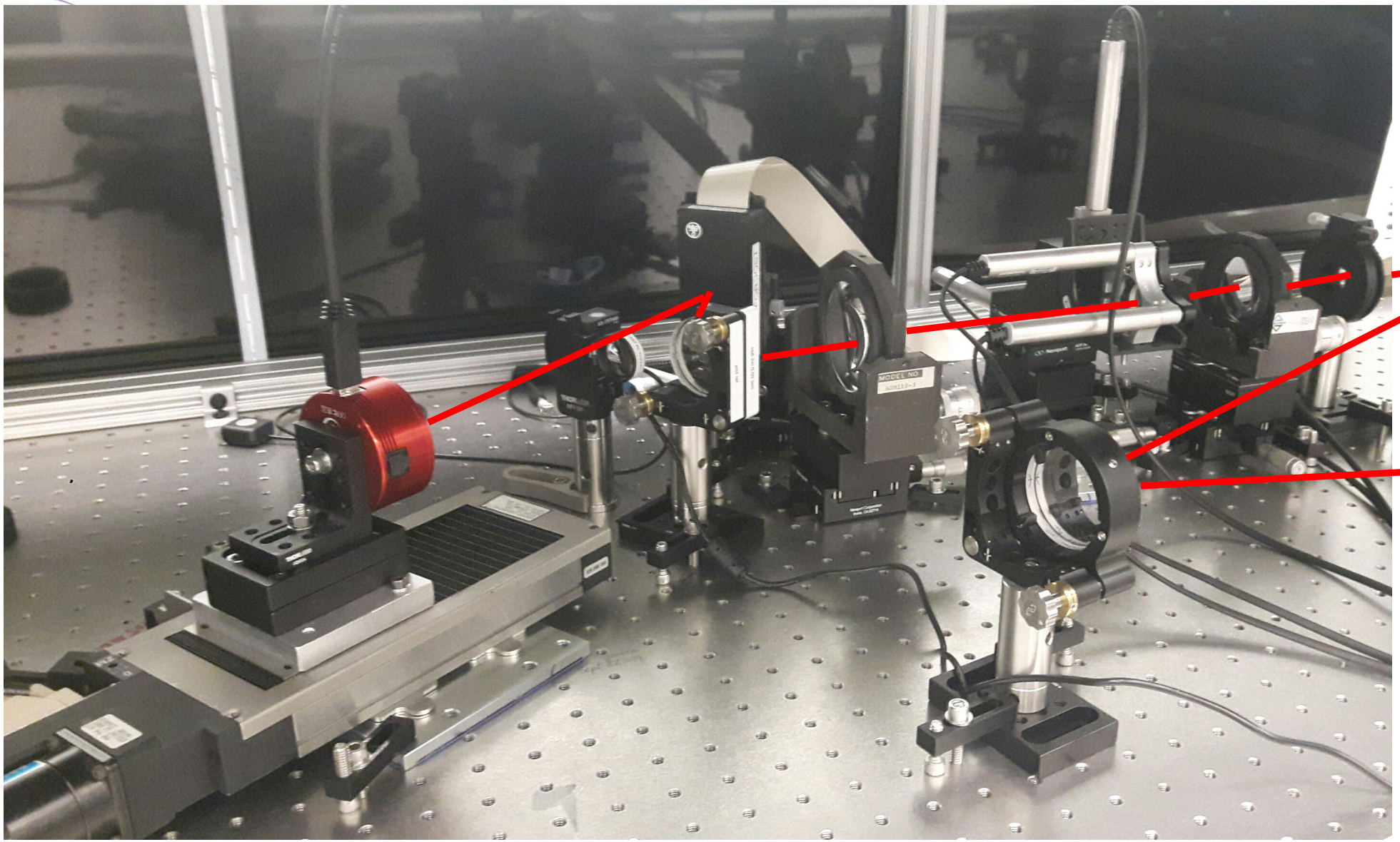
- Improving the **dark hole contrast** with nulling methods: electric field conjugation (EFC), speckle nulling, non-linear dark hole

Wavefront sensing and control for segmented apertures: James Webb Space Telescope Optical Simulation Testbed - JOST

JWST Optical Simulation Testbed (JOST)

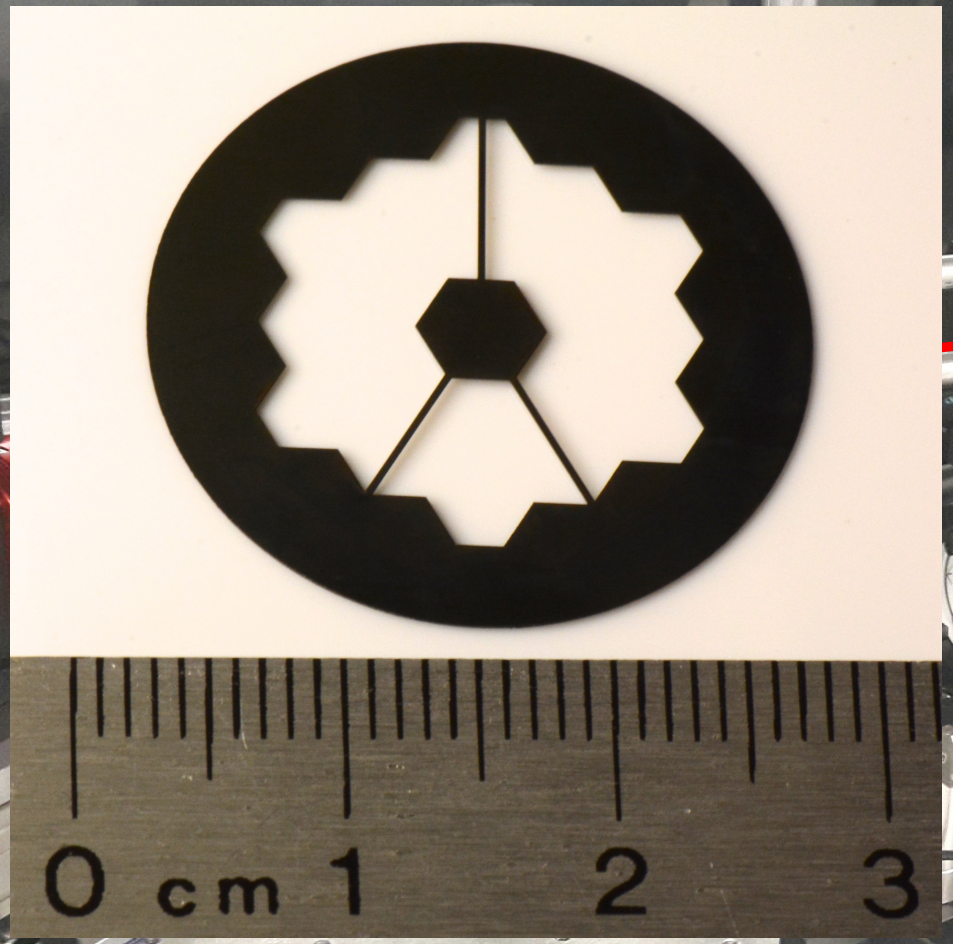
→ Wavefront sensing and control for segmented apertures

JWST Optical Simulation Testbed (JOST)



JWST-like pupil

- Laser cut pupil mask of JWST pupil
- Struts are about 200 microns wide
- Conjugated with Iris AO segmented mirror
- Limits the Iris AO to the 19 segments we need for JWST optical simulation

