

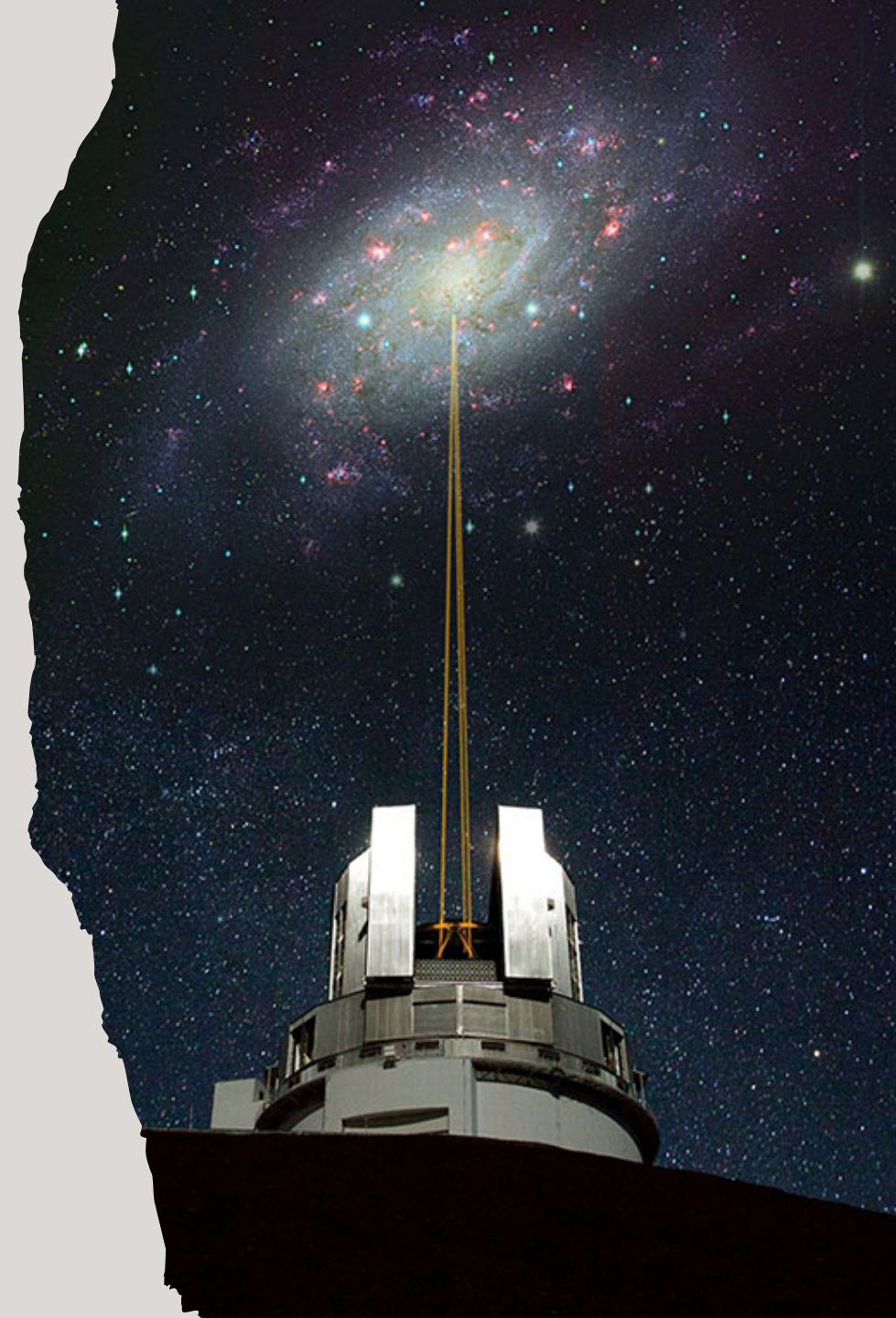


Focal Plane Wavefront Control using Reinforcement Learning for High-Contrast Imaging

Iremsu Taskin

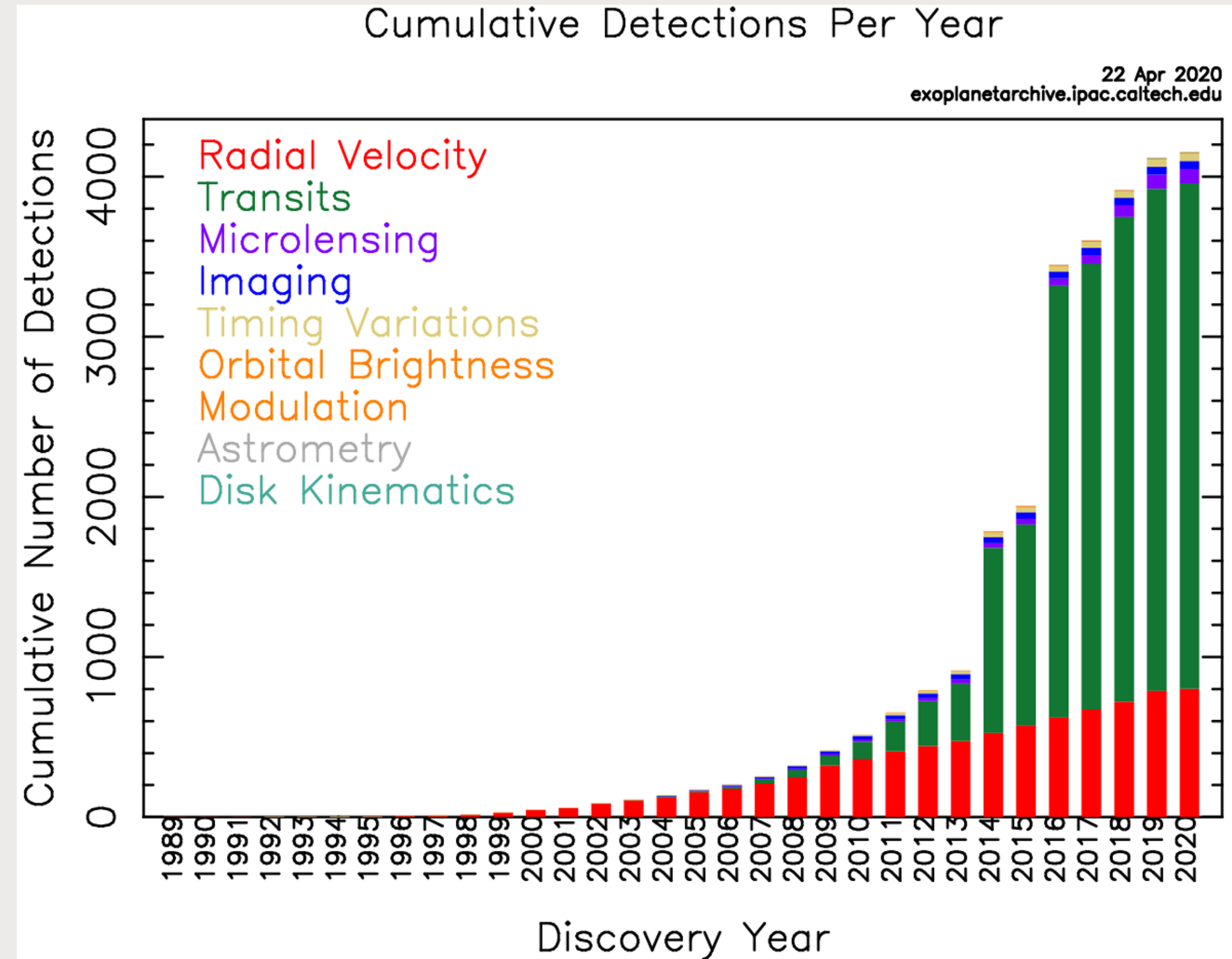
ESO: Jalo Nousiainen, Markus Kasper

ULiege: Olivier Absil, Gilles Orban de Xivry



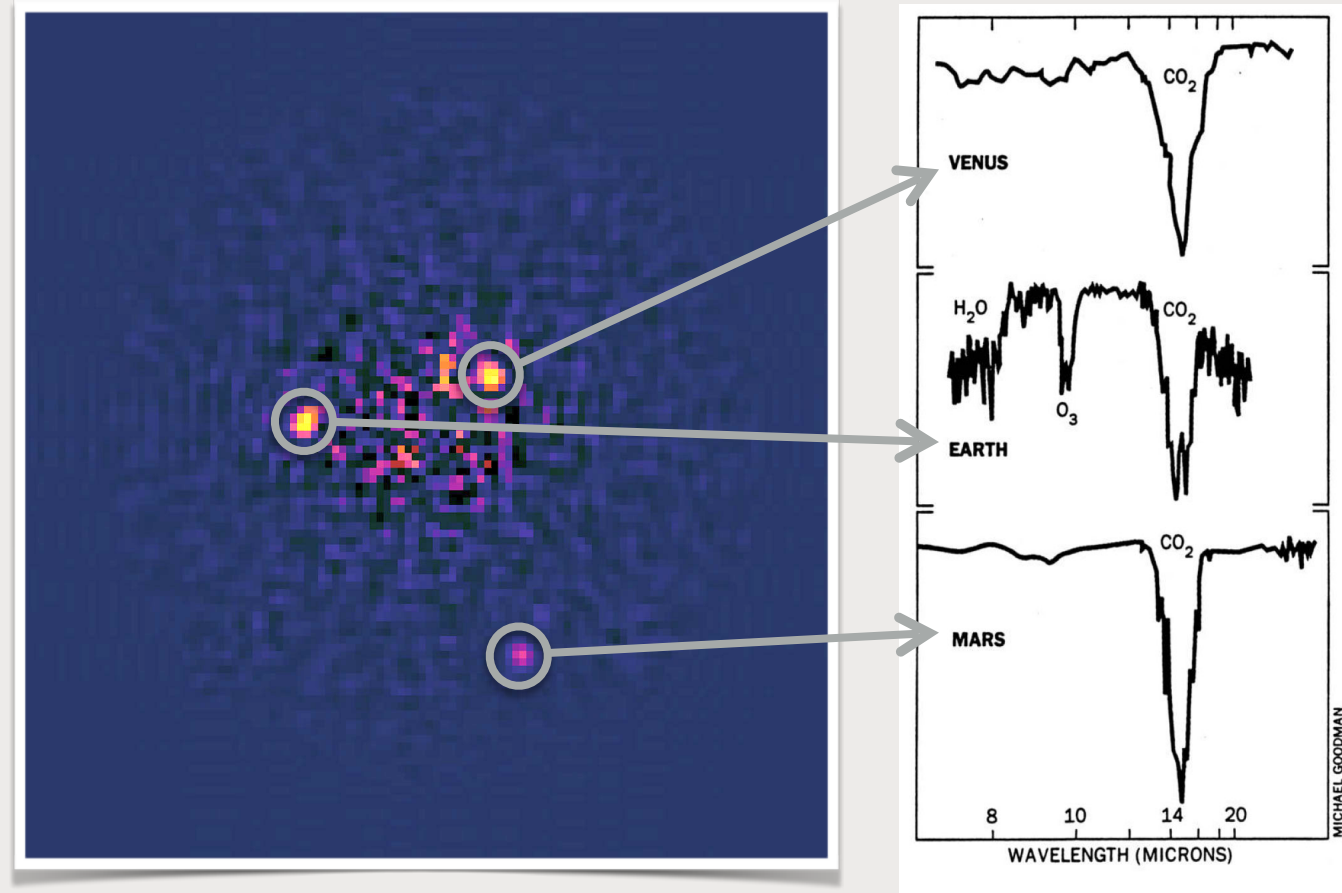
Aim

- Exoplanet detections by imaging are rare but important
- **High Contrast Imaging (HCI)**
 - Exo-Earth characterisation
 - Challenging
 - Active research area



Aim

- Exoplanet detections by imaging are rare but important
- **High Contrast Imaging (HCI)**
 - Exo-Earth characterisation
 - Challenging
 - Active research area
- ▶ Measure and control aberrations with focal-plane wavefront sensing in coronagraphs



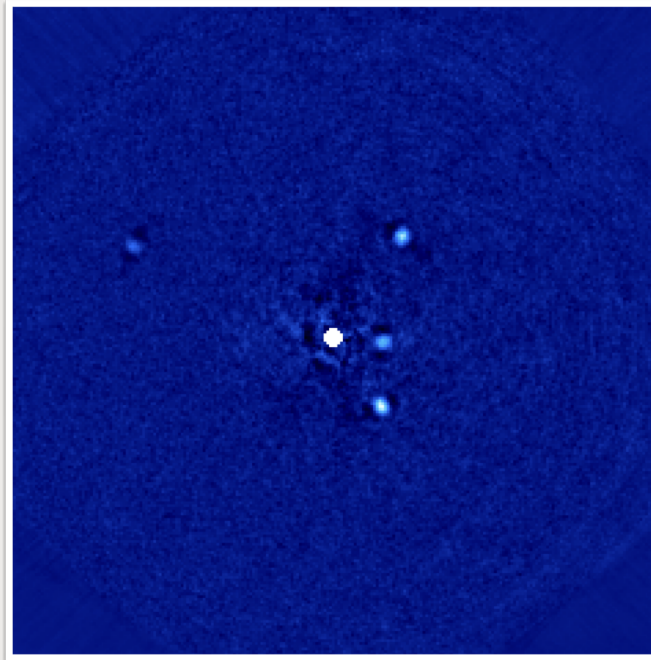
Coronagraphy

- Block star light, transmit planet light

no coronagraph



vortex coronagraph



Gomez et al. 2017

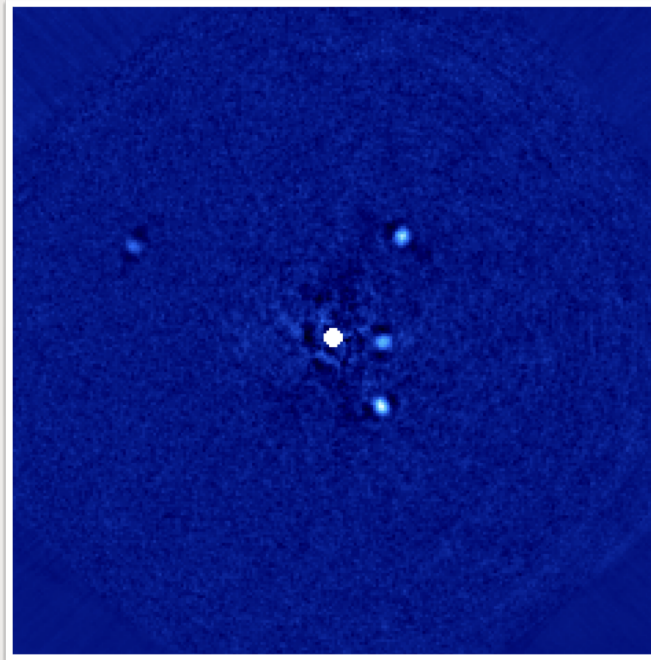
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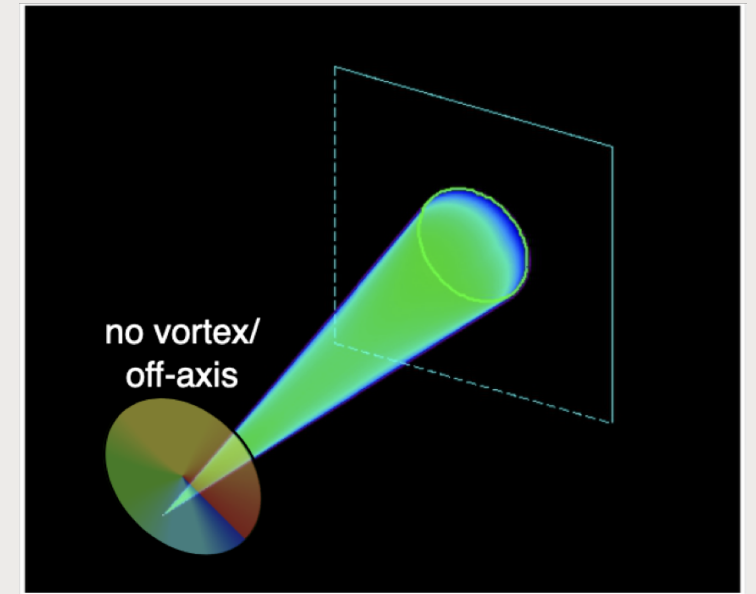
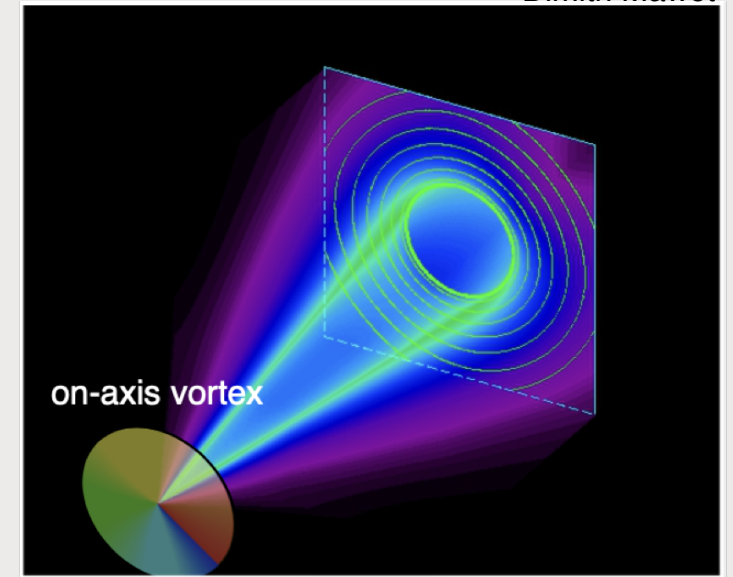
no coronagraph