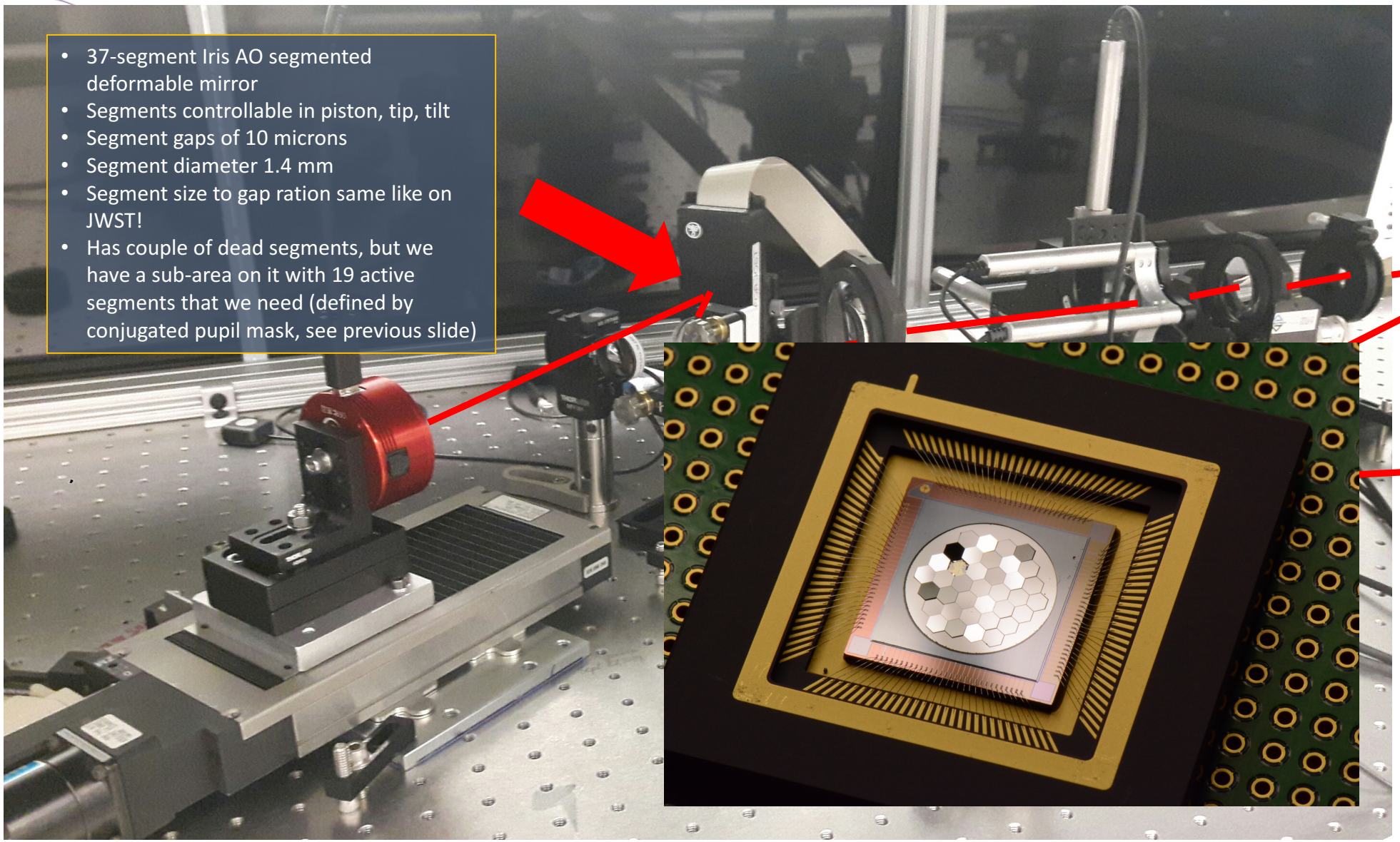


Motorized steering mirror

Laser input 638 nm

Segmented mirror

- 37-segment Iris AO segmented deformable mirror
- Segments controllable in piston, tip, tilt
- Segment gaps of 10 microns
- Segment diameter 1.4 mm
- Segment size to gap ration same like on JWST!
- Has couple of dead segments, but we have a sub-area on it with 19 active segments that we need (defined by conjugated pupil mask, see previous slide)

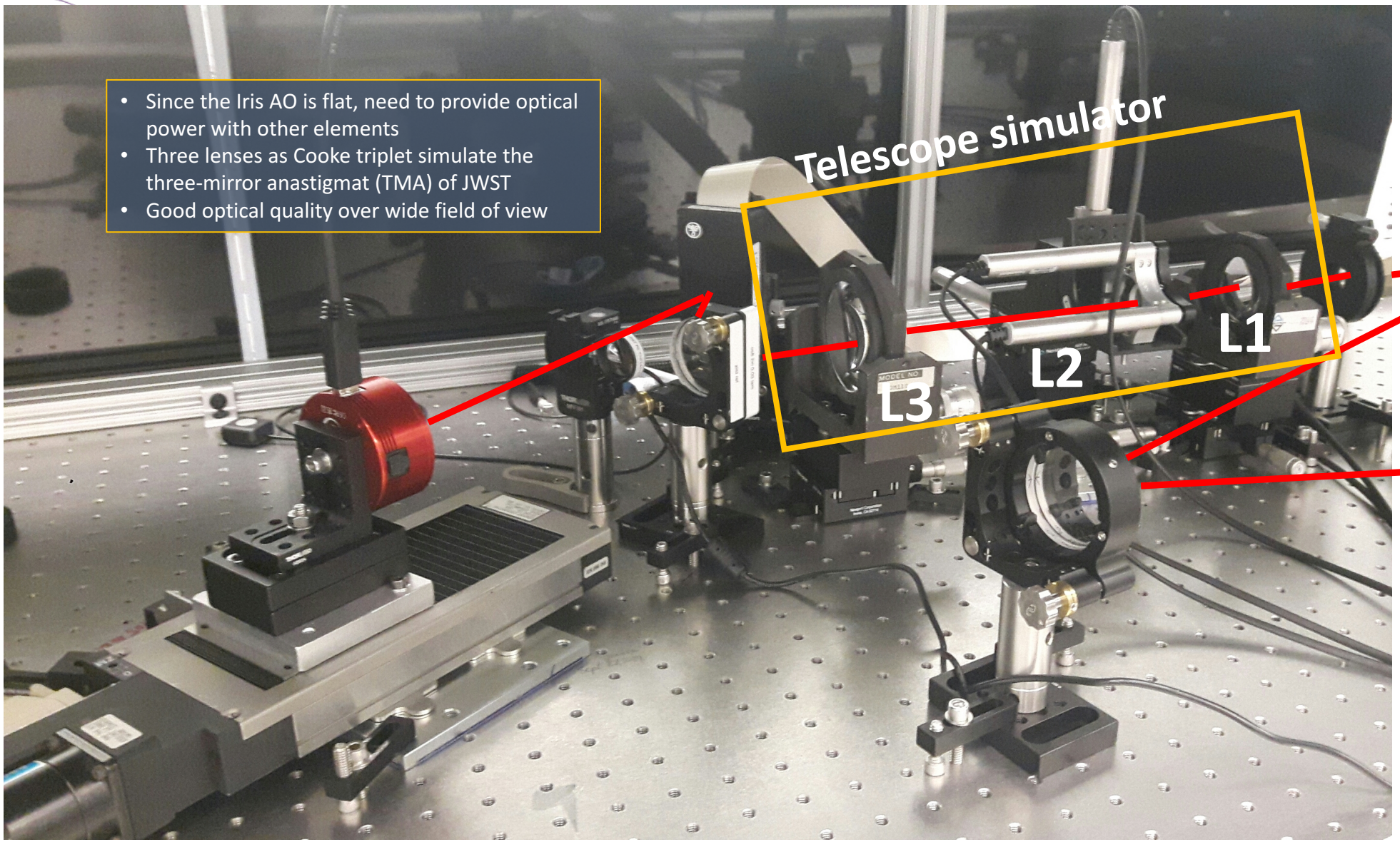


Motorized steering mirror

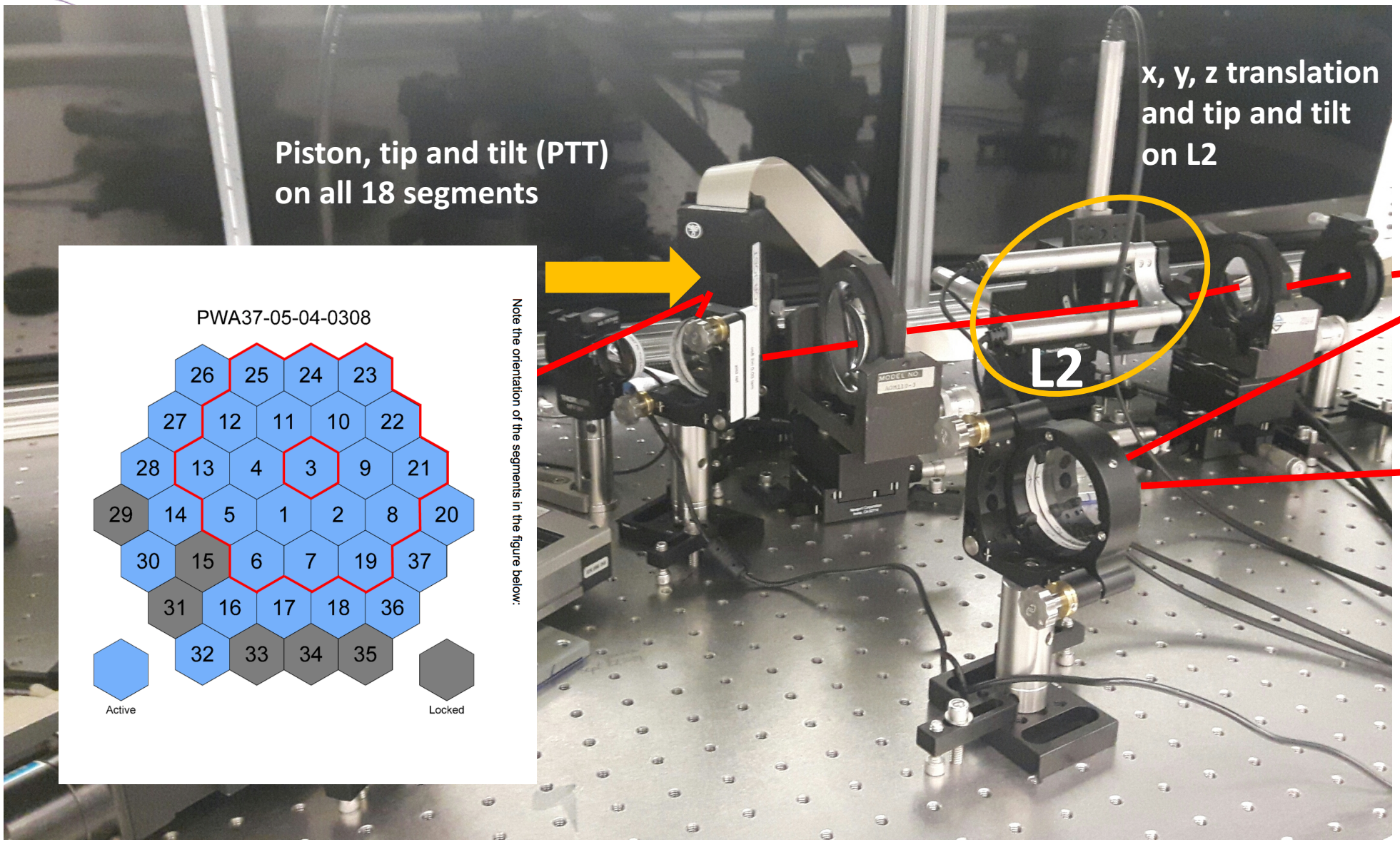
Laser input 638 nm

Telescope simulator

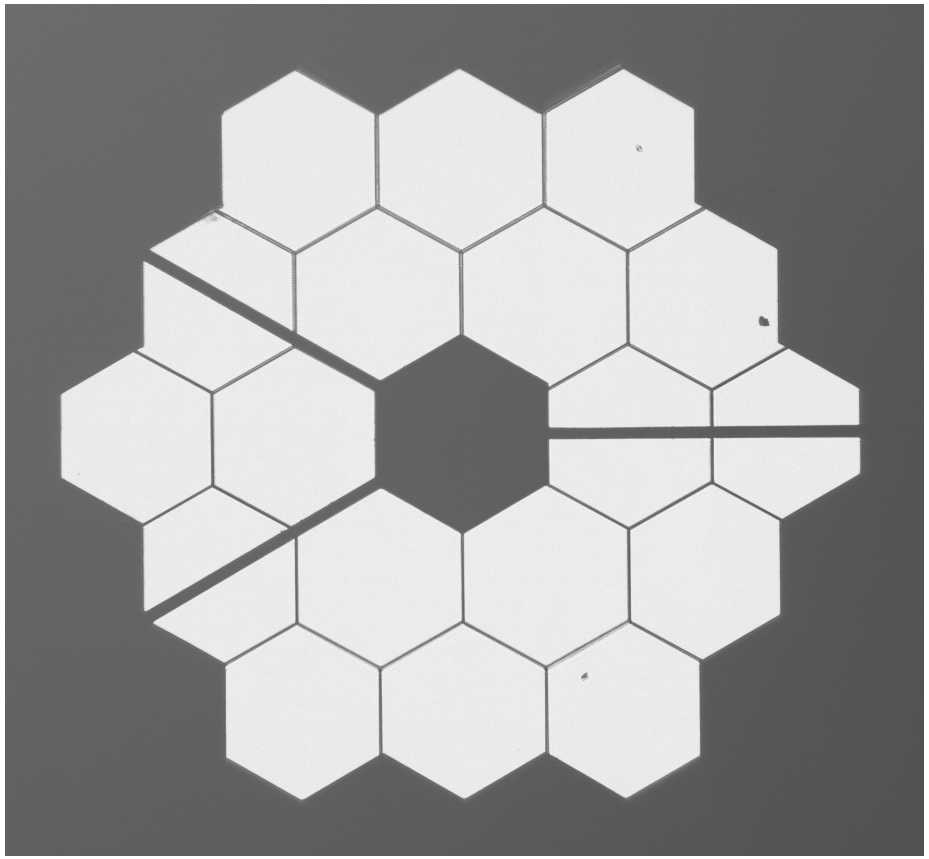
- Since the Iris AO is flat, need to provide optical power with other elements
- Three lenses as Cooke triplet simulate the three-mirror anastigmat (TMA) of JWST
- Good optical quality over wide field of view



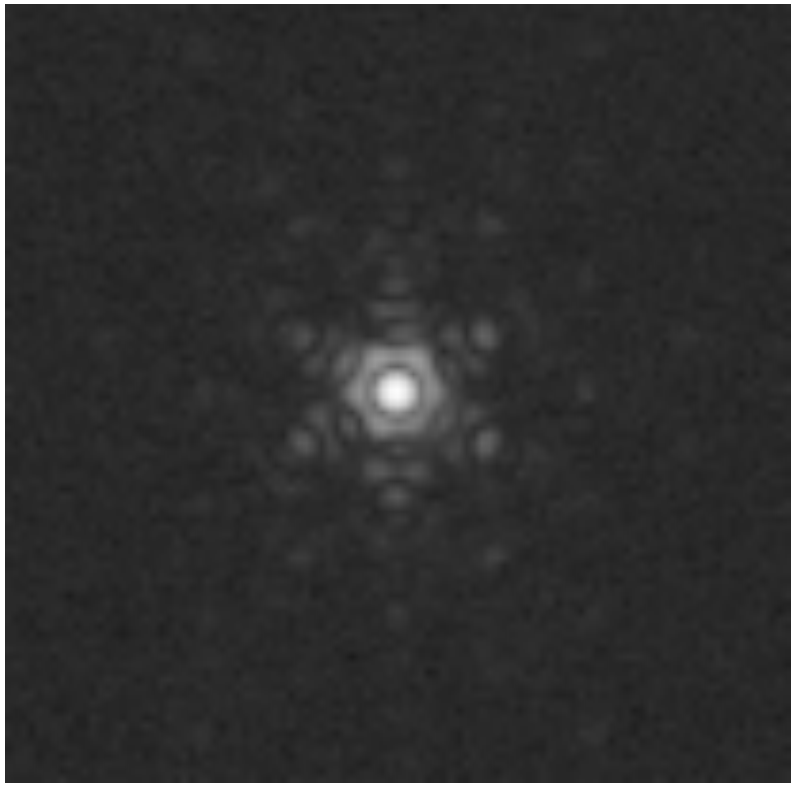
Total degrees of freedom of JOST = 59 vs. JWST = 131



JOST aligned images



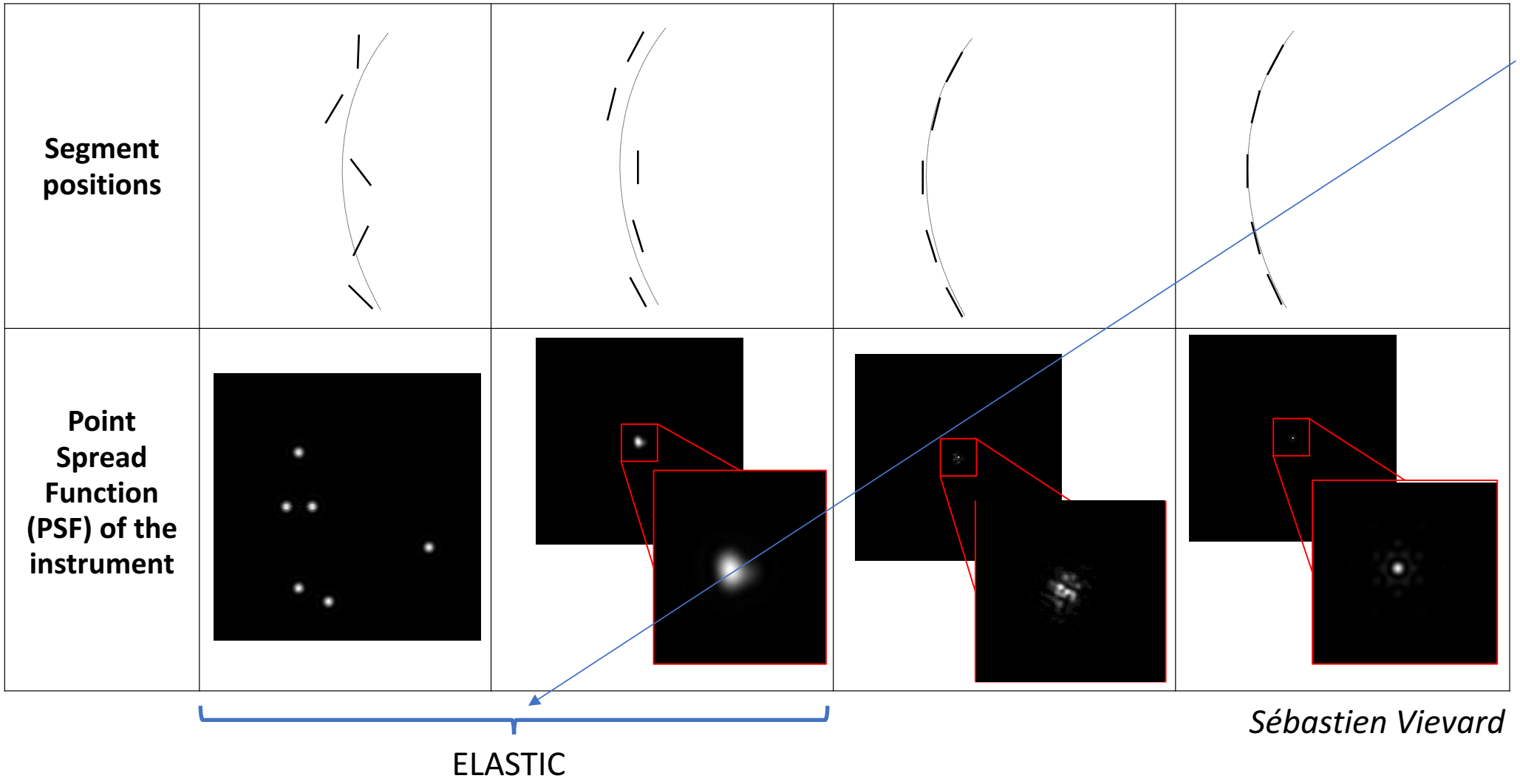
JOST pupil image



JOST focal plane image

PSF stacking:
Estimation of Large Amplitude Subaperture Tip-tilt by Image Correlation - ELASTIC