vortex coronagraph

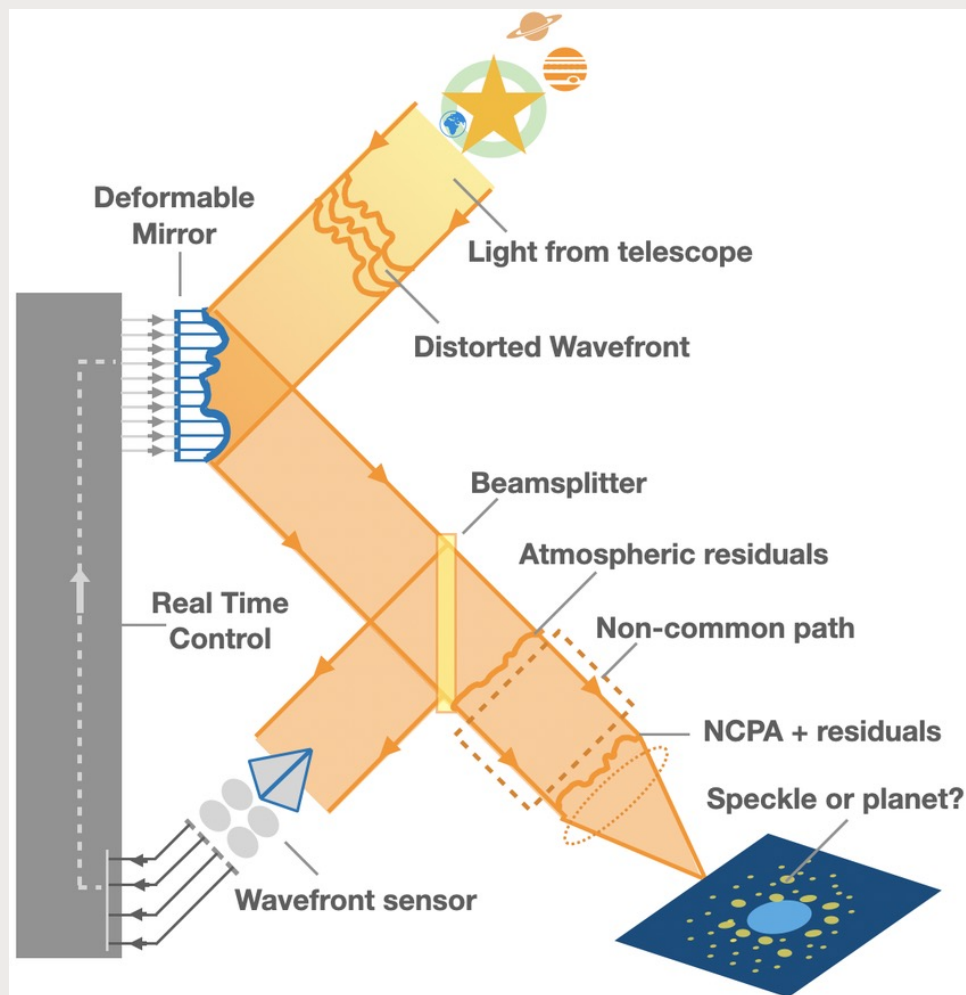


Gomez et al. 2017

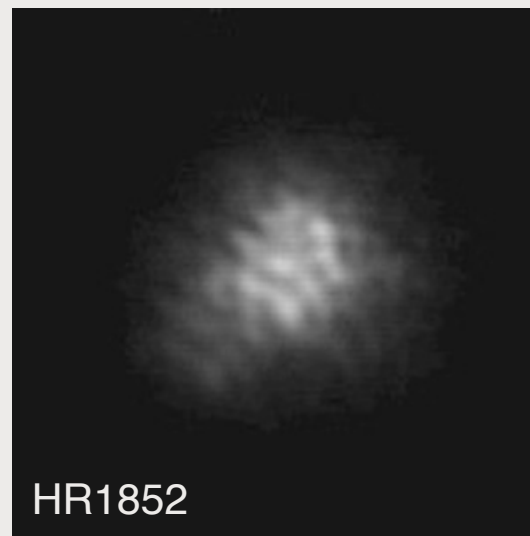


Adaptive Optics (AO)

Skaf et al. 2022



AO: **OFF**

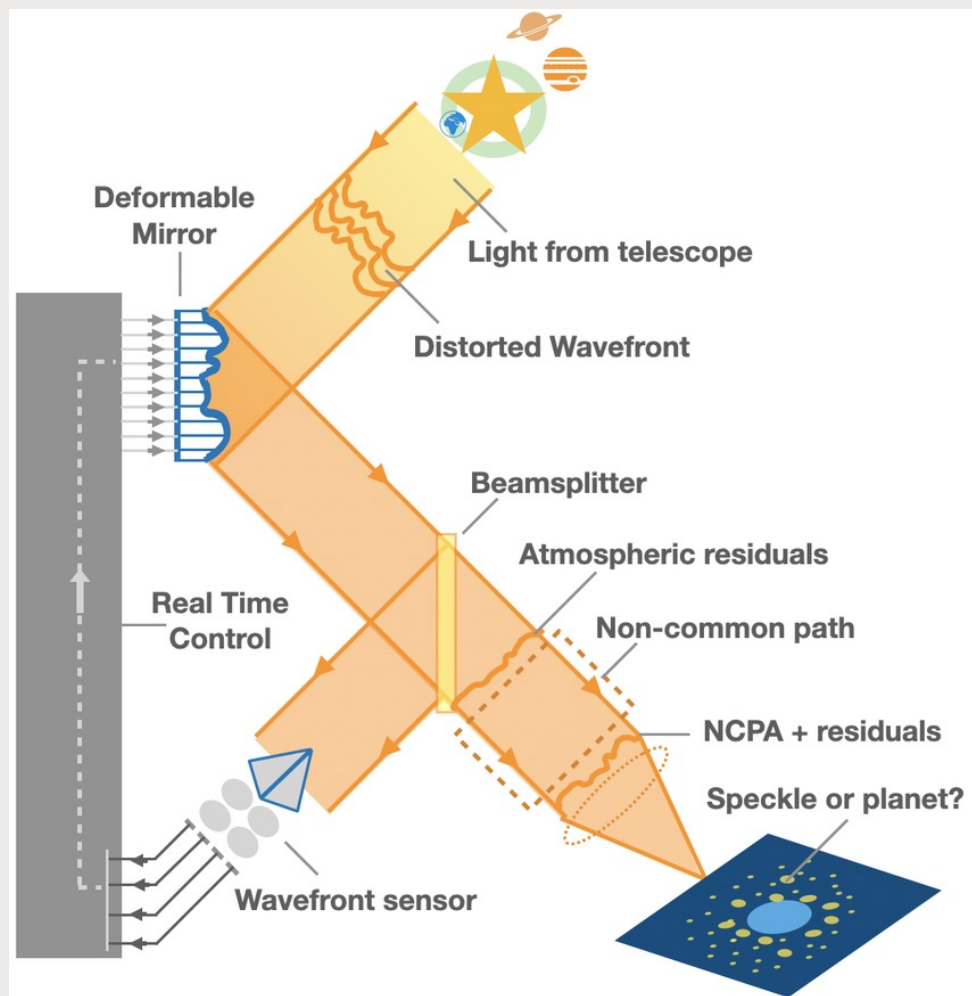


AO: **ON**

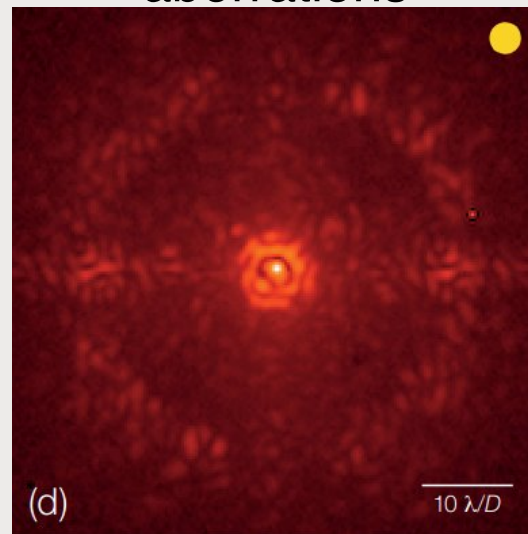


Subaru Telescope, Hawai'i

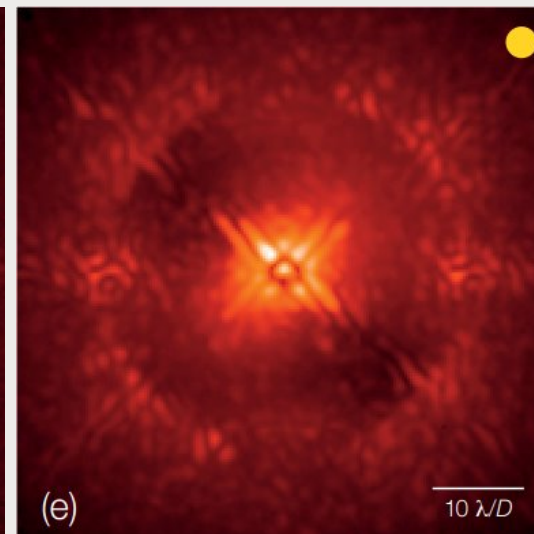
Adaptive Optics (AO)



Non-common path
aberrations



Low wind effect

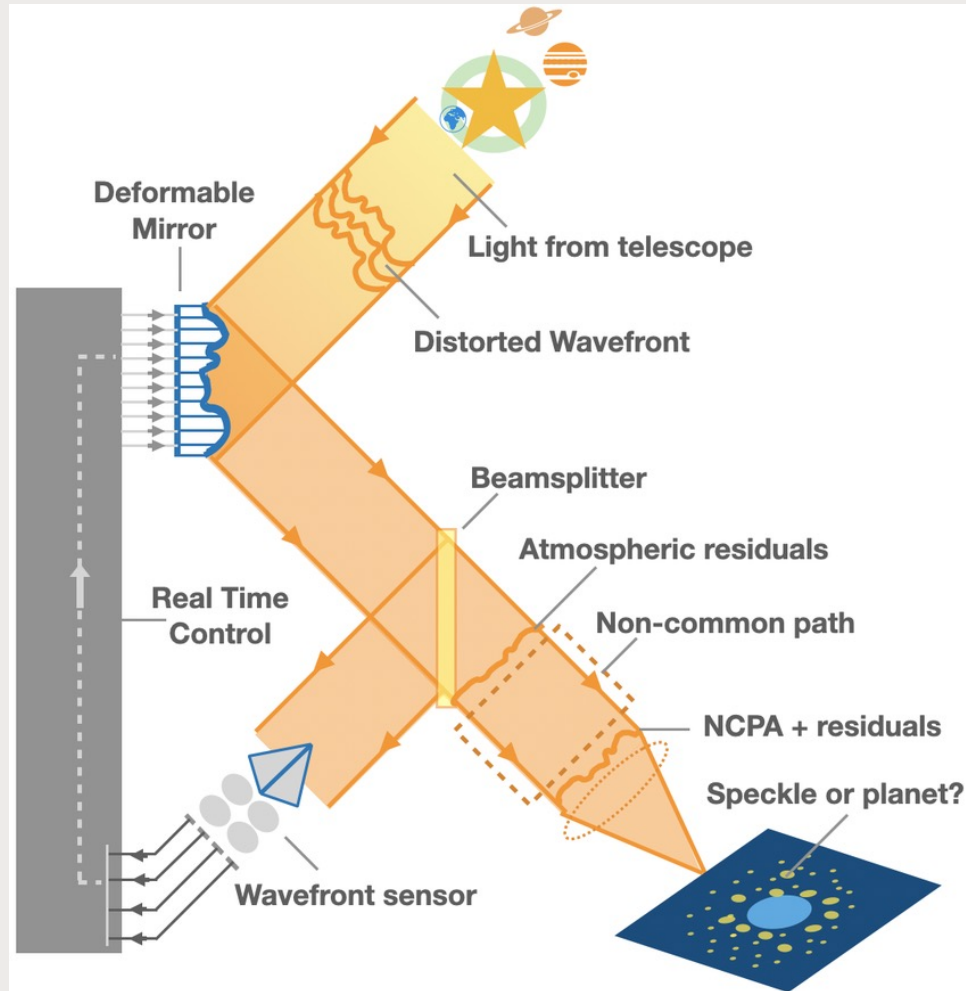


SPHERE, Cantalloube et al. 2019

Skaf et al. 2022

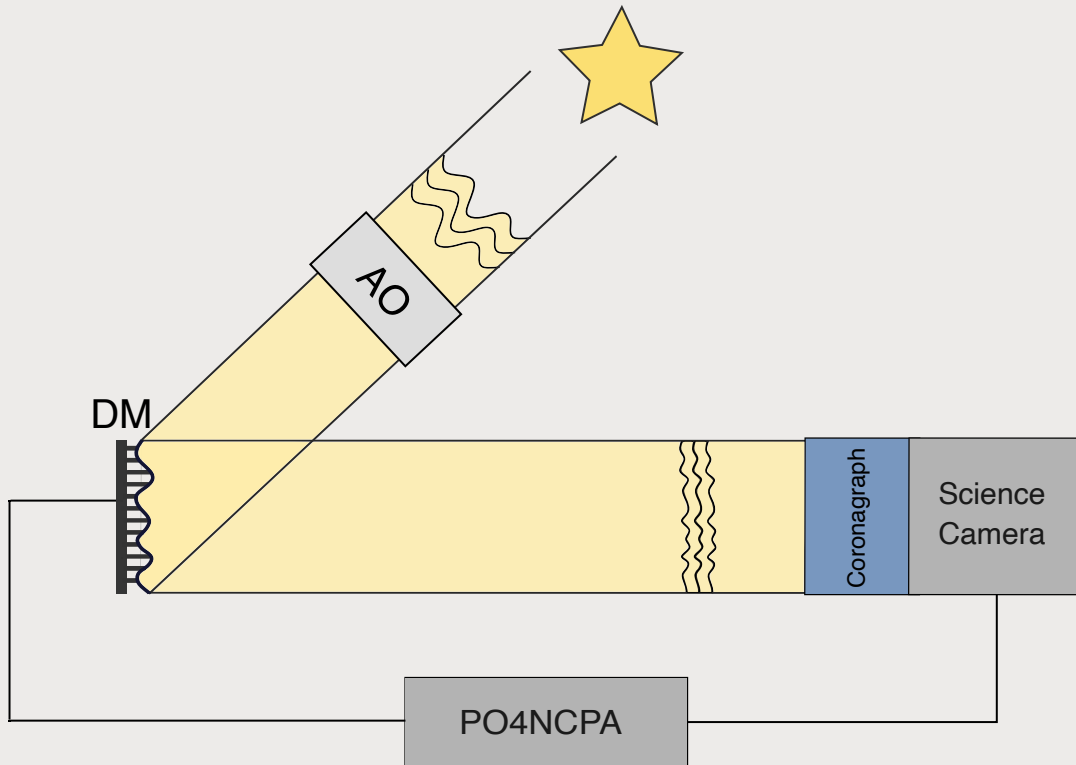
Non-Common Path Aberrations (NCPA)

Skaf et al. 2022



- Wavefront propagating to detectors $\neq$ wavefront measured by wavefront sensor
 - Optics located after the beamsplitting, **chromatic aberrations**

Non-Common Path Aberrations (NCPA)