Alignment of a segmented telescope



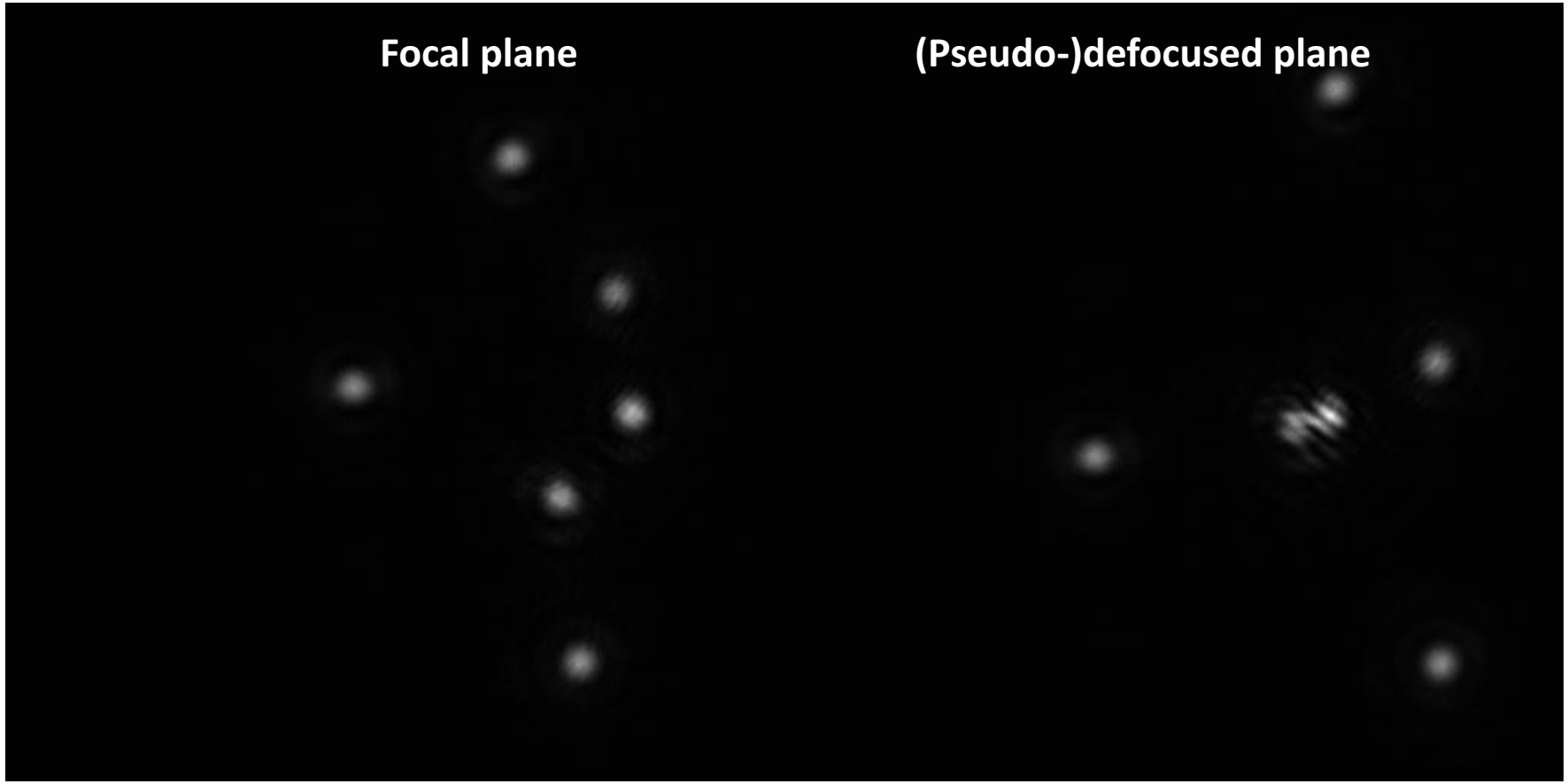
First step: geometrical alignment mode, bringing PSF in capture range of fine-phasing solutions

JWST uses temporal modulation for this – wiggling one segment at a time

On first light they predict to only have 1-2 segments visible on NIRCam

Alignment of a segmented telescope

- ELASTIC: PSF stacking in one single step with **image correlation**
- PhD thesis Sebastien Vievard at ONERA
- Publications: Vievard et al. 2016 (SPIE), 2017 (JOSAA)



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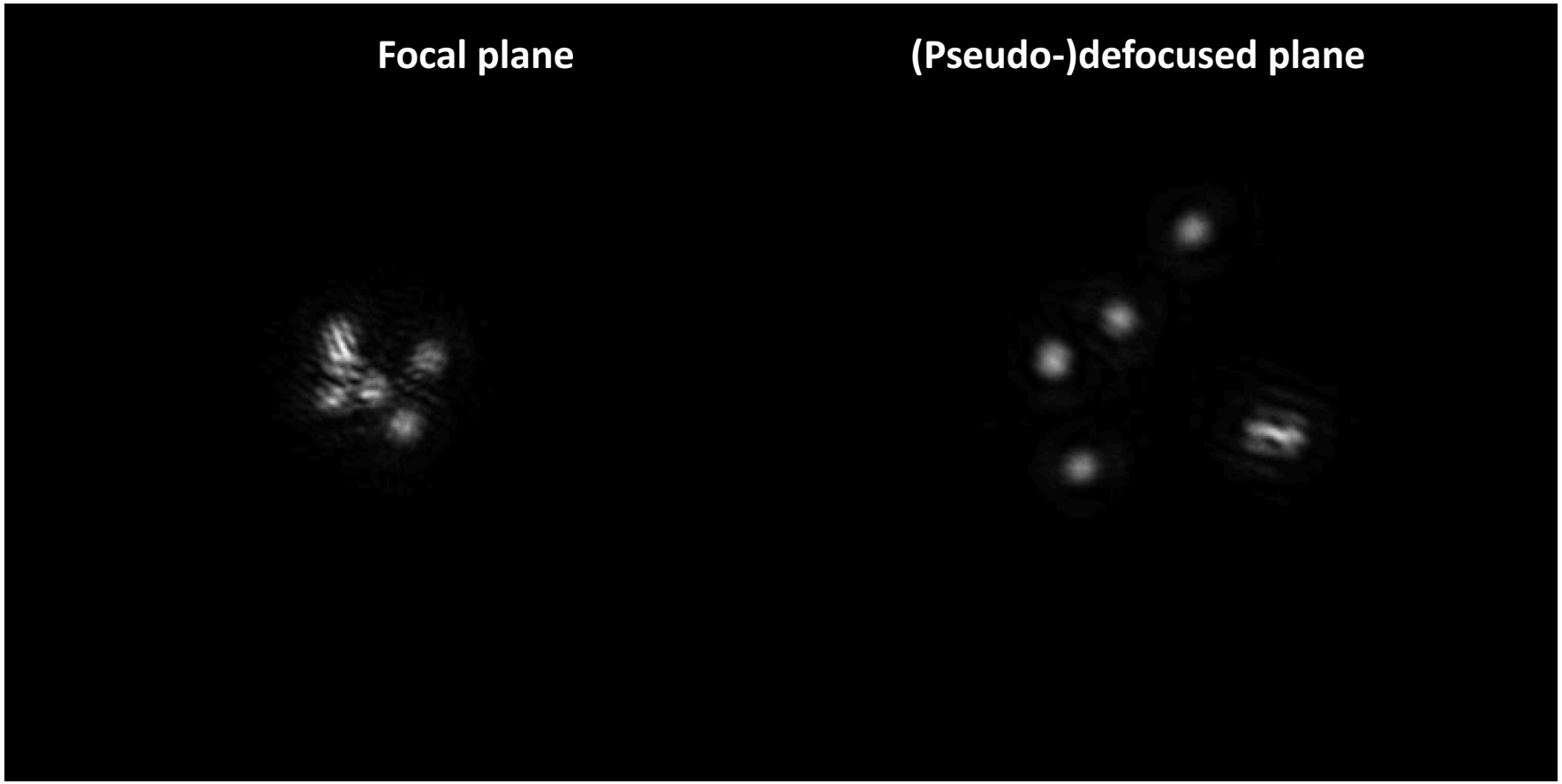

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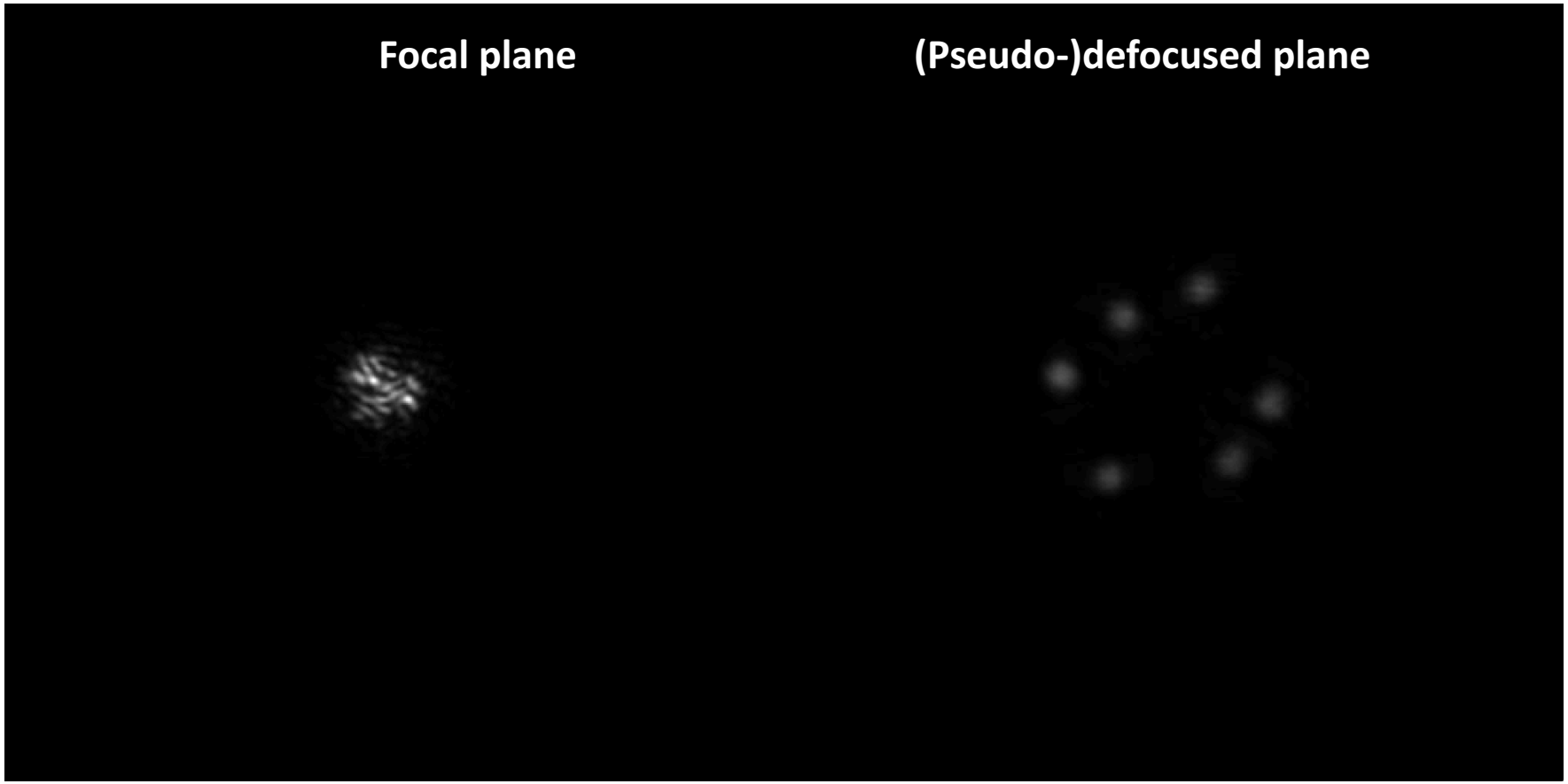

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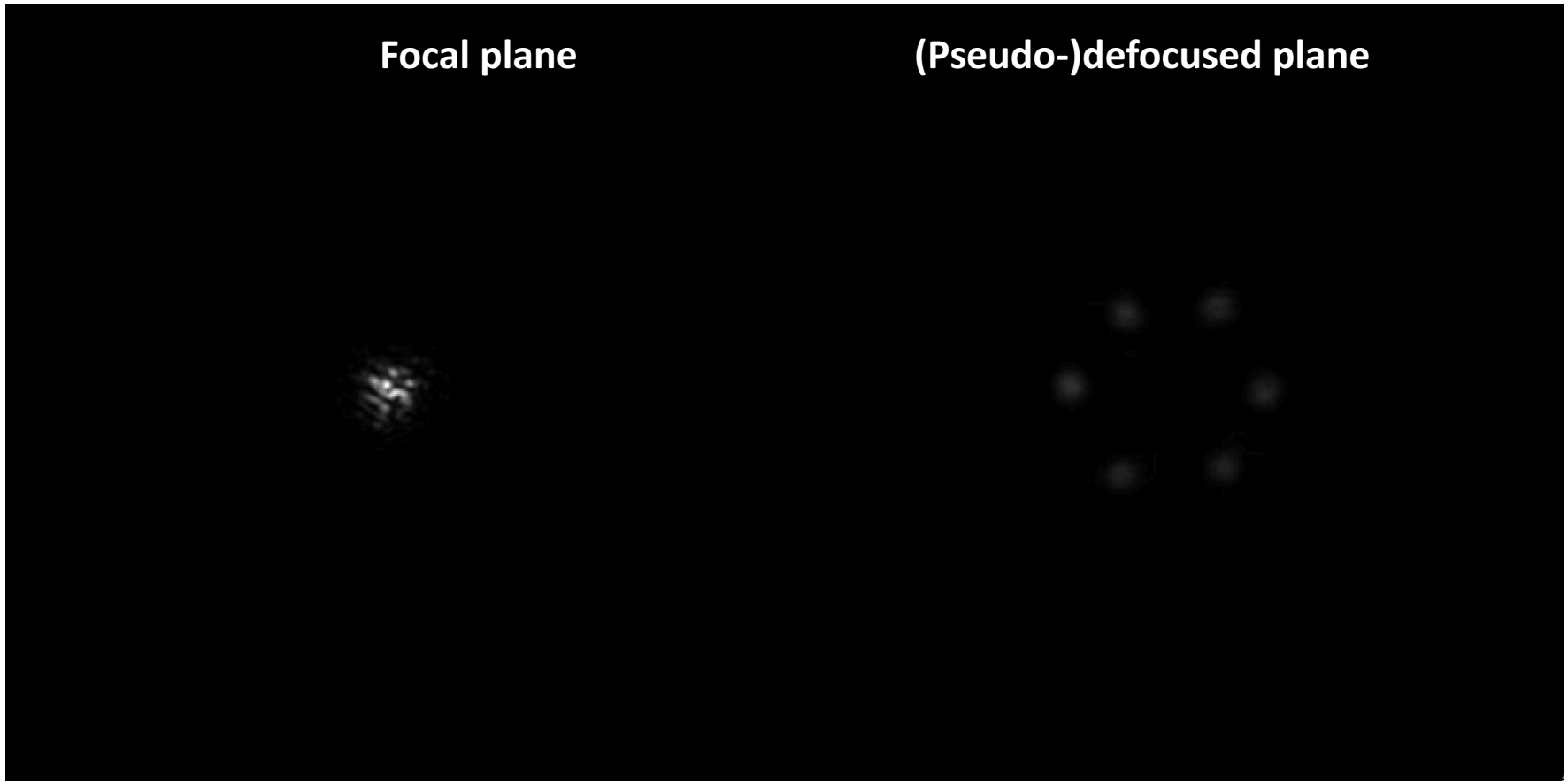

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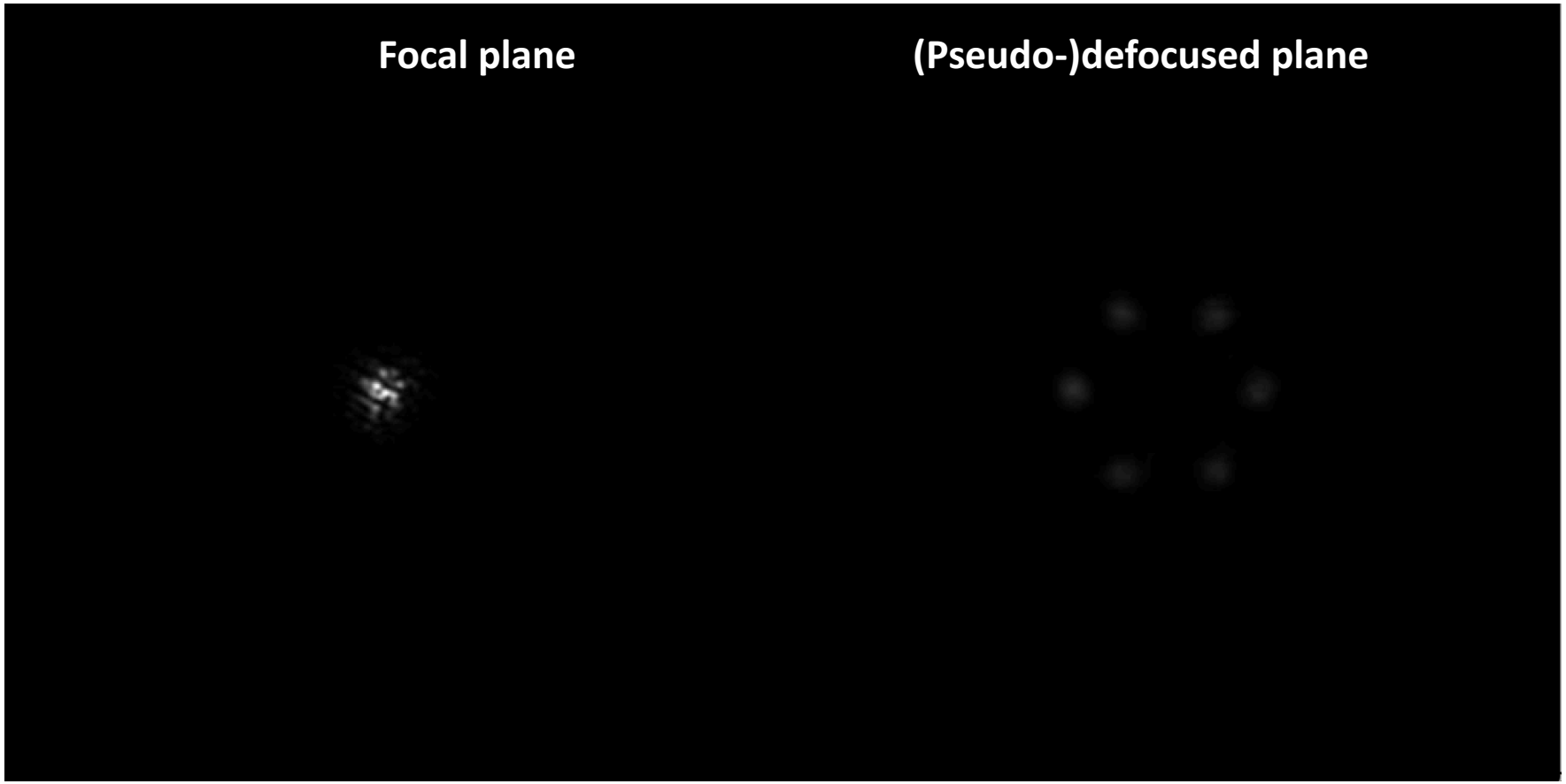

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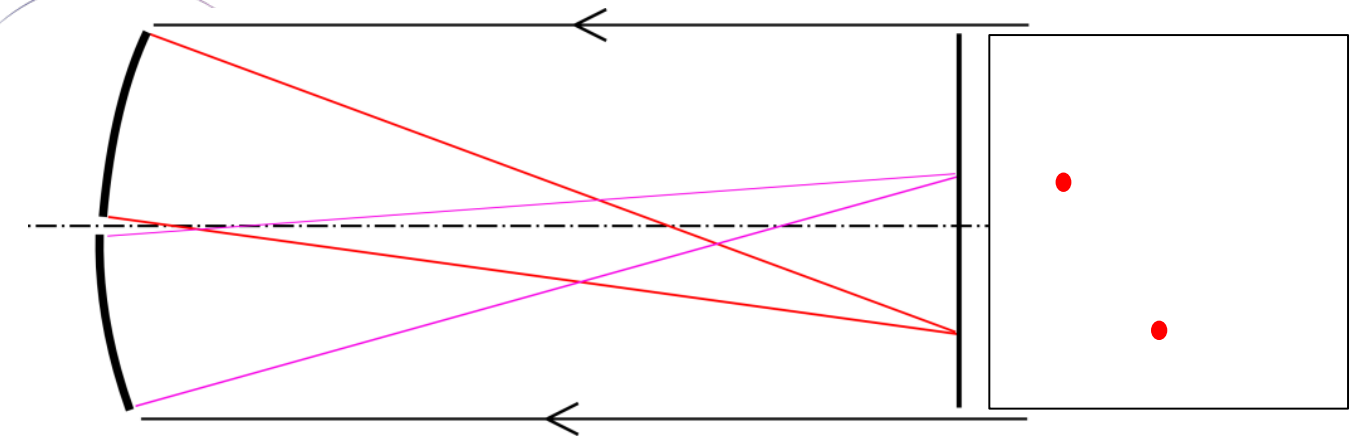
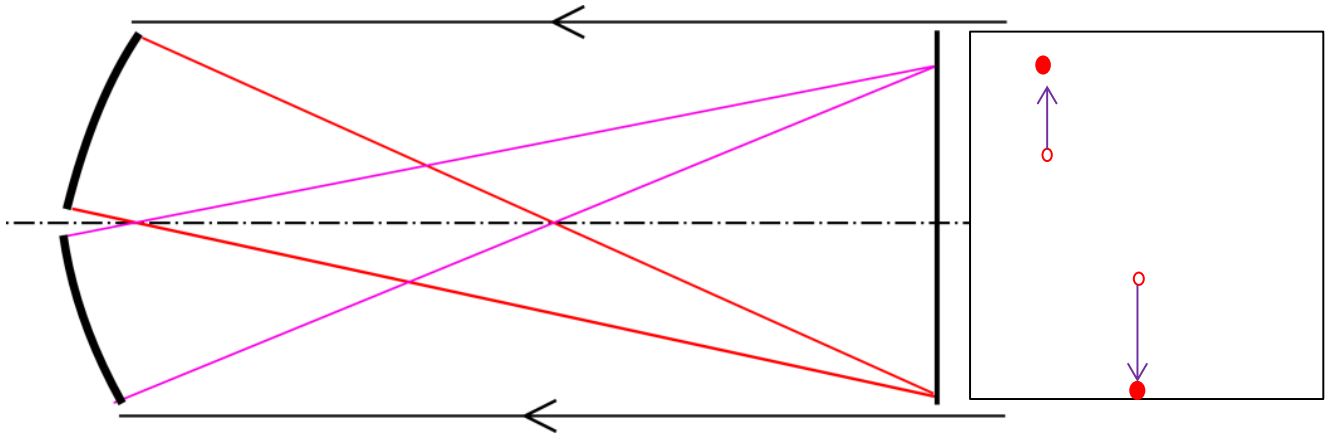
PSF stacking with ELASTICS