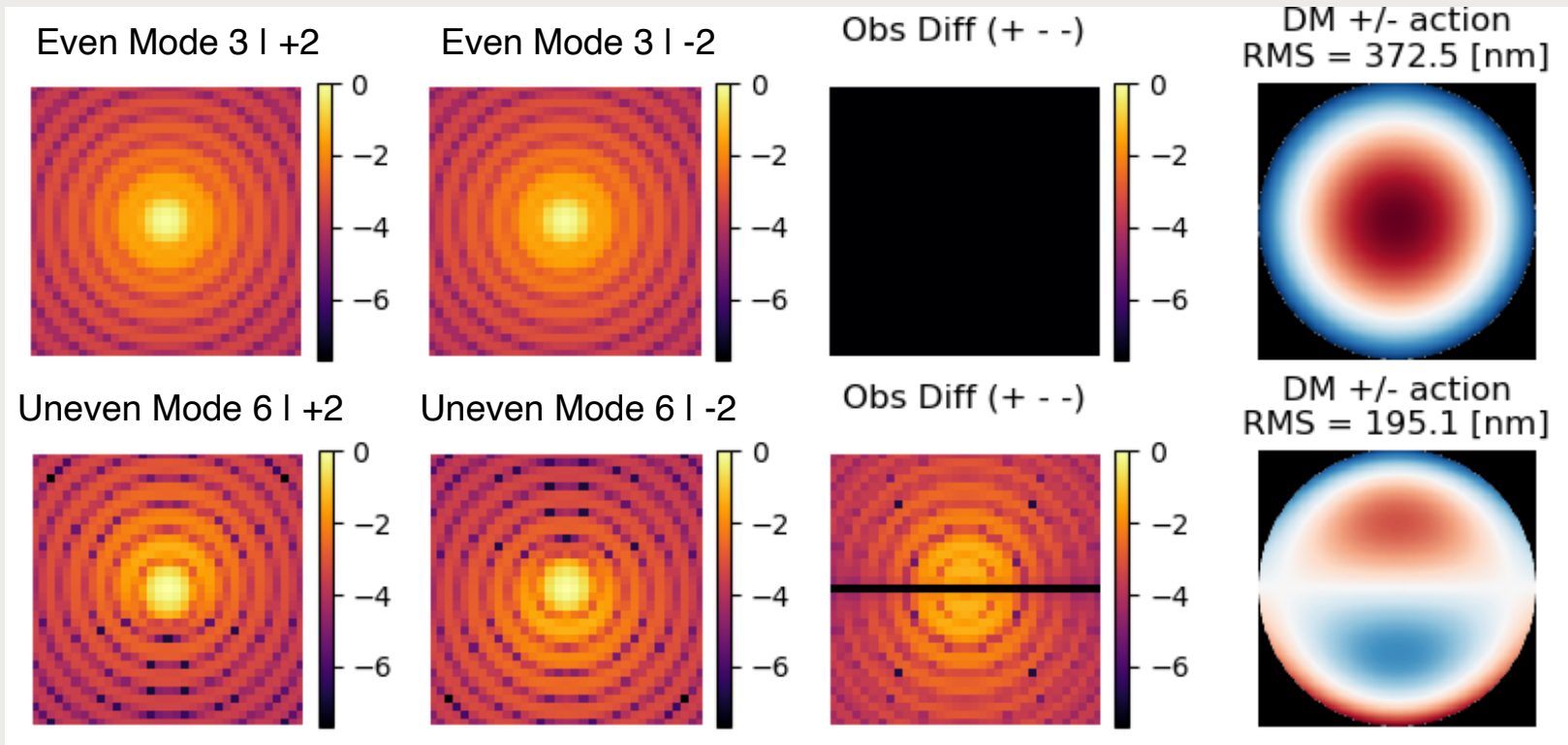


- Wavefront propagating to detectors $\neq$ wavefront measured by wavefront sensor
 - Optics located after the beamsplitting, **chromatic aberrations**
- ▶ Focal plane wavefront sensor (FP-WFS)
 - ✦ Intensity measured at focal plane
 - ✦ Estimation of the aberrations on the complete optical path → images taken by the scientific sensor

Non-Common Path Aberrations (NCPA)

- NCPAs may have **sign ambiguity**

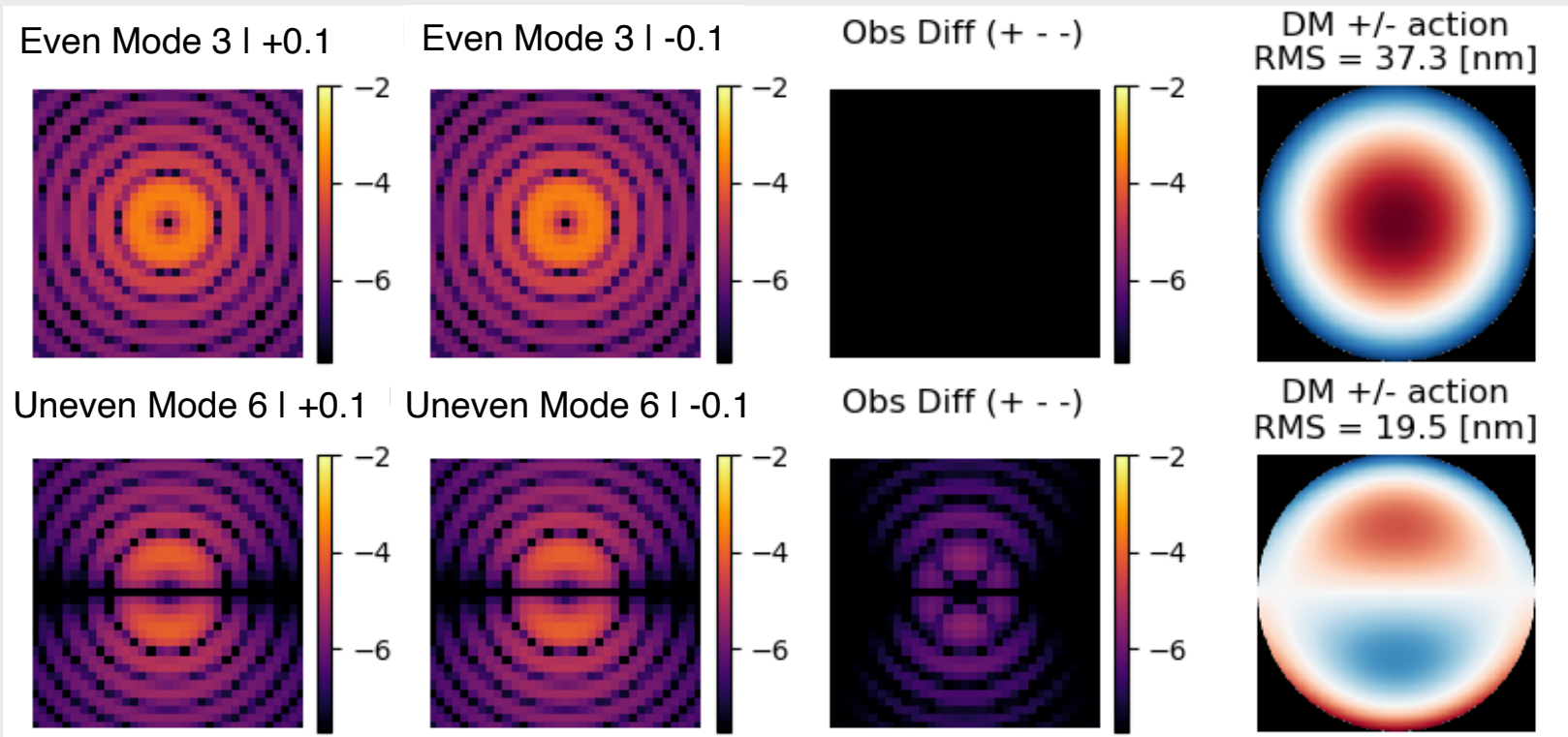
Standard Imaging



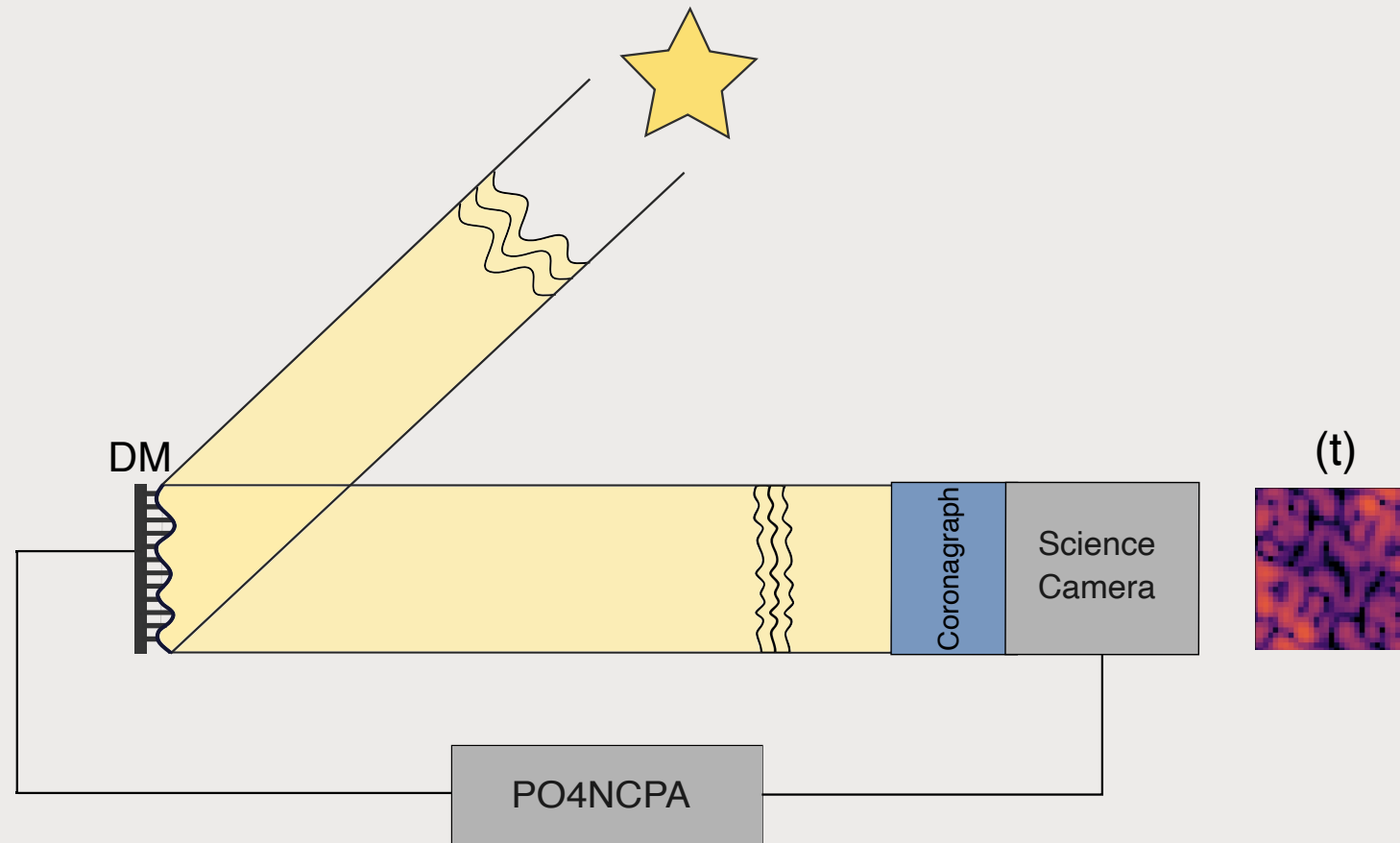
Non-Common Path Aberrations (NCPA)

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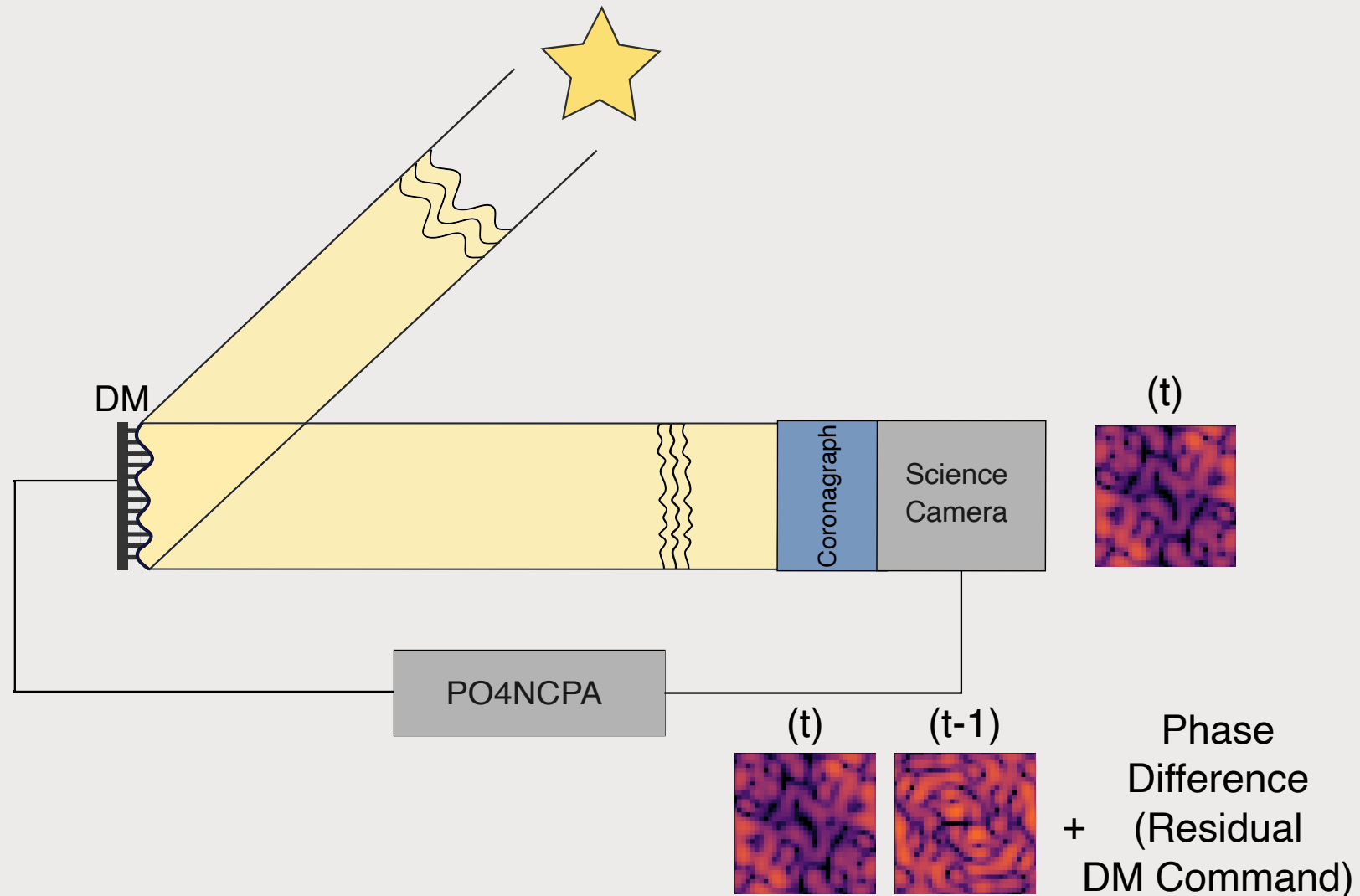
Perfect Coronagraph