Focus image



(Pseudo-)defocused image: approximating a global defocus by local segment-level tips and tilts
→ Distinguishable shifts of sub-PSFs

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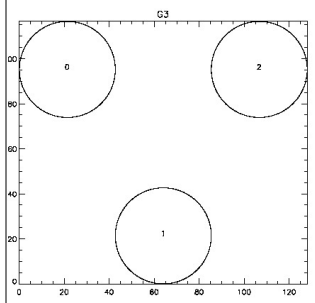
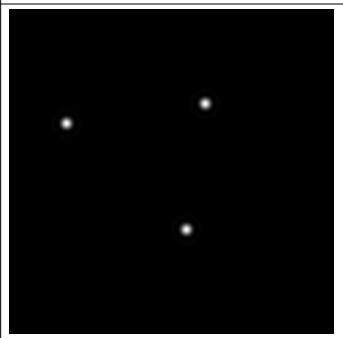
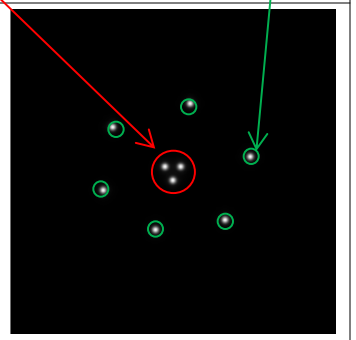
PSF stacking with ELASTIC

Image correlation of focus and defocus image:

→ N_a^2 correlation terms = N_a **auto-terms** + $N_a (N_a - 1)$ **inter-terms**

Pupil	Focus image	Defocus image	Correlation
			

Inter-terms change with **aberration**

Auto-terms change with **diversity**

→ **Make aberration info show up in auto-terms?**

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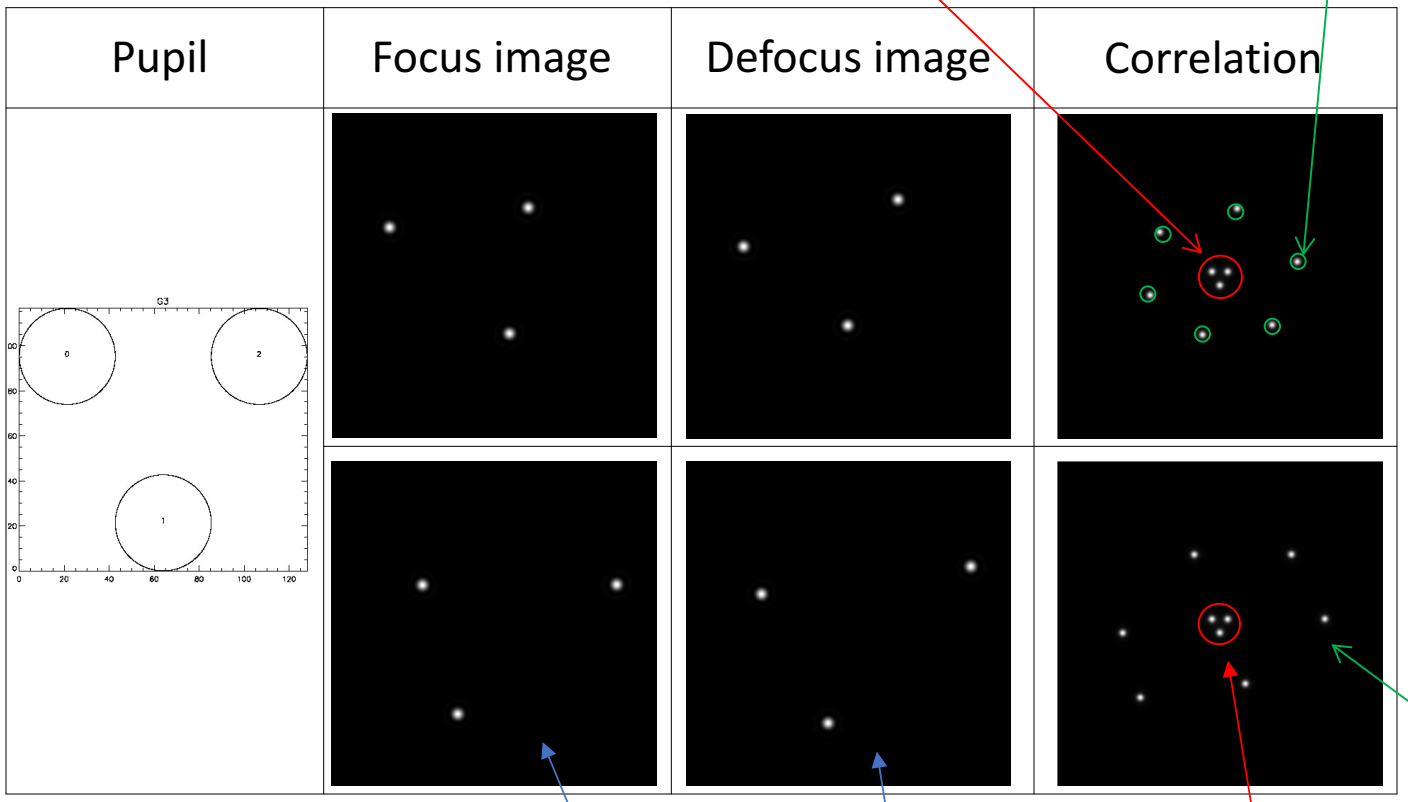
PSF stacking with ELASTIC

Image correlation of focus and defocus image:

→ N_a^2 correlation terms = N_a **auto-terms** + $N_a(N_a-1)$ **inter-terms**



Inter-terms change with **aberration**

Auto-terms change with **diversity**

→ **Make aberration info show up in auto-terms?**

Inter-terms change

Different aberration

Auto-terms the same

Same diversity

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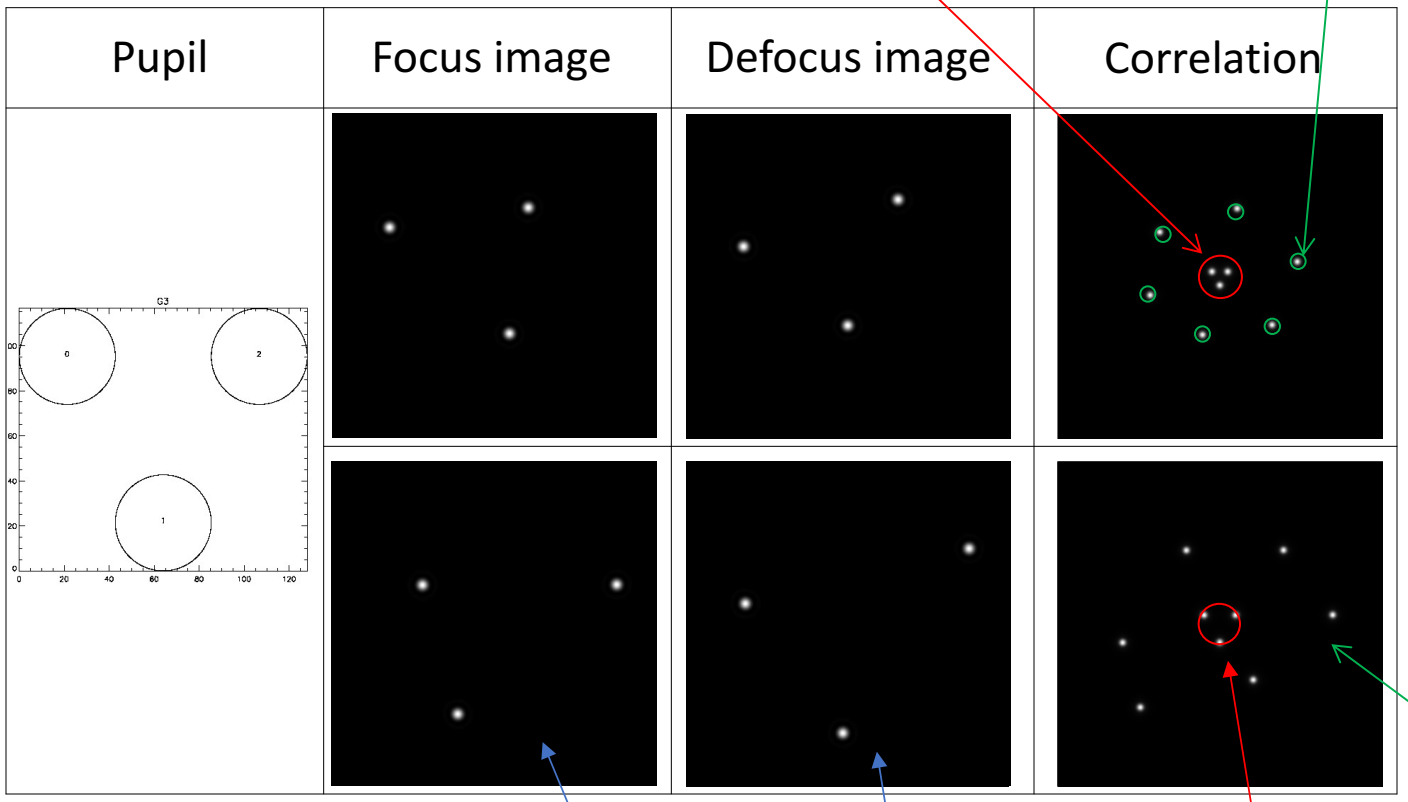
PSF stacking with ELASTIC

Image correlation of focus and defocus image:

→ N_a^2 correlation terms = N_a **auto-terms** + $N_a(N_a-1)$ **inter-terms**



Inter-terms change with **aberration**

Auto-terms change with **diversity**

→ **Make aberration info show up in auto-terms?**

Inter-terms already changed

Different aberration

Auto-terms change!