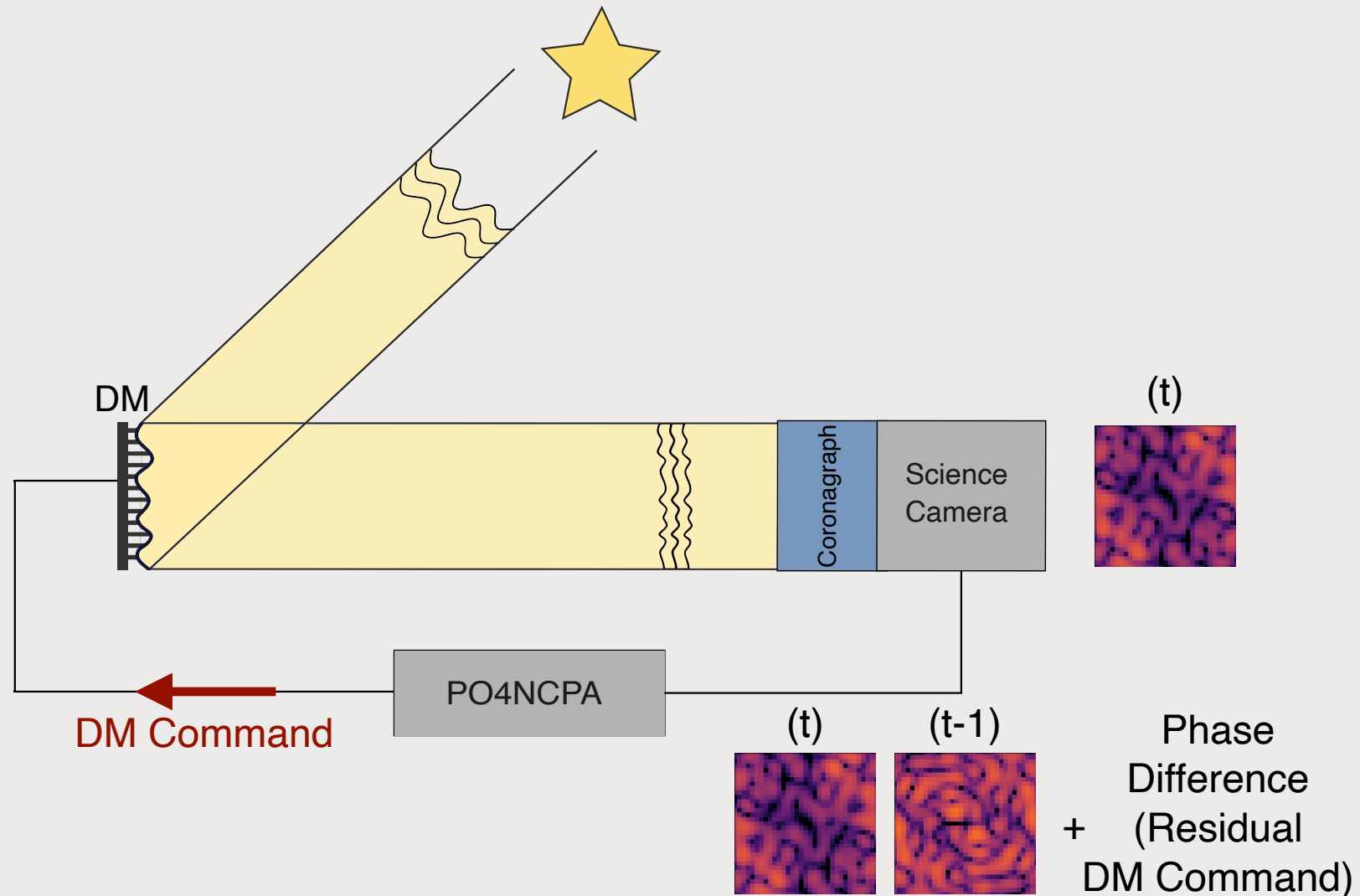
Sequential Phase Diversity



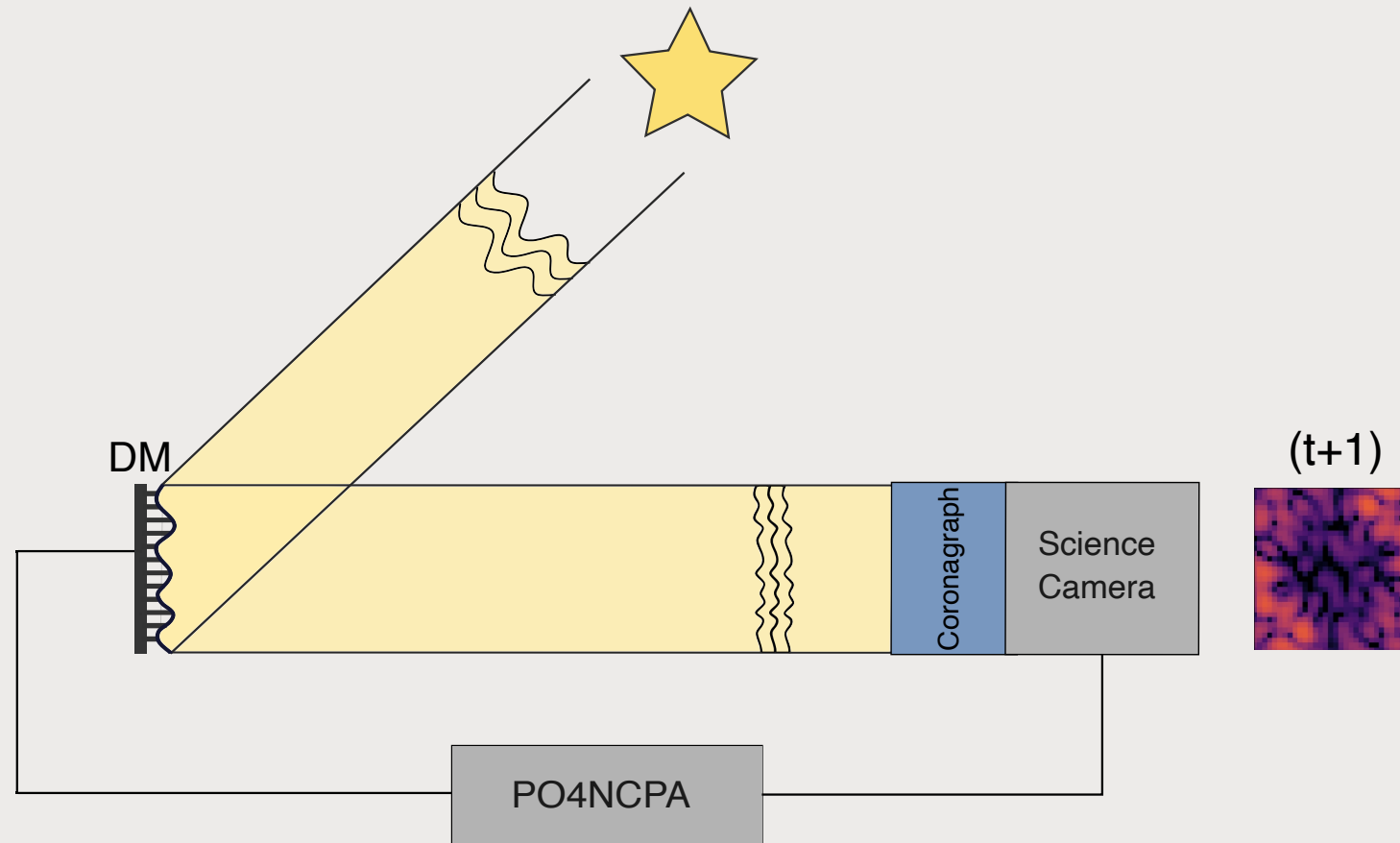
Sequential Phase Diversity



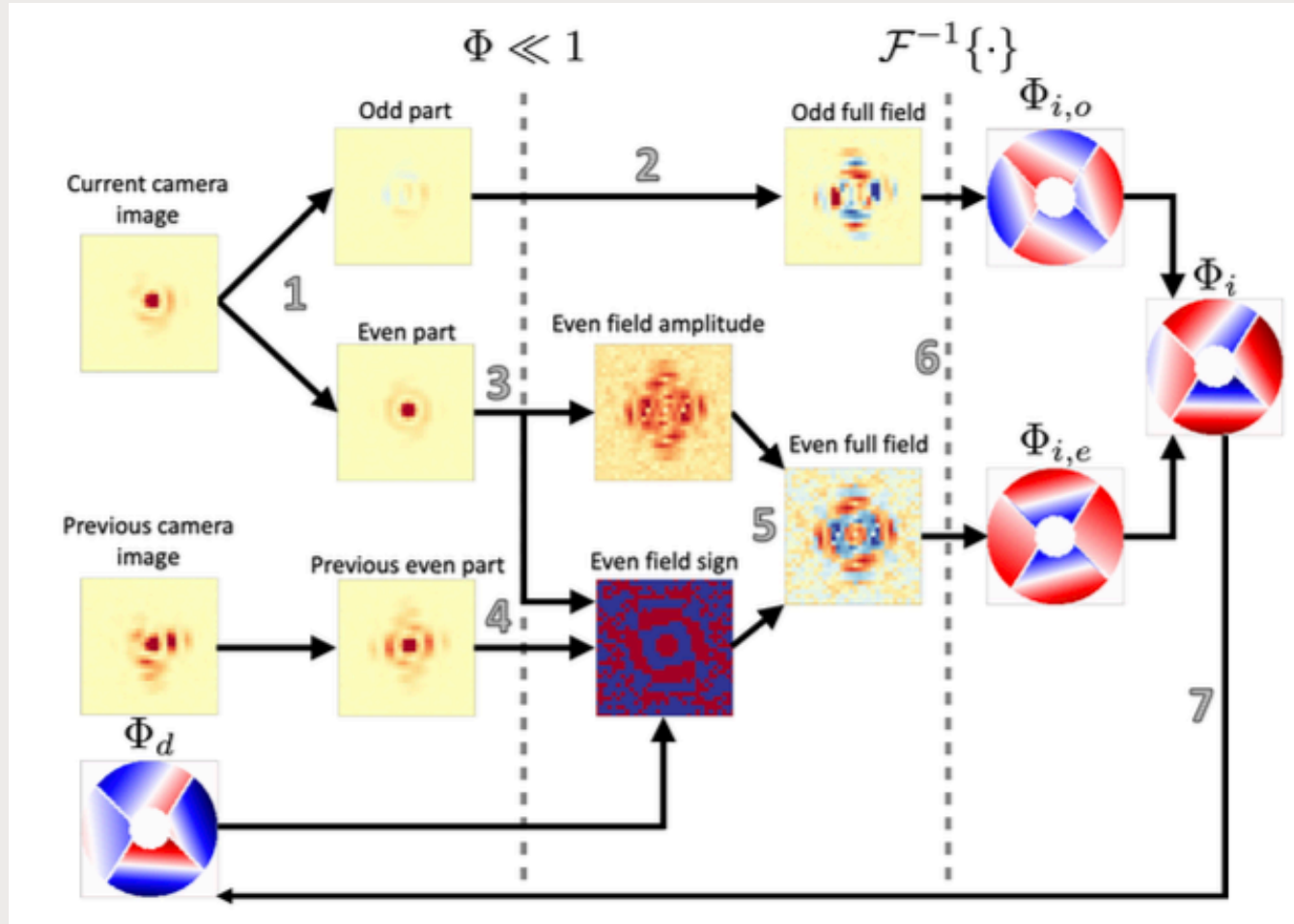
Sequential Phase Diversity



Sequential Phase Diversity

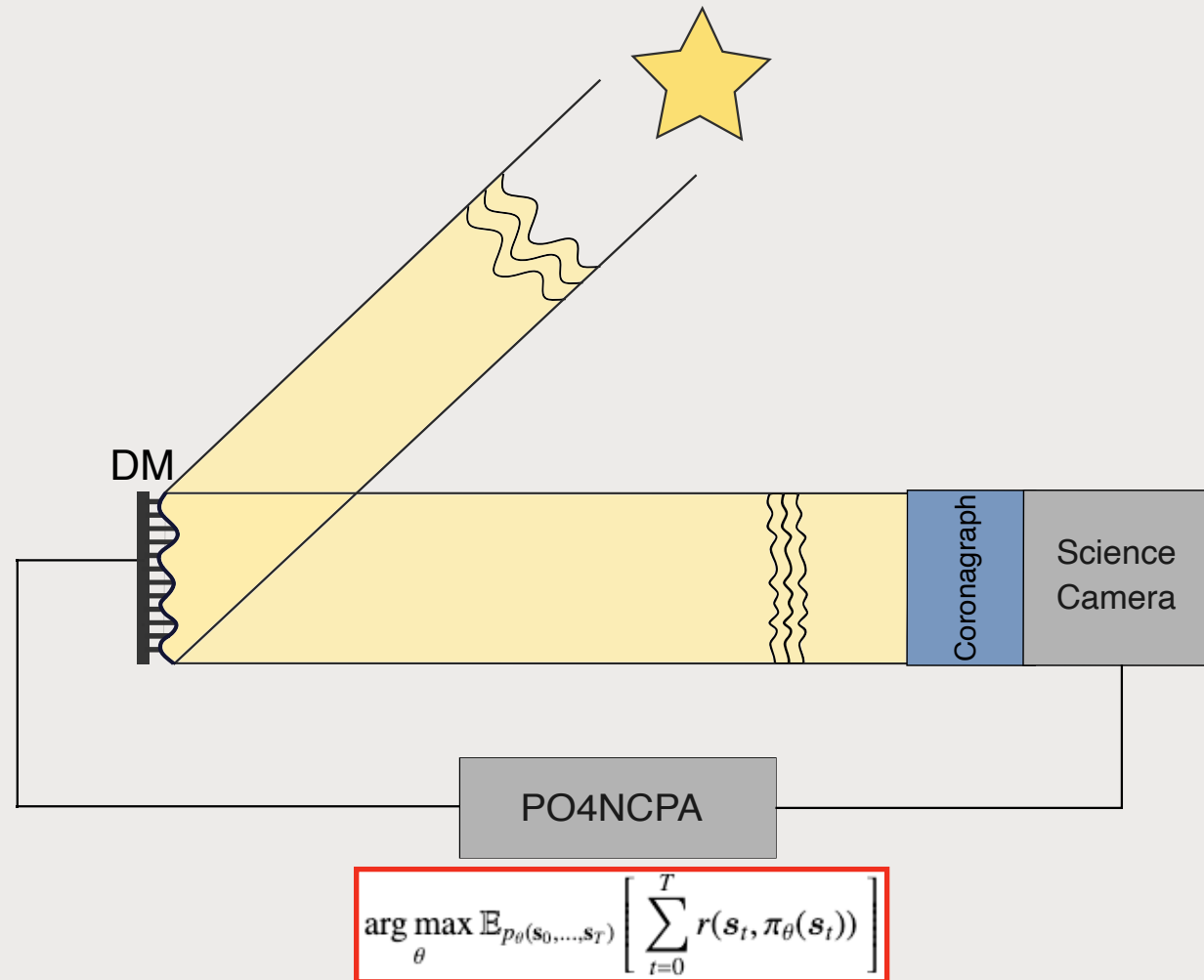


Fast and Furious

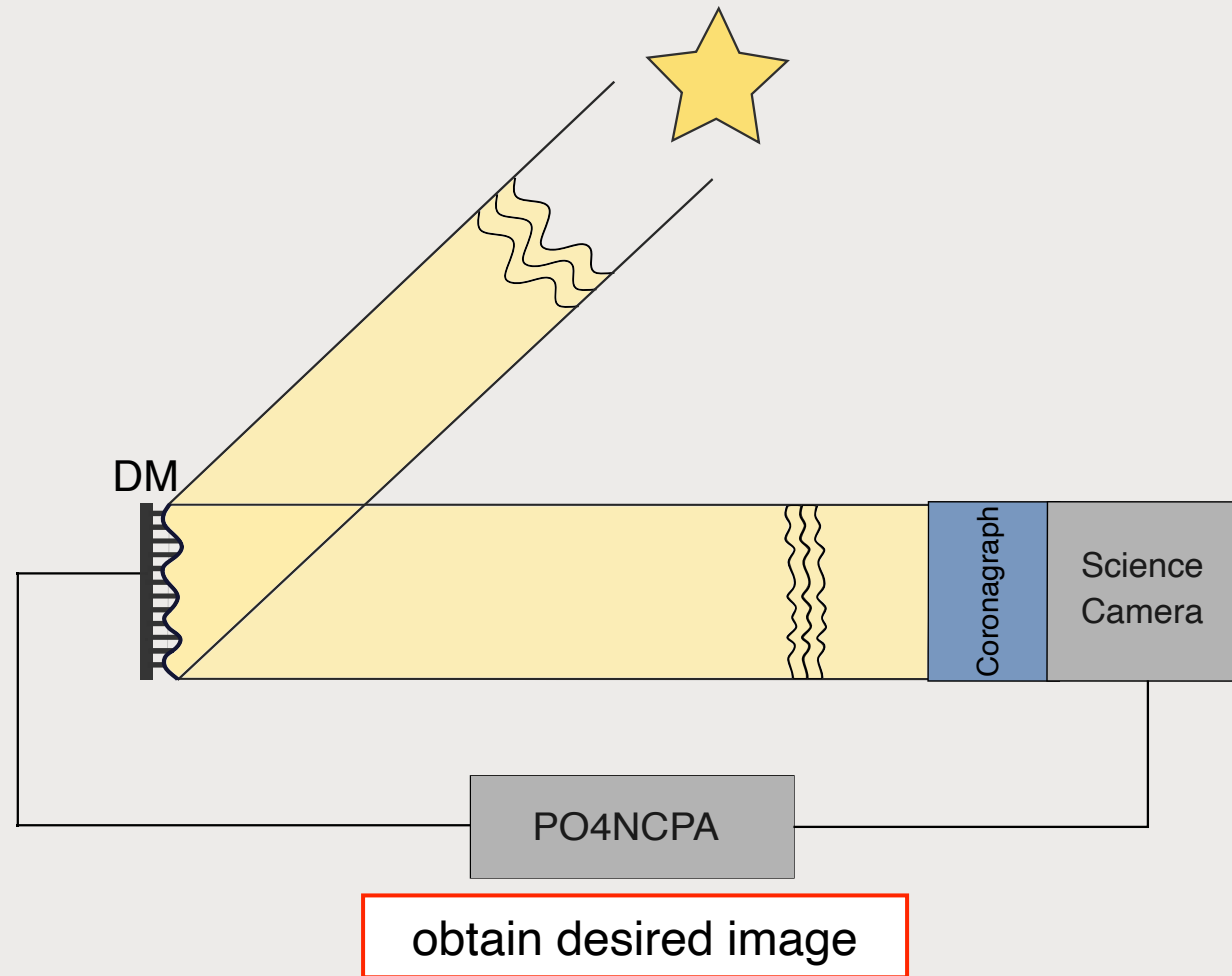


- Low wind effect
- Iteratively minimise focal plane aberrations
- On-sky testing (Keck & Subaru)
- Not compatible with coronagraphs

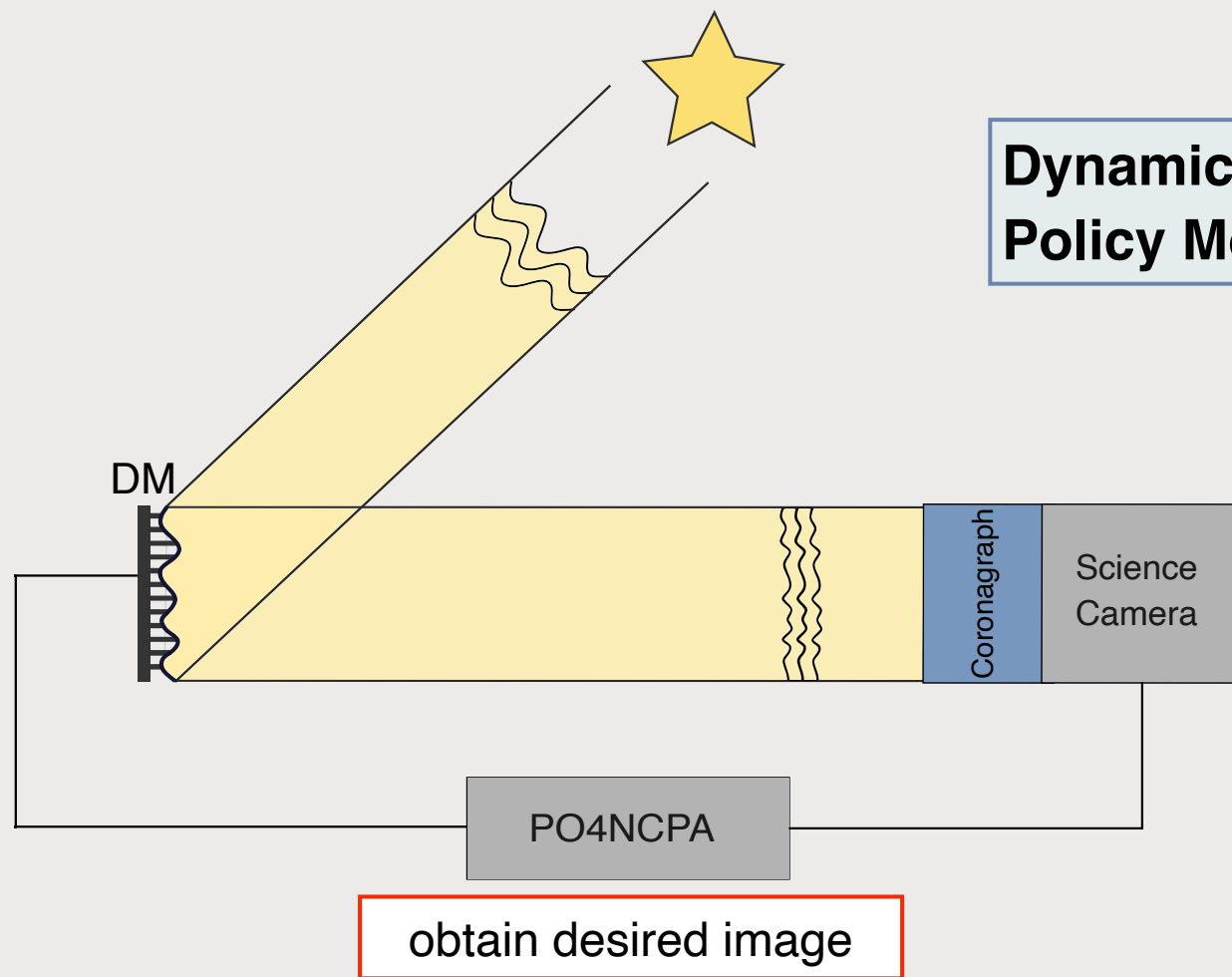
PO4NCPA



PO4NCPA

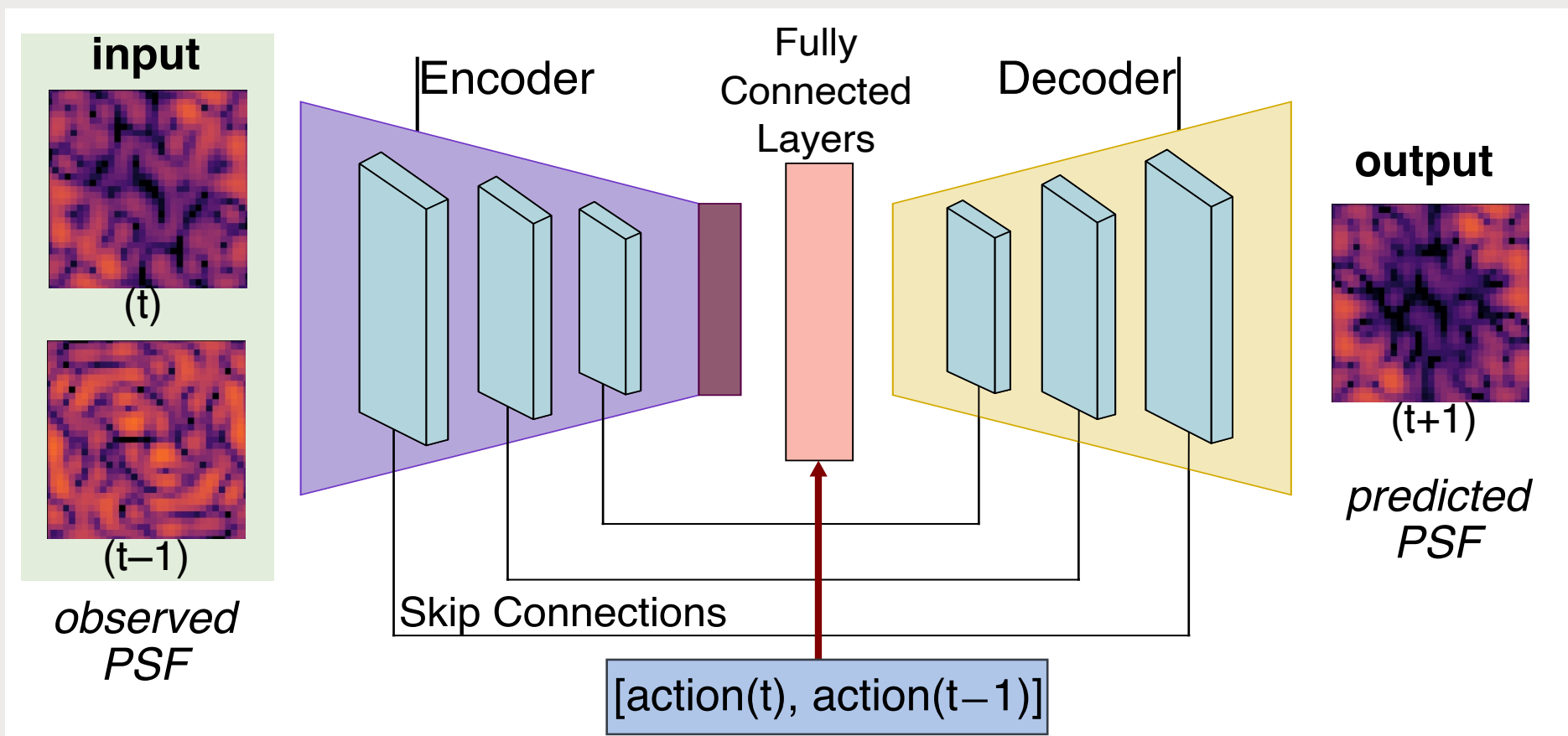


PO4NCPA

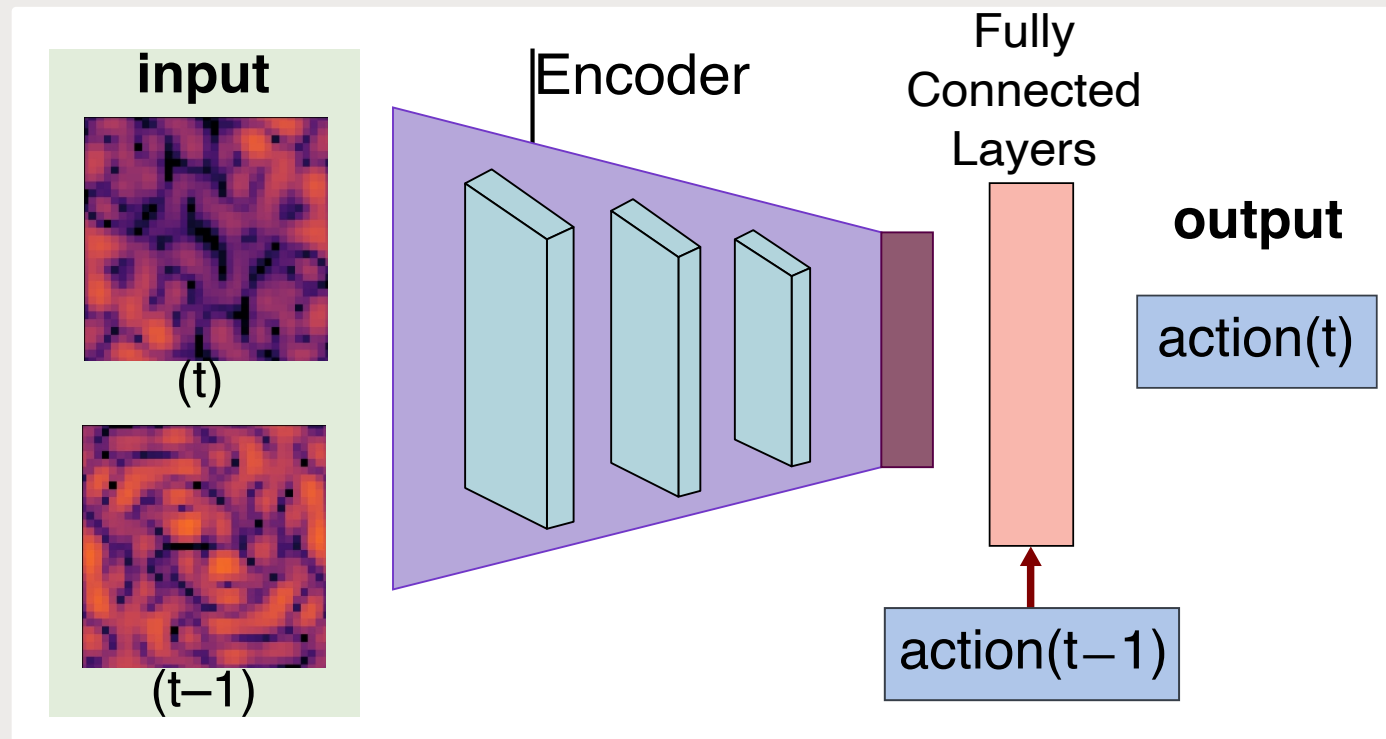


Dynamics Model: environment model
Policy Model: control algorithm

PO4NCPA: Dynamics Model



PO4NCPA: Policy Model



PO4NCPA: Simulation

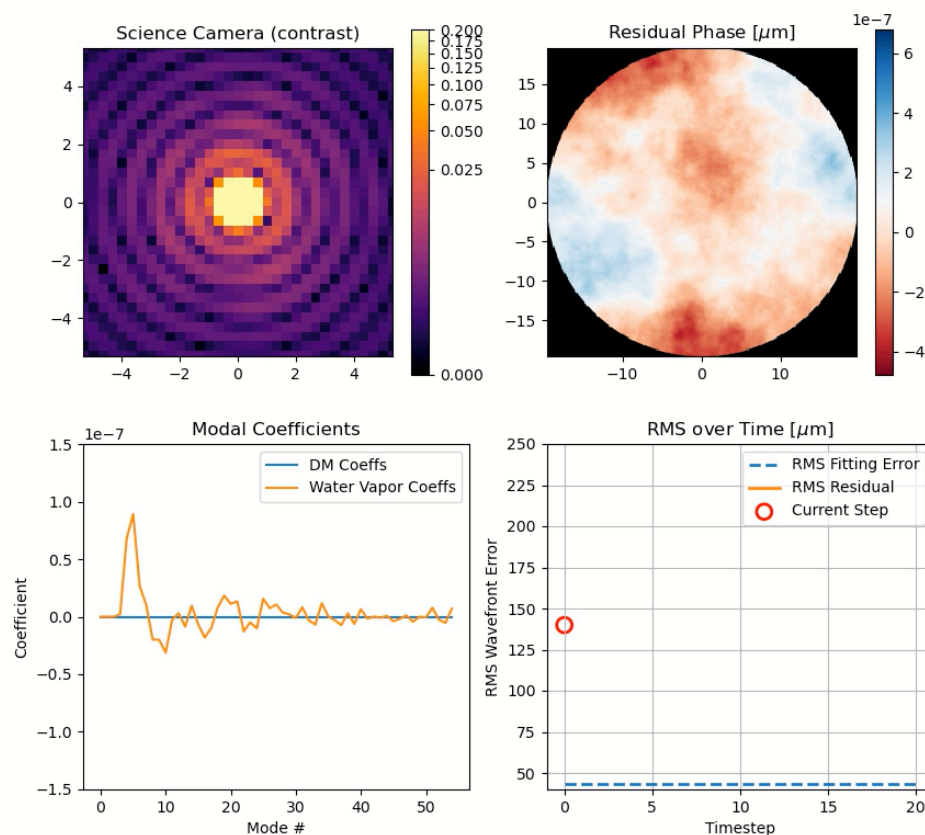
- **Static NCPA:** Single frame of aberrations, constant throughout the simulation
- **Dynamic NCPA:** Water vapour effects, evolving throughout the simulation
- Coronagraphs:
 - Normal imaging (no coronagraph)
 - Perfect coronagraph
 - *Vector vortex coronagraph*

Telescope Diameter	39.3 m
Observation Band	Mid-IR (11 μm)
# Modes Corrected	55
Frame Rate	10 Hz
Median NCPA RMS	286 nm
Fried Parameter	95 m (at 11 μm)
Wind Speed	10 m/s