Different diversity

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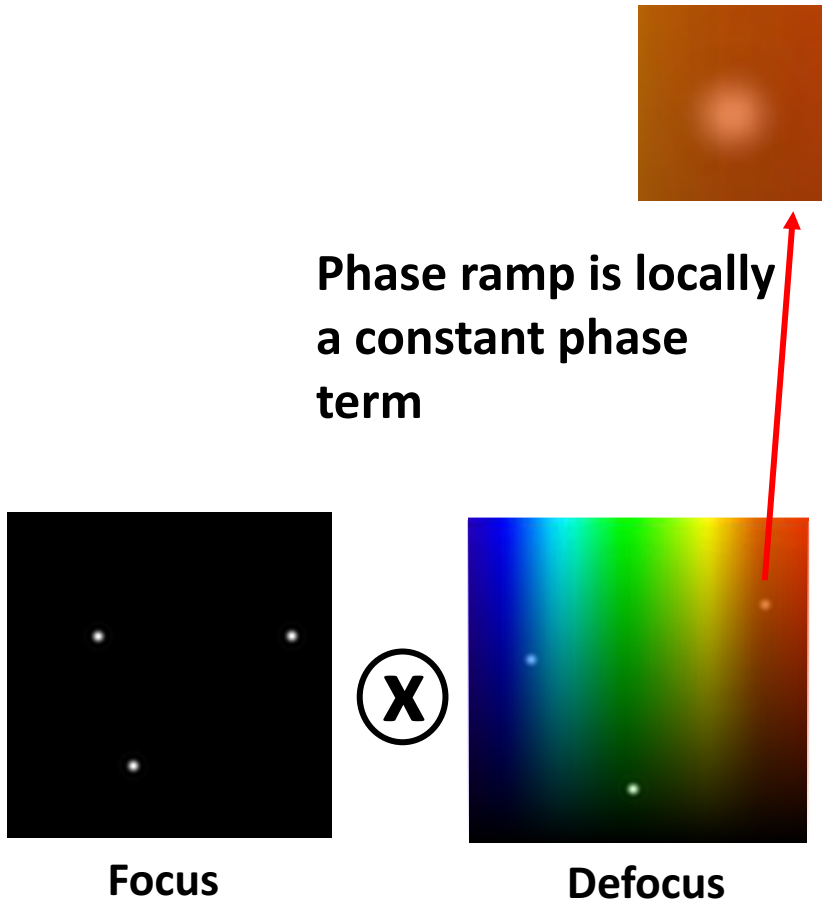
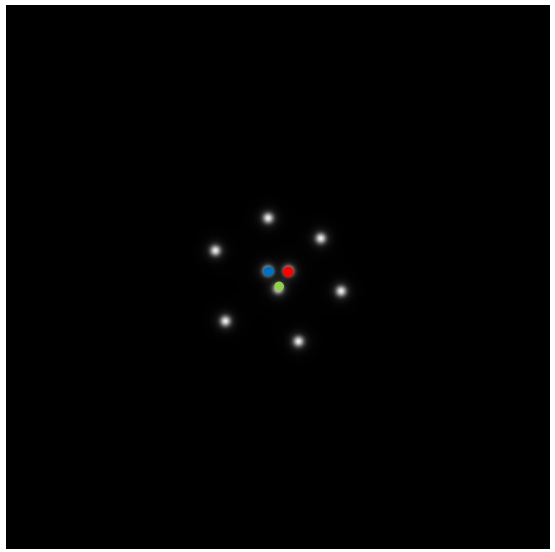
PSF stacking with ELASTIC



This local phase constant can be used to connect auto-terms with according segments



(We ignore the inter-terms)

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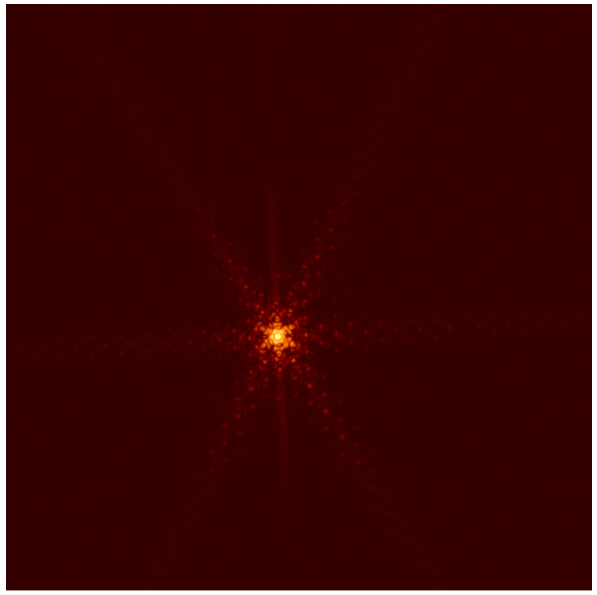
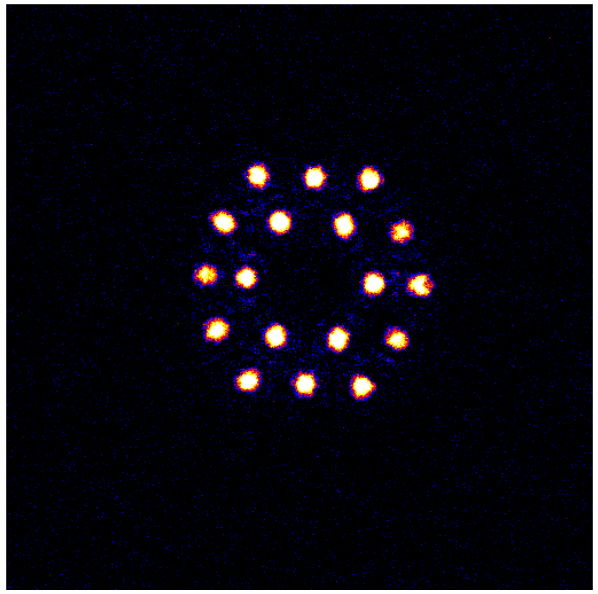
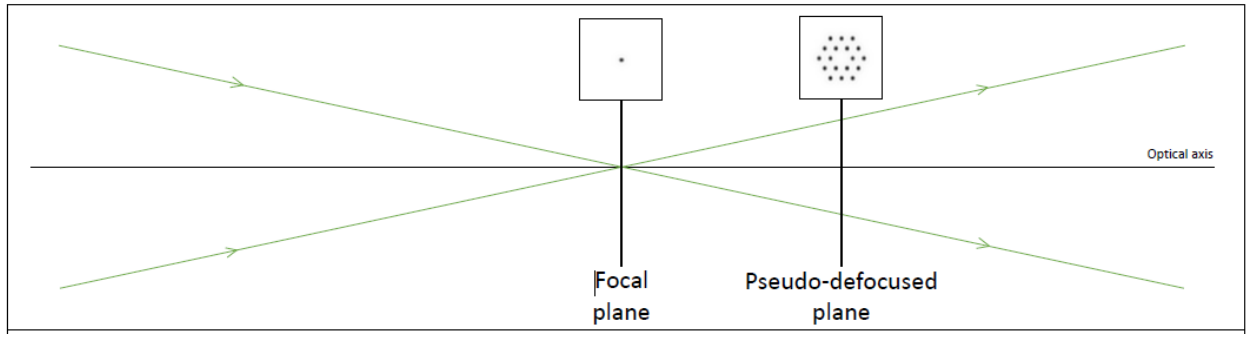
ELASTIC on JOST



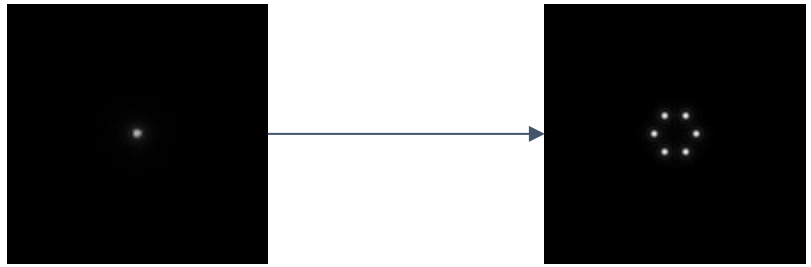




- **Limited by segmented mirror stroke**
- **Introduced “hybrid defocus” → global defocus by camera shift and pseudo-defocus with mirror segments**
- **Global defocus supports getting sub-PSFs apart, but it also smears them out**

ELASTIC on JOST

Test: Can we go from superimposition to “parking position”?



ELASTIC on JOST

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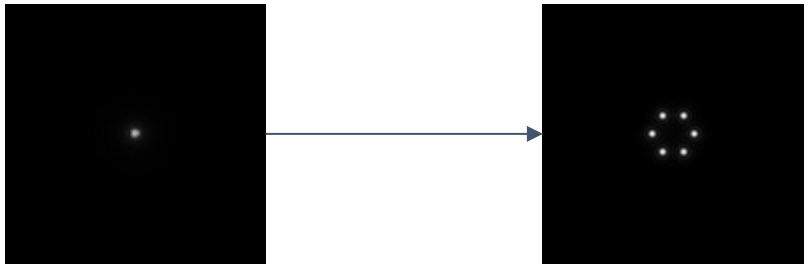
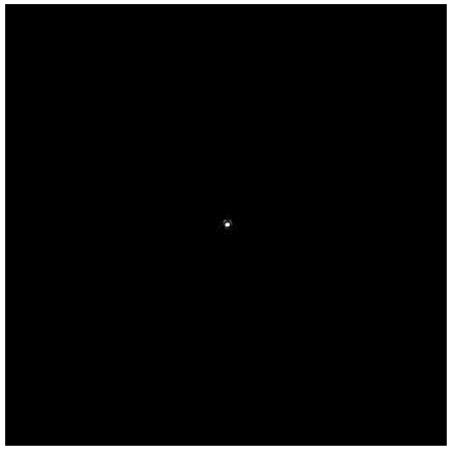
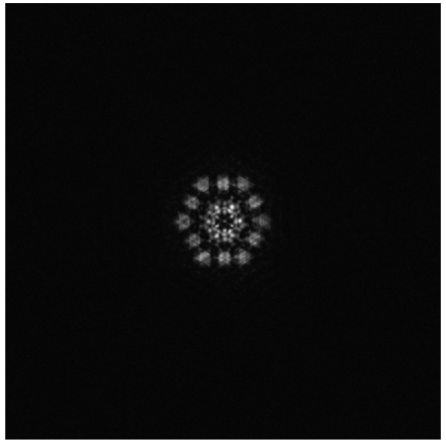
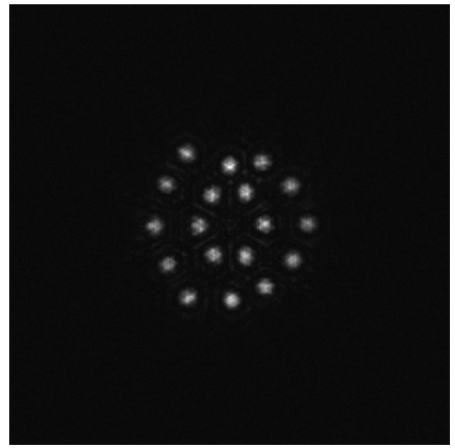




Iteration 1



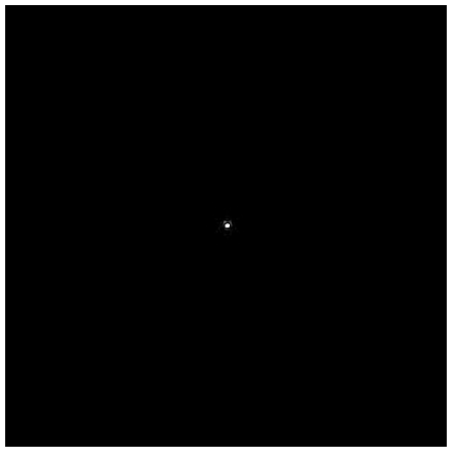
Iteration 2



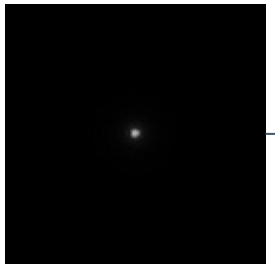
Iteration 5

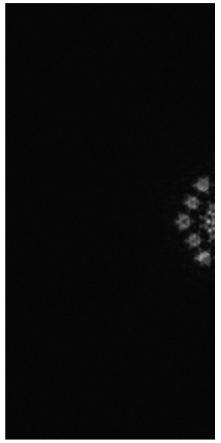
ELASTIC on JOST

Test: Can we go from superimpos

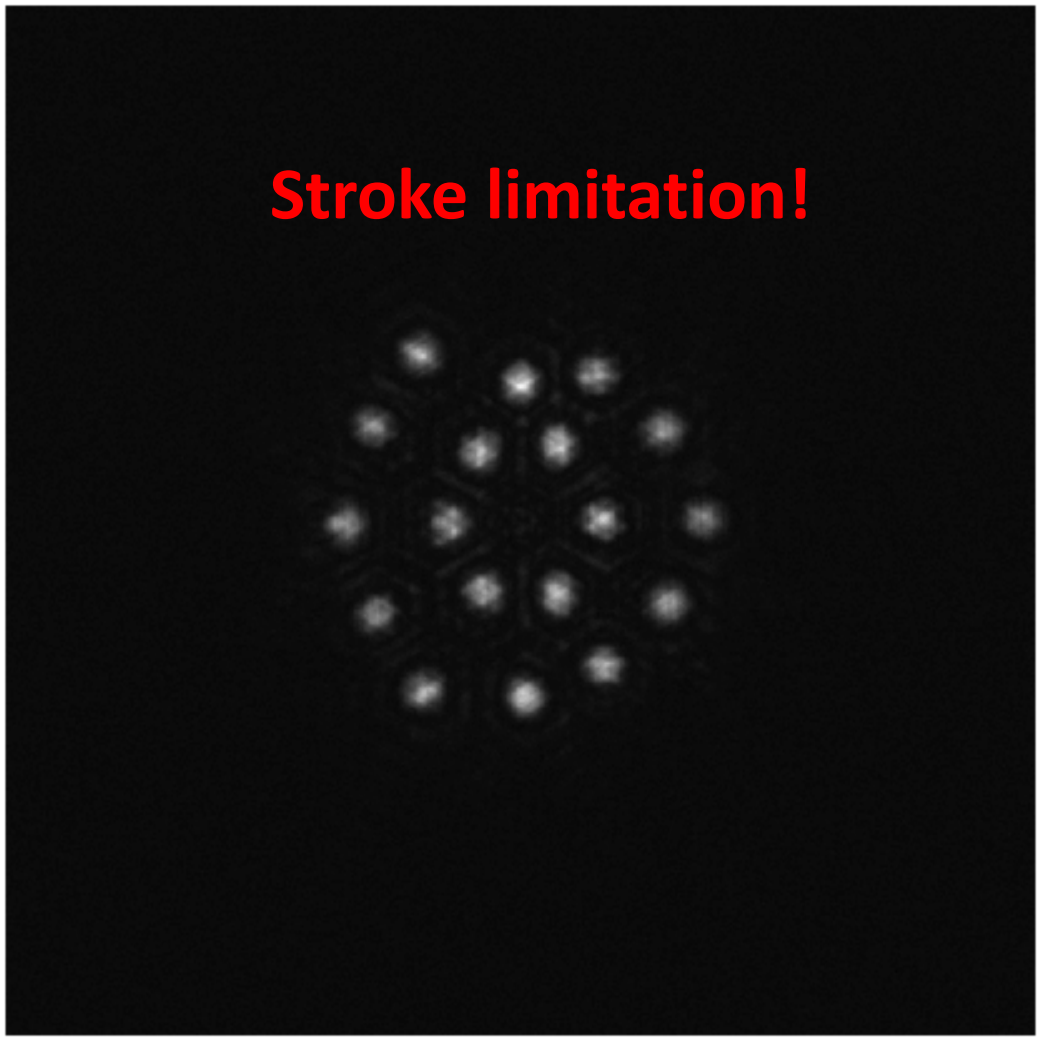


Iteration 1





Iteration 2



Iteration 5

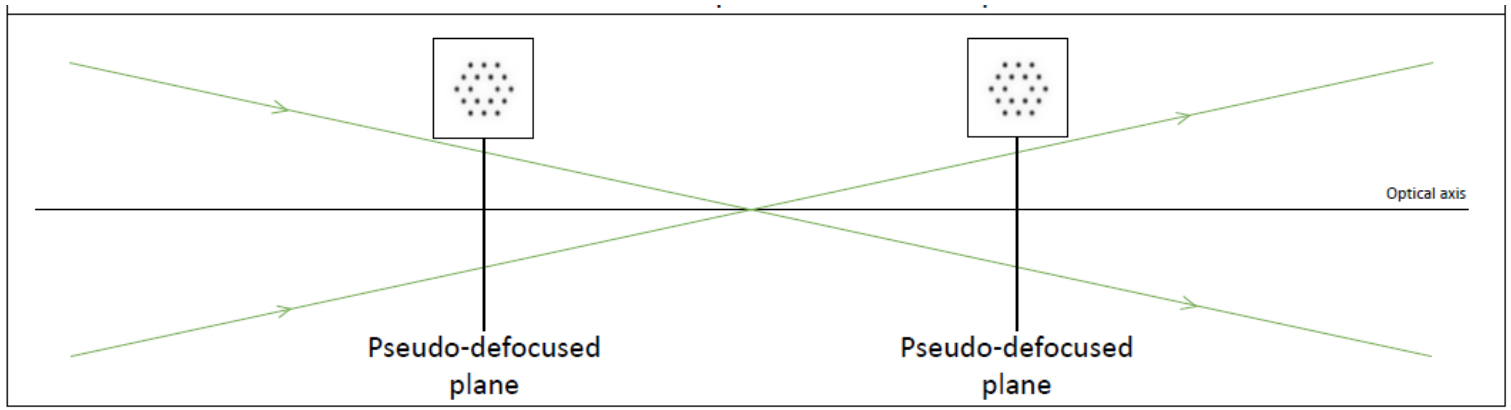
ELASTIC on JOST

Test: Can we go from superimposition to “parking position”?
→ Nope.

ELASTIC on JOST

Test: Can we go from superimposition to “parking position”?
→ Nope.

Solution: enhance ELASTIC → ELASTICS
→ Make use of the inter-terms in image correlation
→ Won’t need the big parking position that uses up all the stroke



Summary

- **HiCAT and JOST are versatile testbeds for WFS&C and high contrast imaging for segmented telescopes**
- **ELASTIC facing difficulties on JOST because of limited segmented mirror stroke**
- **Implementation of enhanced ELASTICS underway**