PO4NCPA: Static NCPA

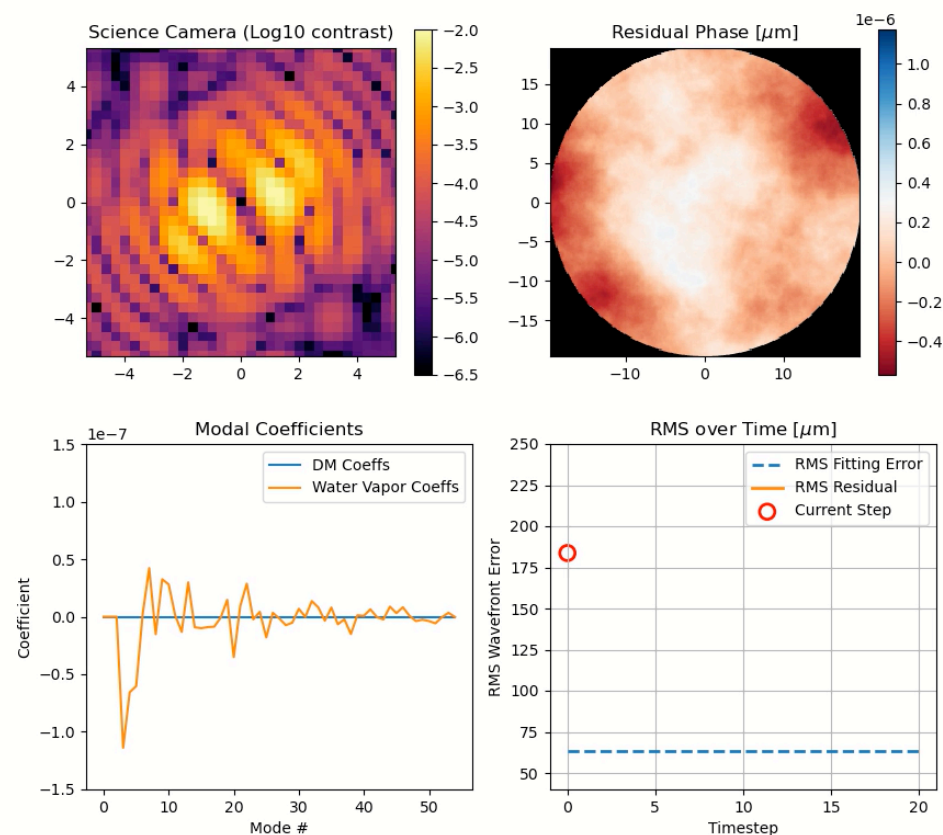
Standard Imaging

Timestep 0 | Fitting RMS: 96.6 nm



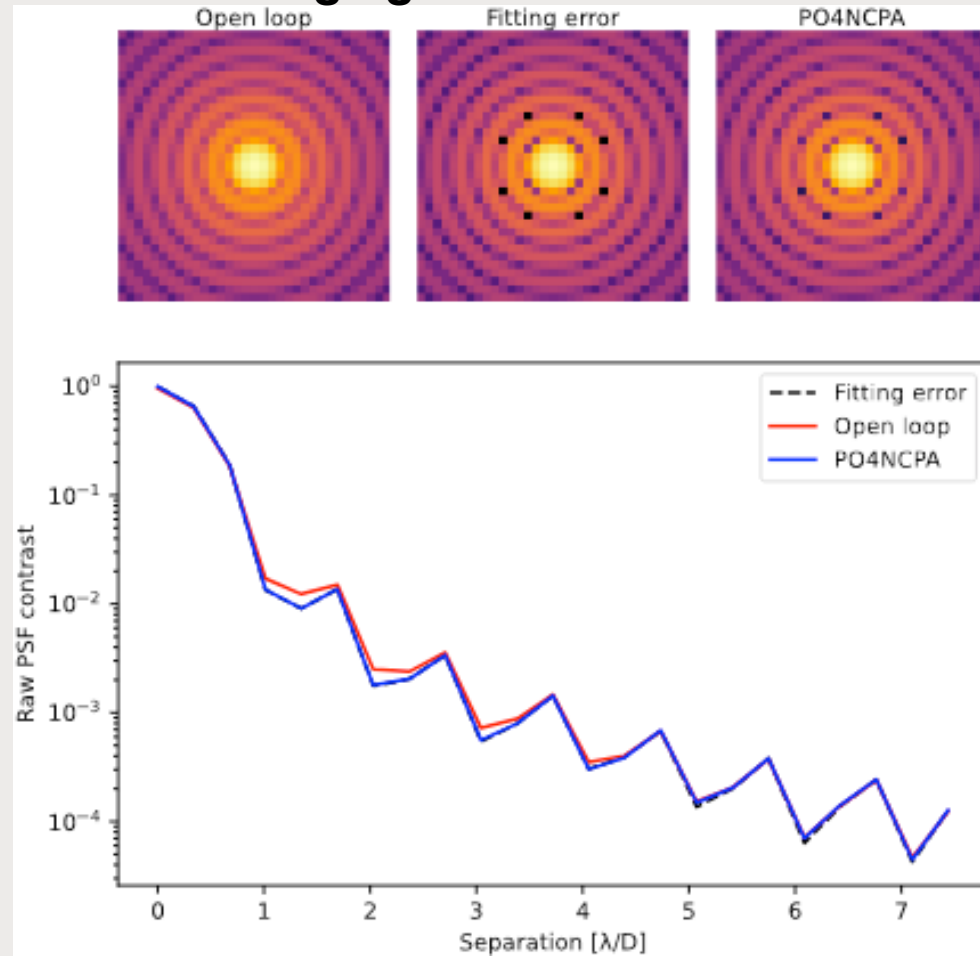
Perfect Coronagraph

Timestep 0 | Fitting RMS: 120.1 nm

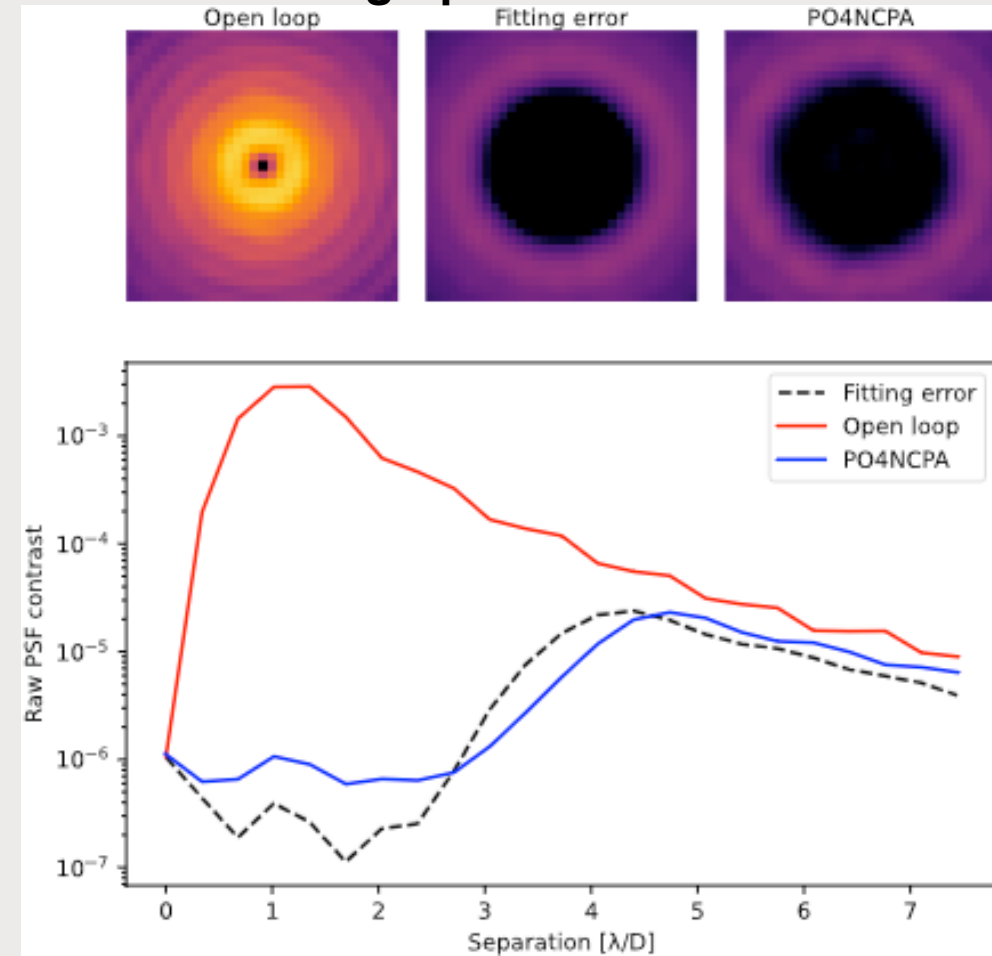


PO4NCPA: Static NCPA

Standard Imaging

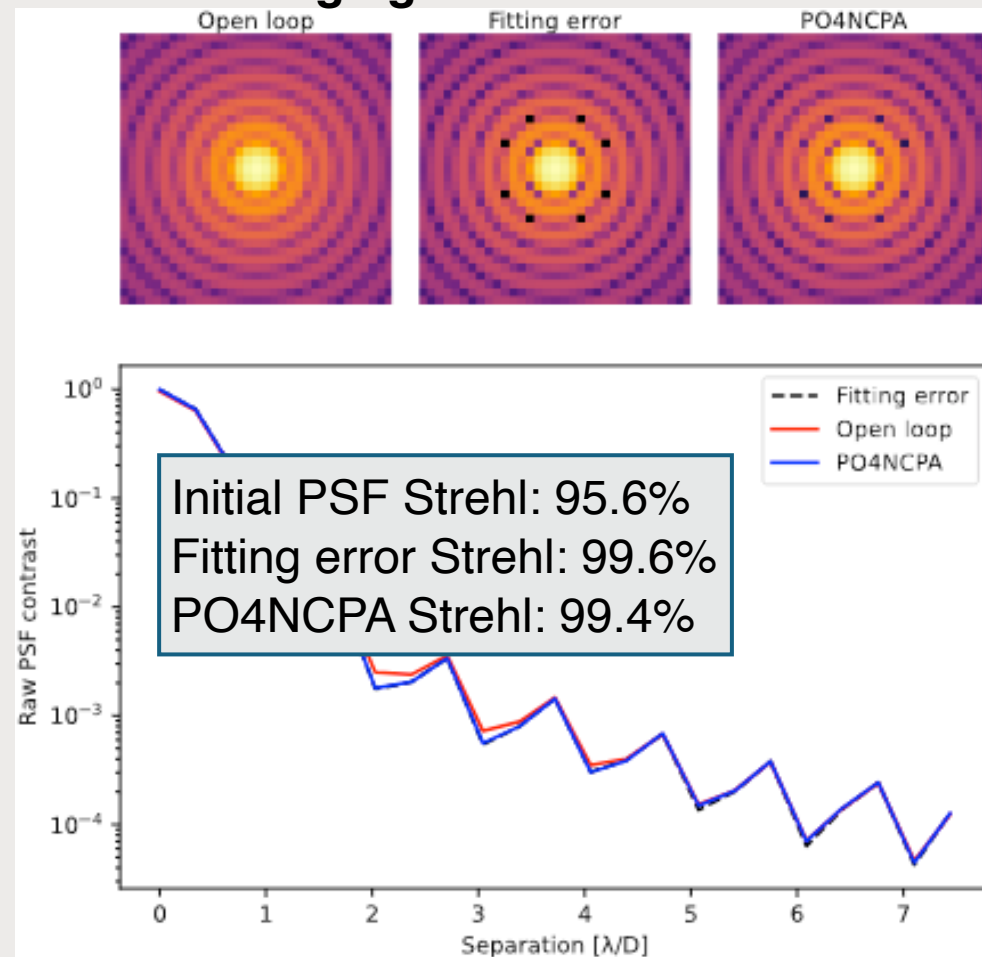


Perfect Coronagraph

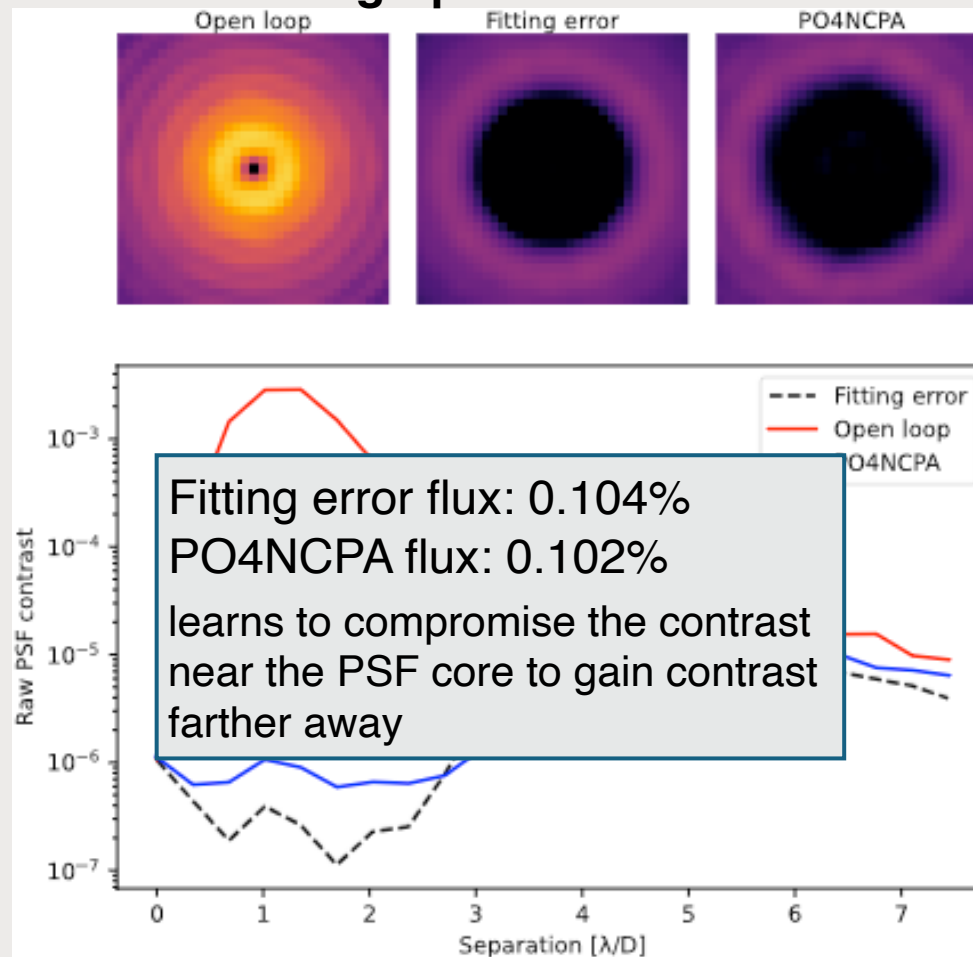


PO4NCPA: Static NCPA

Standard Imaging



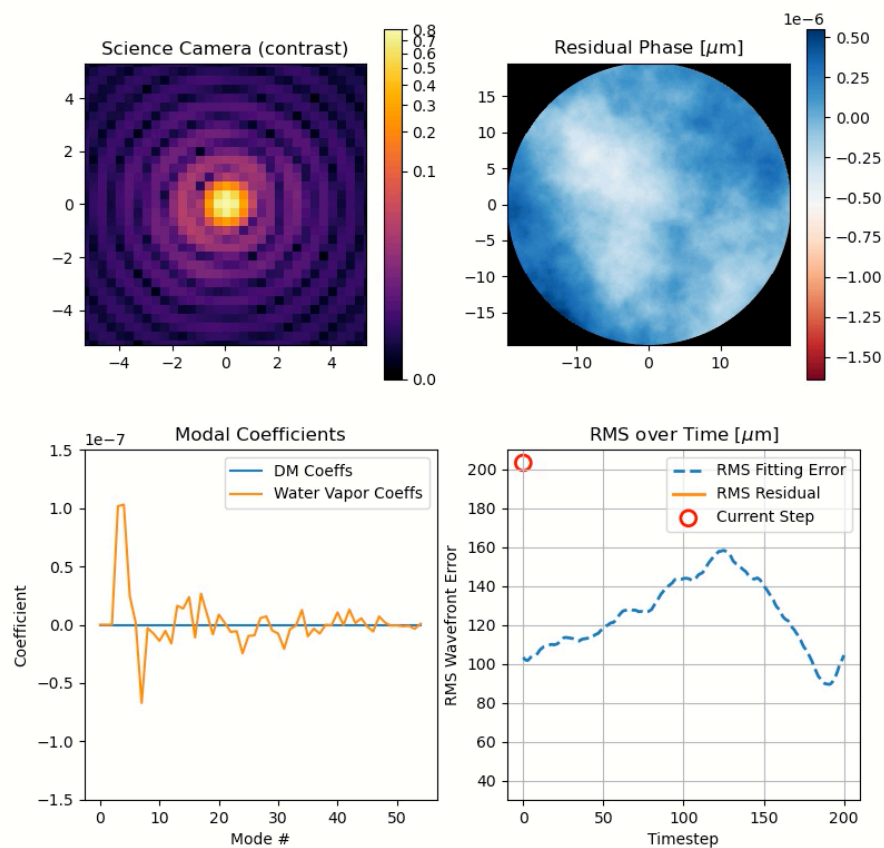
Perfect Coronagraph



PO4NCPA: Dynamic NCPA

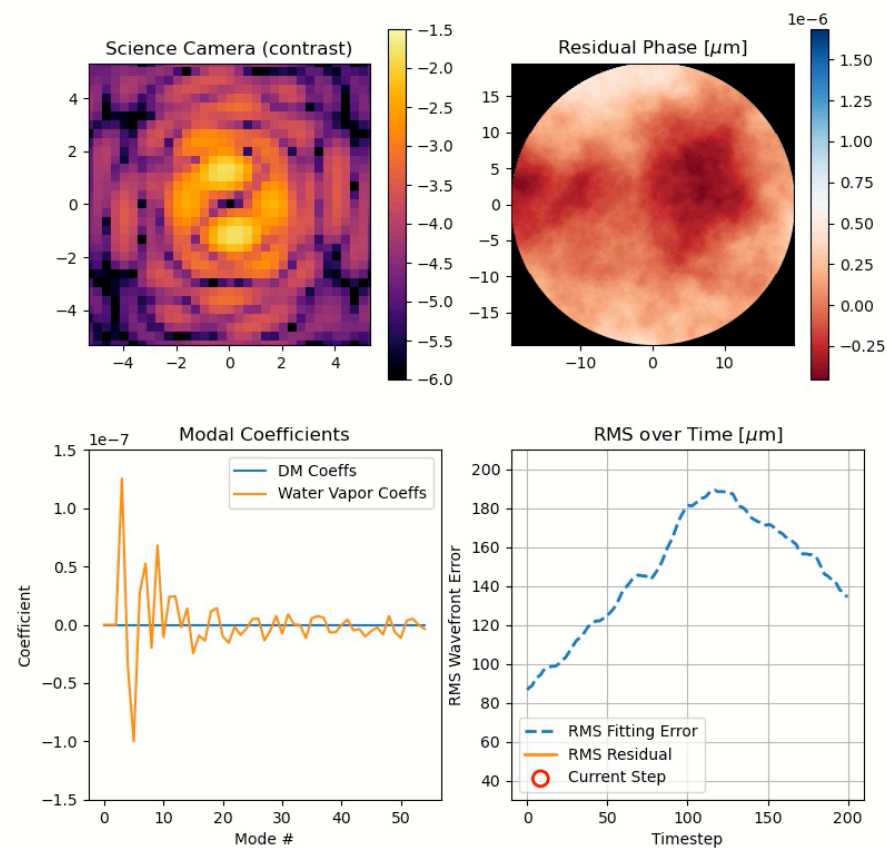
Standard Imaging

Timestep 0 | RMS: 203.2 nm



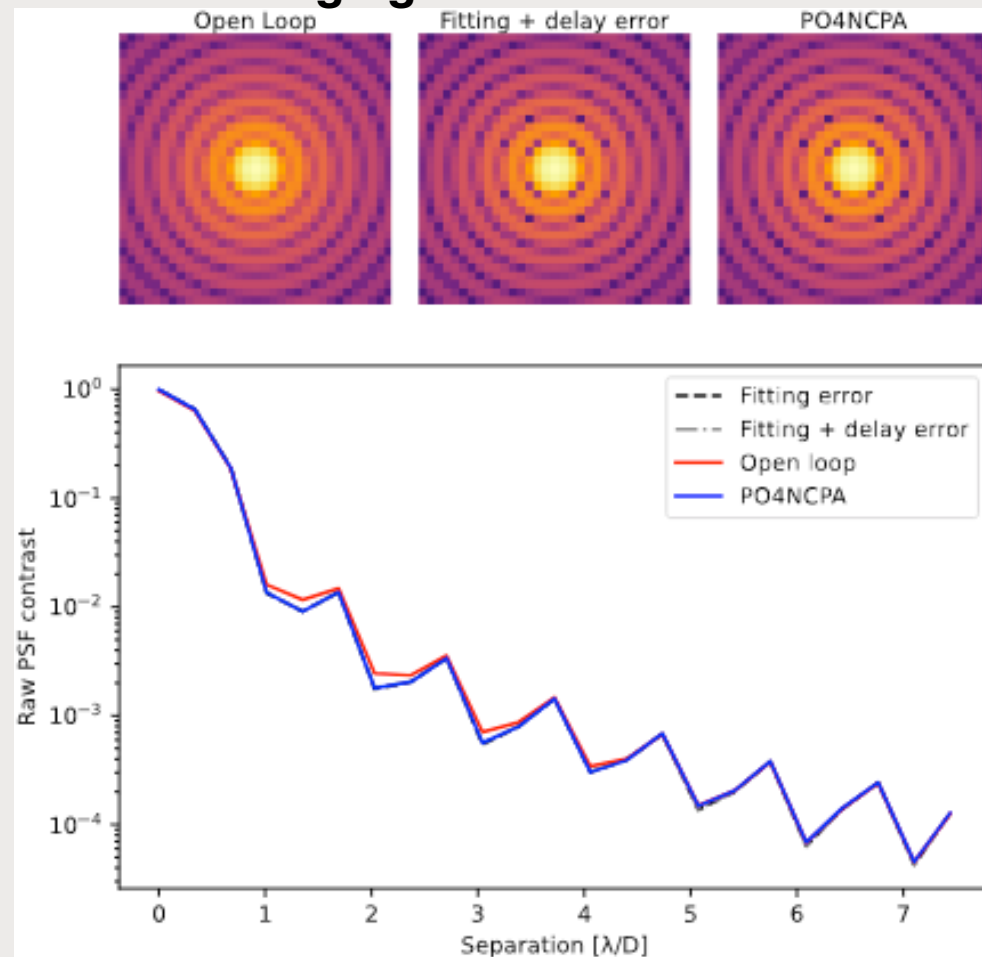
Perfect Coronagraph

Timestep 0 | RMS: 217.1 nm

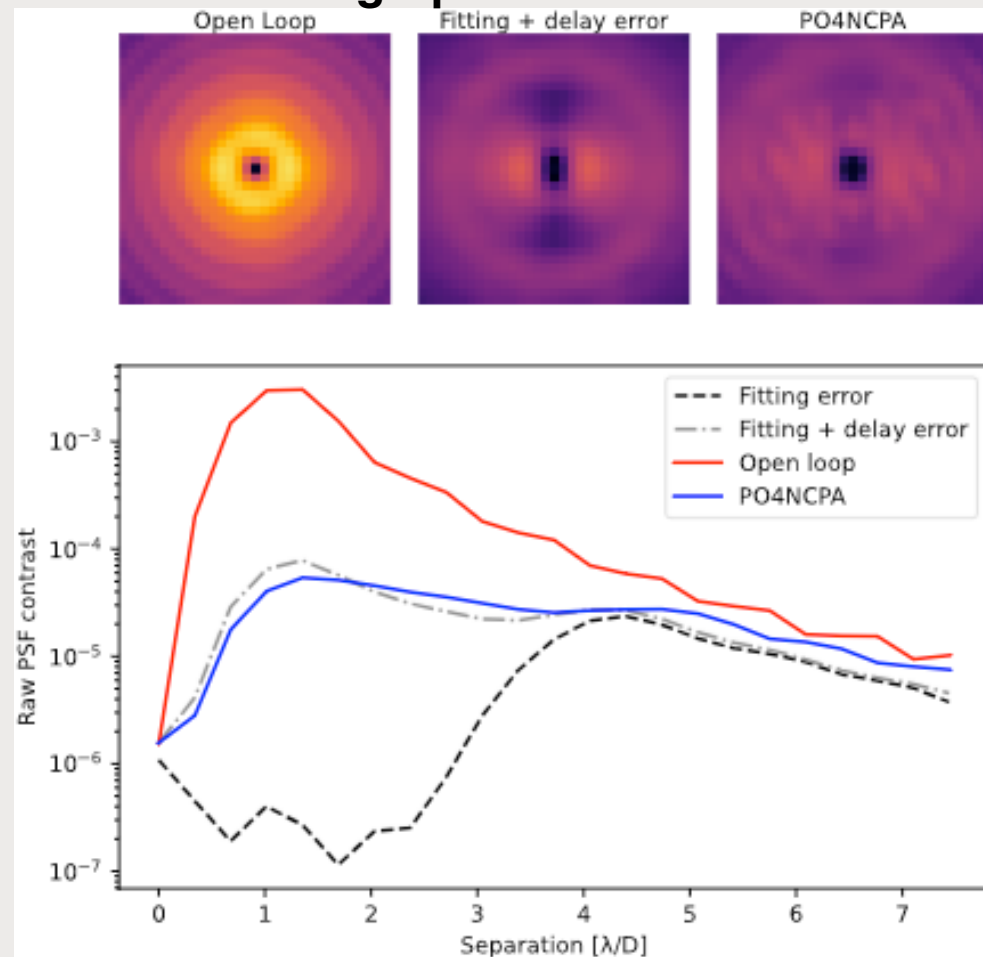


PO4NCPA: Dynamic NCPA

Standard Imaging

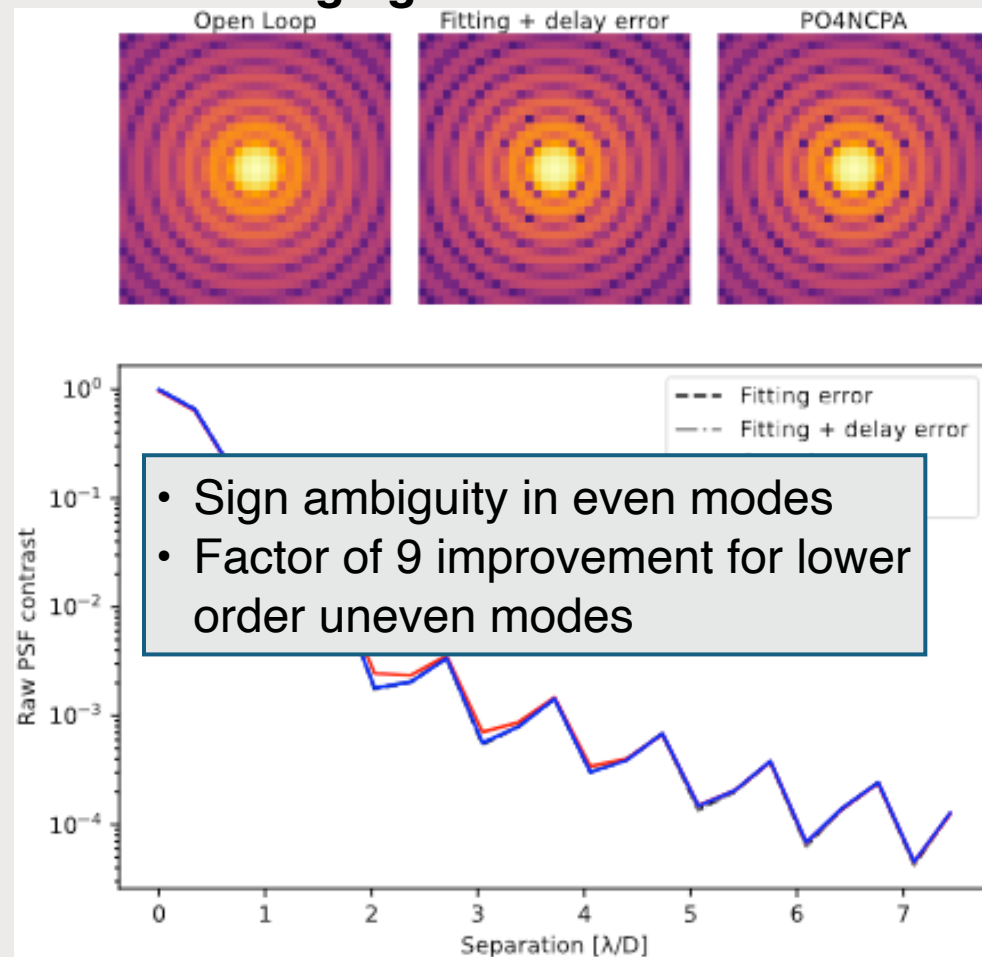


Perfect Coronagraph

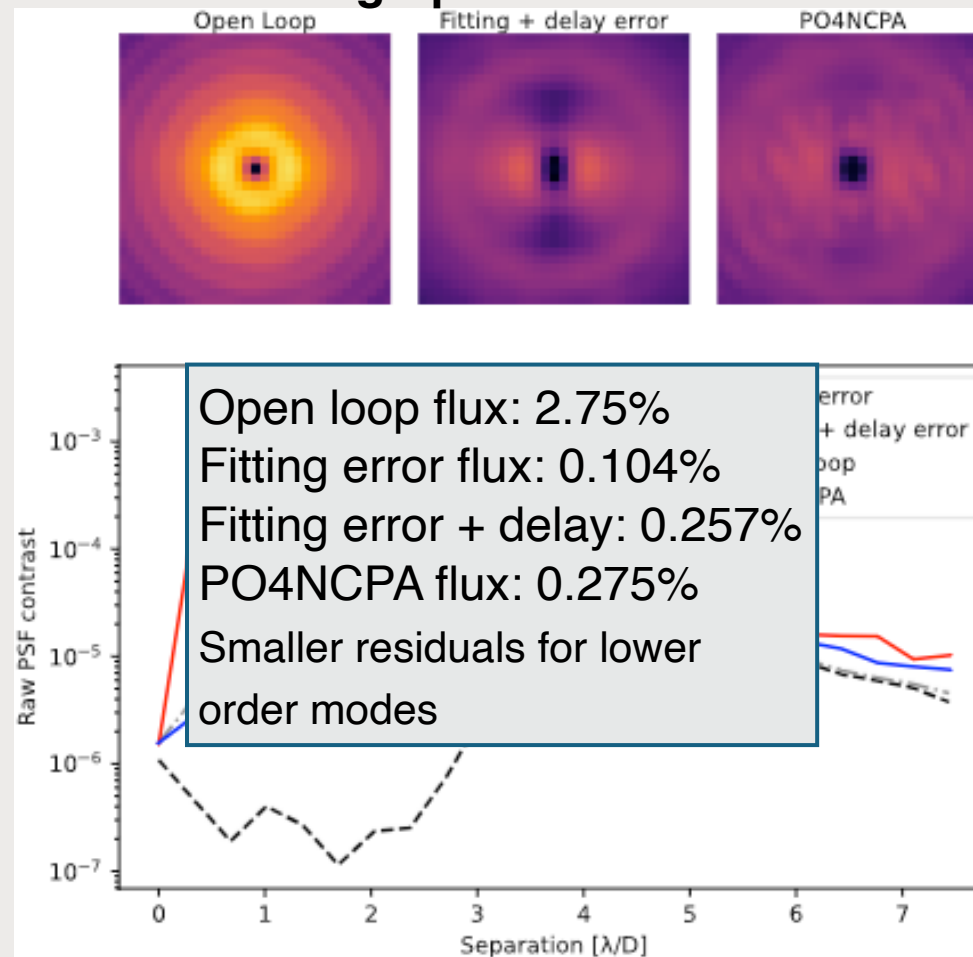


PO4NCPA: Dynamic NCPA

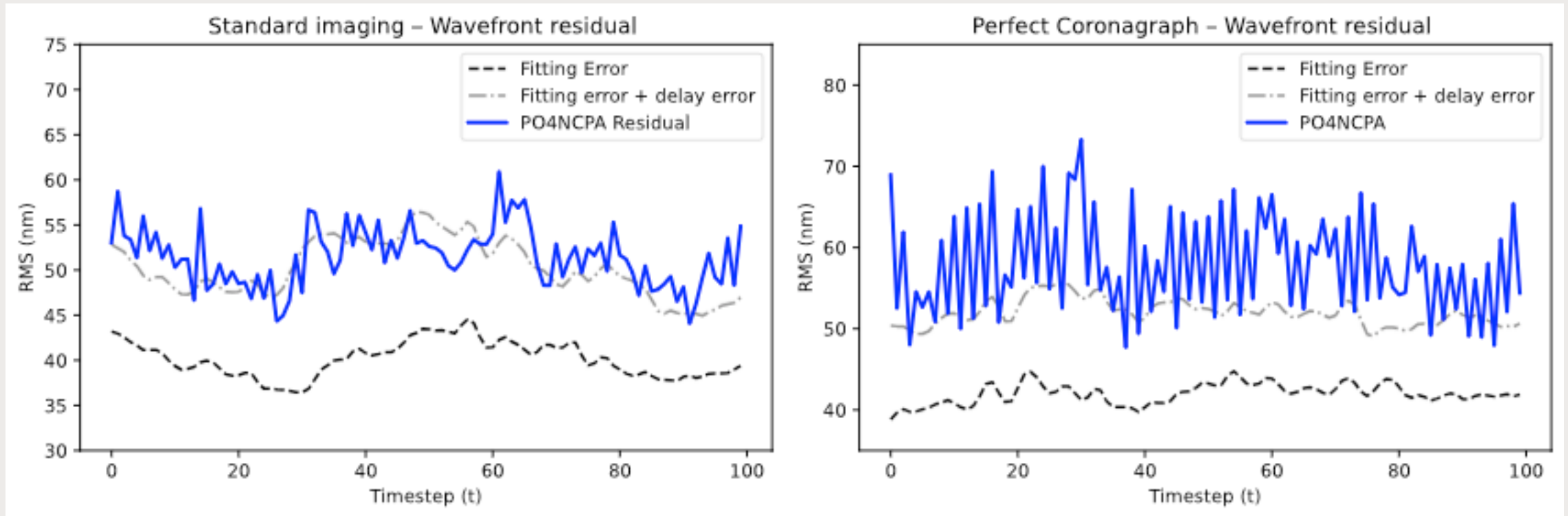
Standard Imaging



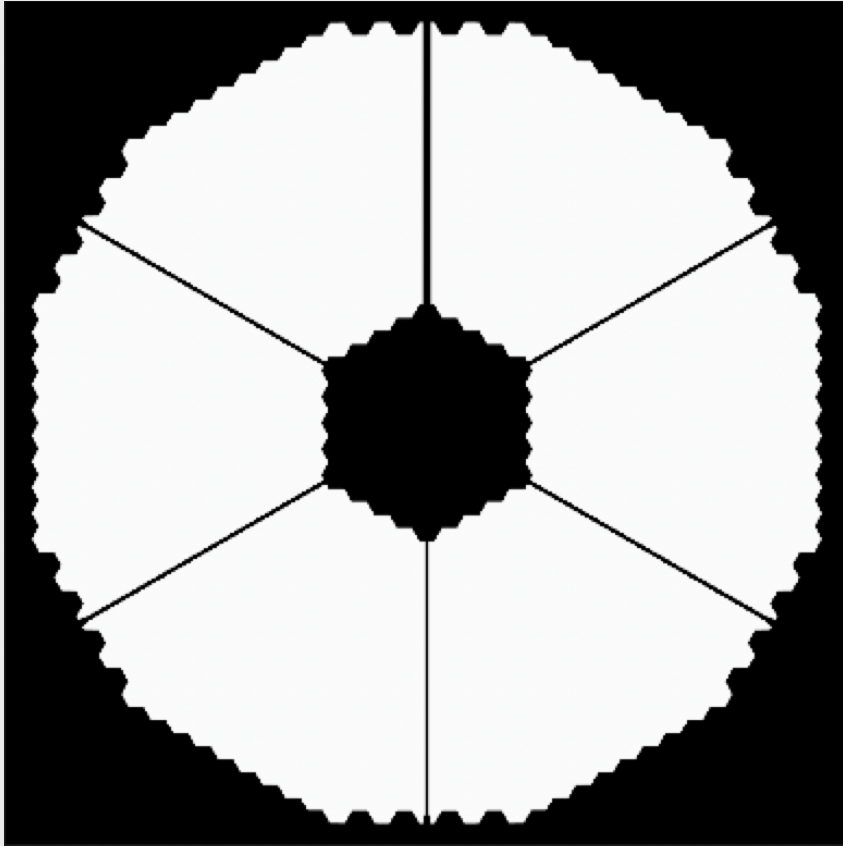
Perfect Coronagraph



PO4NCPA: Dynamic NCPA

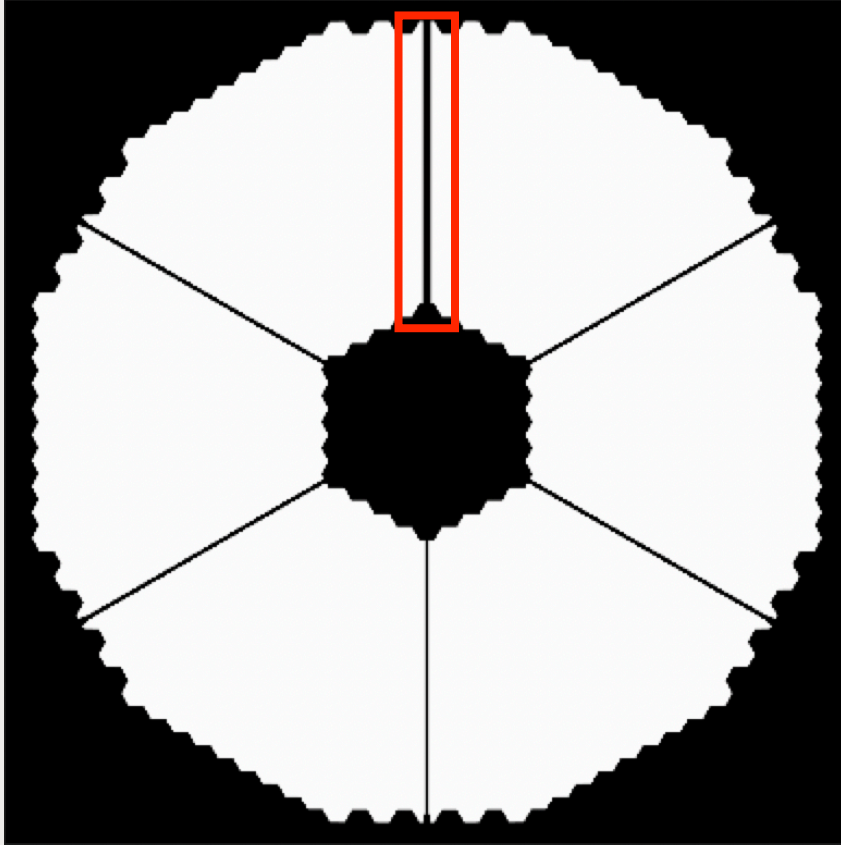


PO4NCPA: Vector Vortex Coronagraph



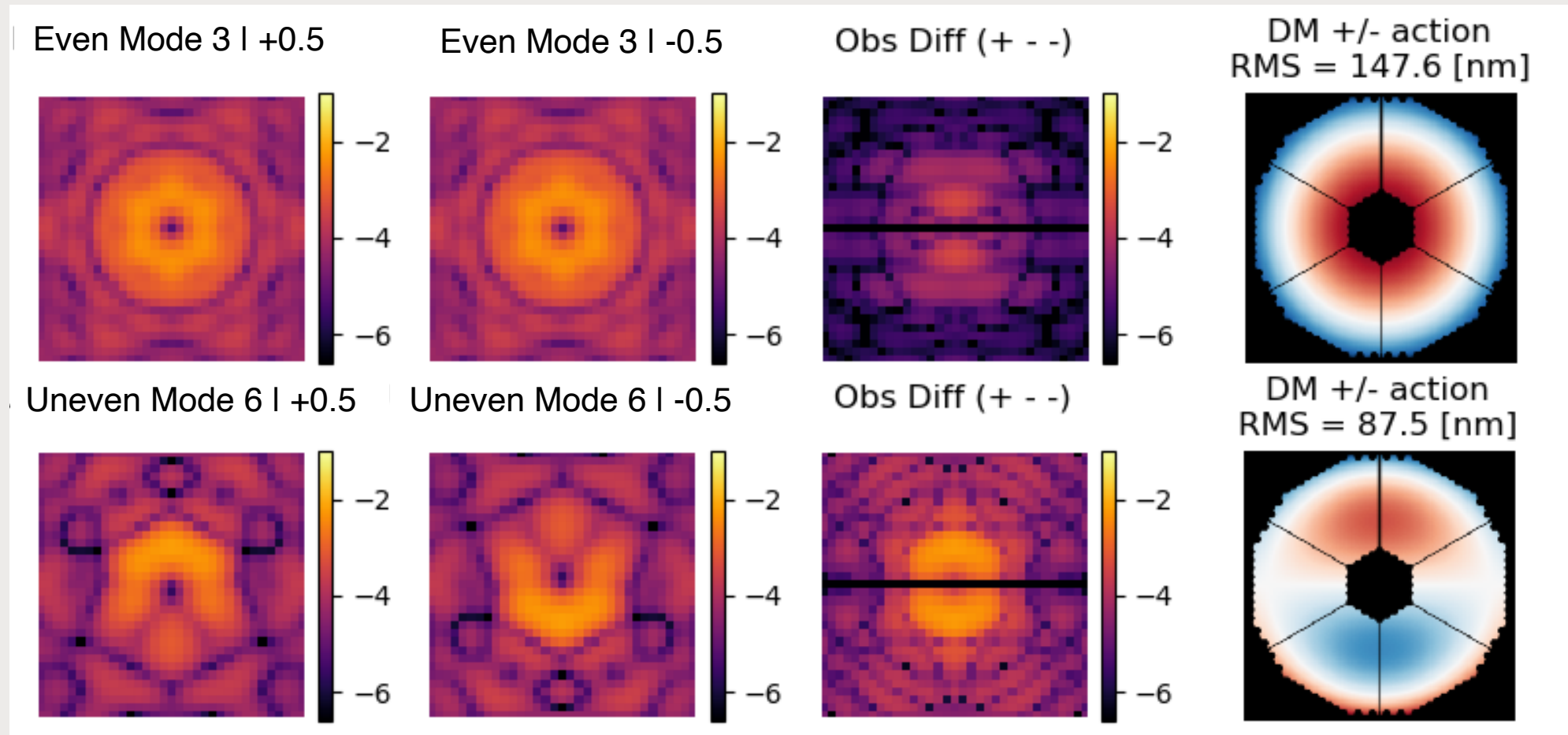
Telescope Diameter	39.3 m
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Wind Speed	10 m/s
Background noise	10e8 #/pix/frame

PO4NCPA: Vector Vortex Coronagraph

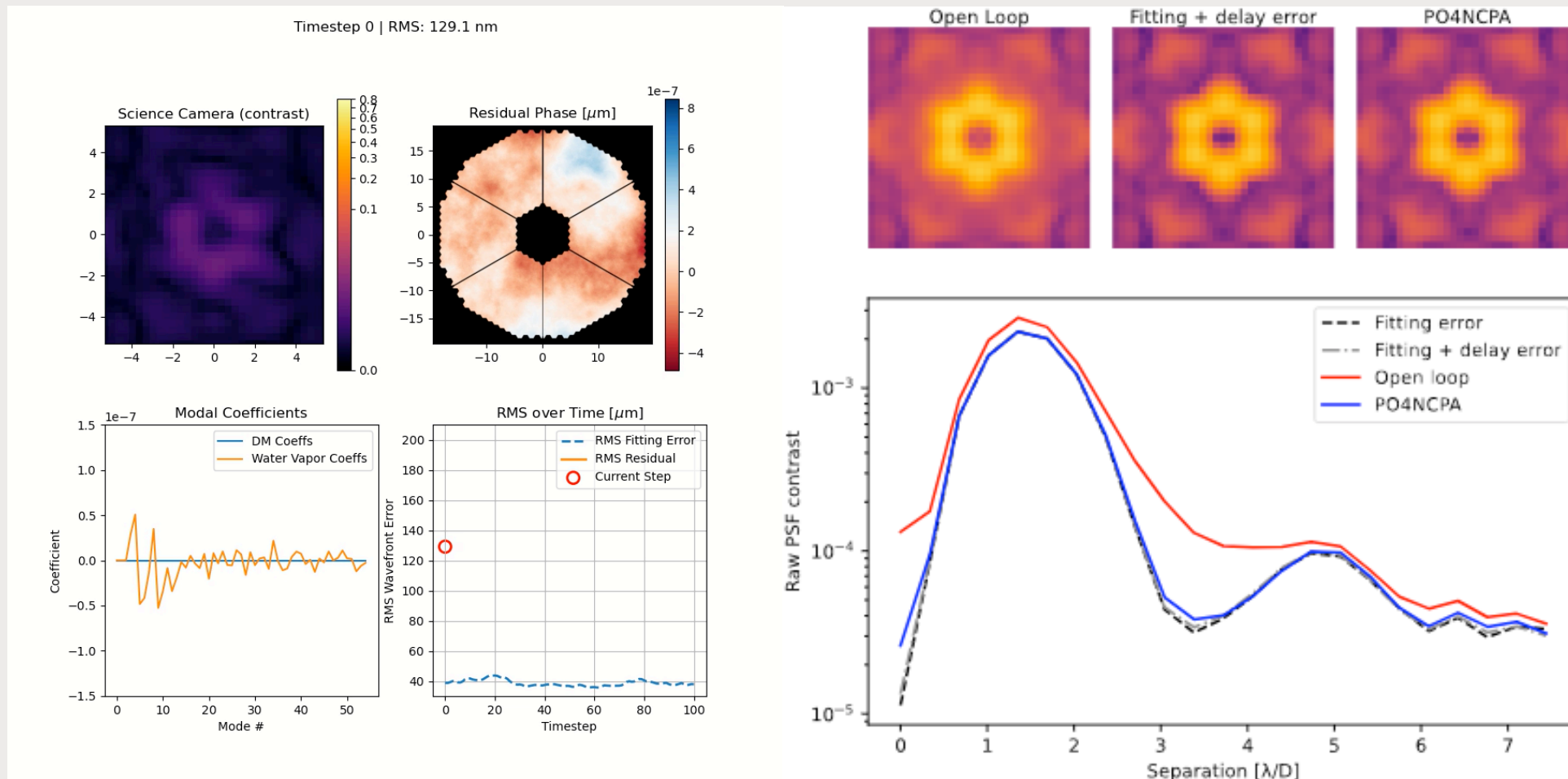


Telescope Diameter	39.3 m
Observation Band	Mid-IR ($11\ \mu\text{m}$)
# Modes Corrected	55
Frame Rate	10 Hz
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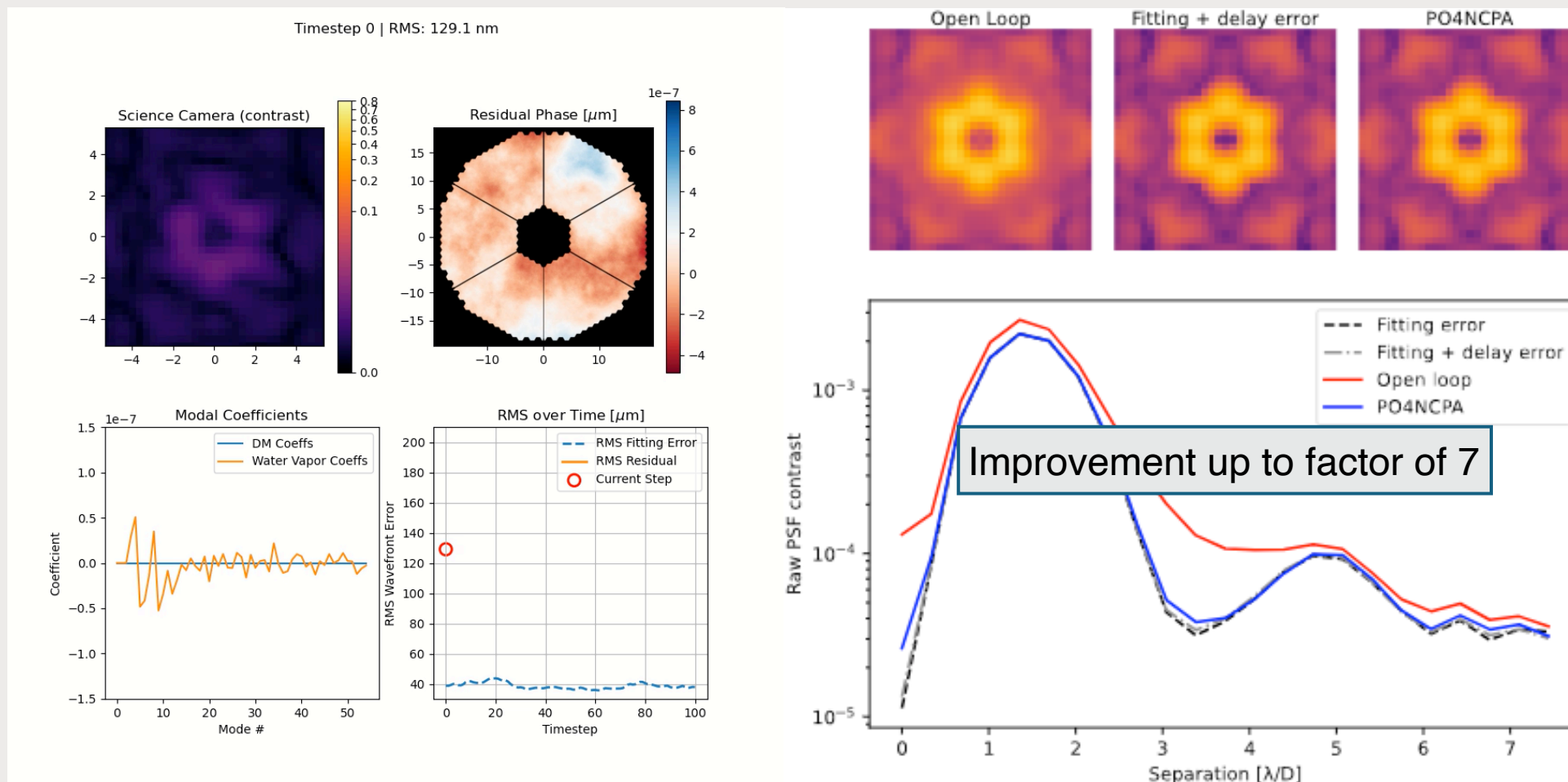
PO4NCPA: Vector Vortex Coronagraph



PO4NCPA: Vector Vortex Coronagraph



PO4NCPA: Vector Vortex Coronagraph



Conclusion

- **Model-free**

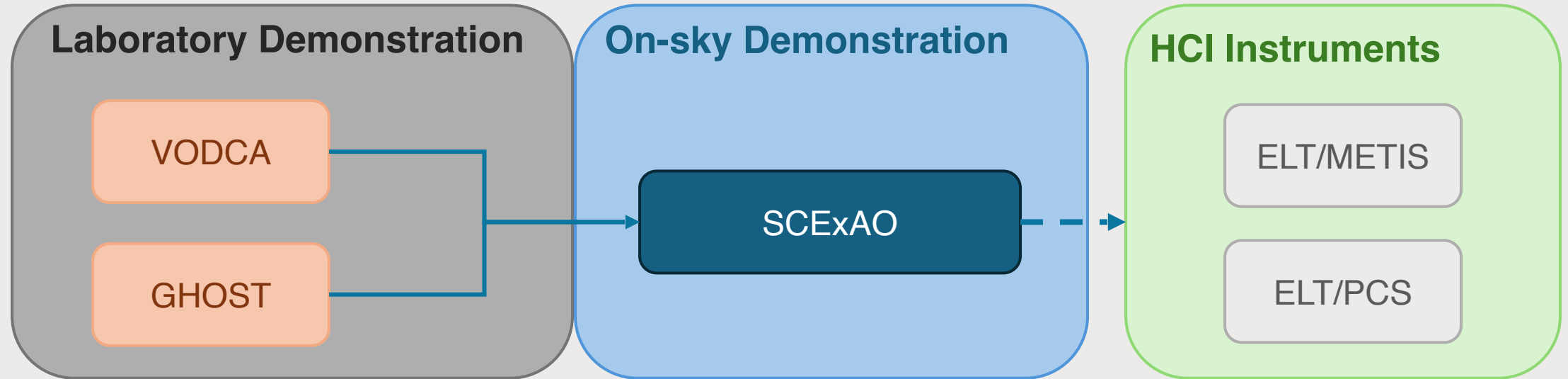
- Works with any aperture, coronagraph
- No flat reference needed

- Fast, sensorless AO adaptive to changing conditions

- Embedded **decision making**

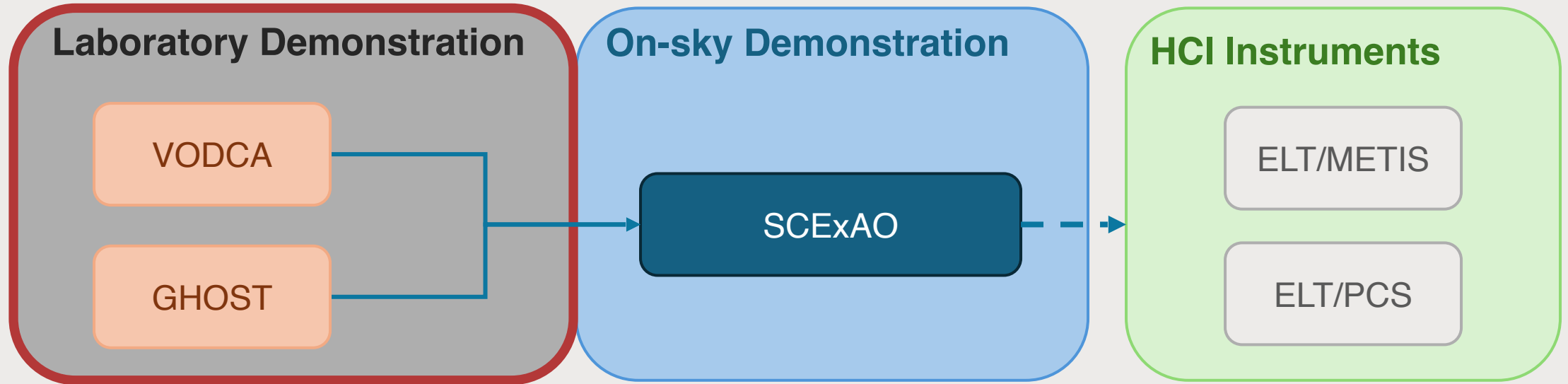
- When to apply phase diversity to achieve the highest reward

Conclusion



- Simulations with AO residuals
- Dark-hole digging

Conclusion



- Simulations with AO residuals
- Dark-hole digging

Focal plane wavefront control with model-based reinforcement learning

Optimizing policies with learned optical models

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e-mail: jalo.nousiainen@eso.org

² STAR Institute, Université de Liège, Allée du Six Août 19C, 4000 Liège, Belgium

For videos:

