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

Iremsu Taskin

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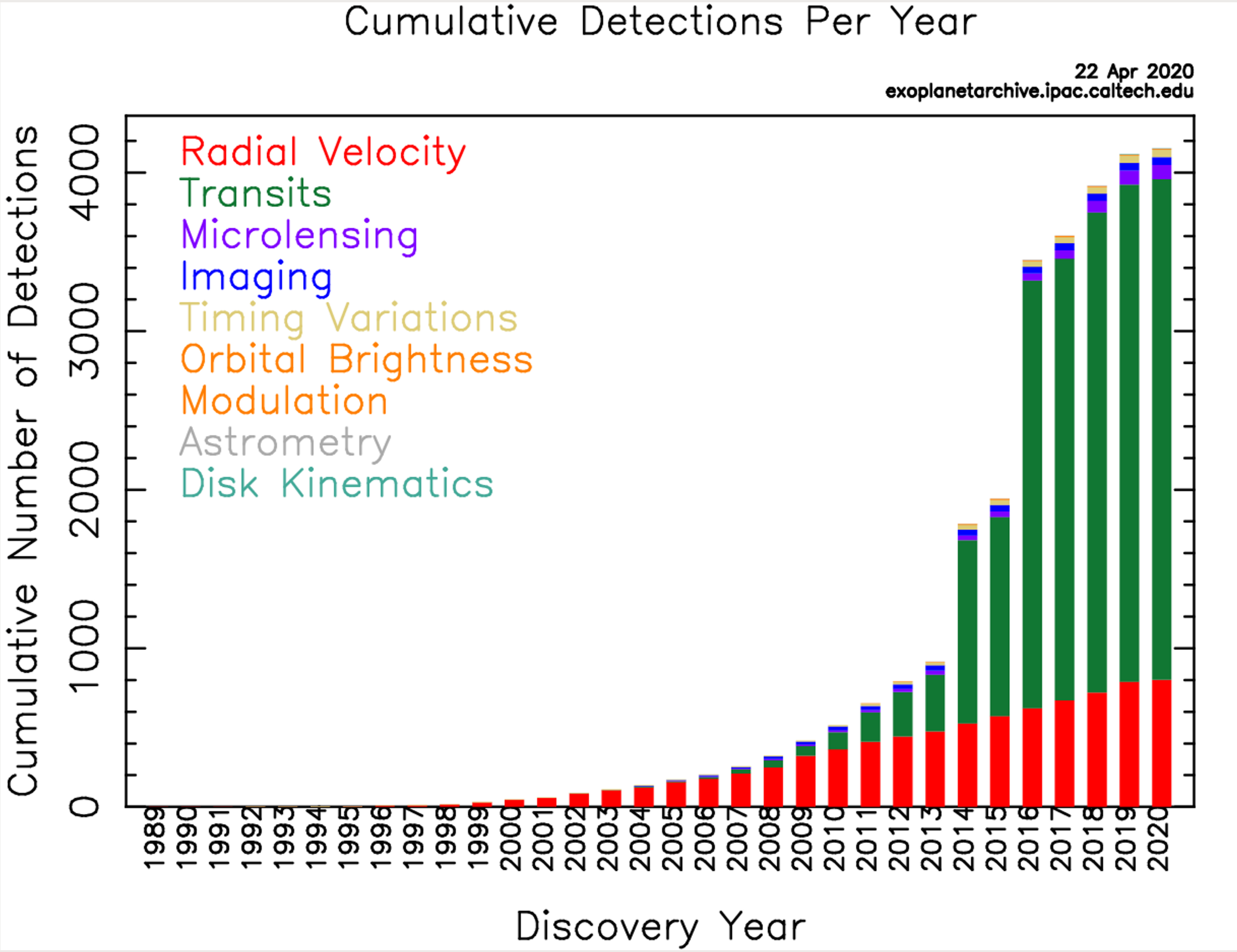
Aim

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



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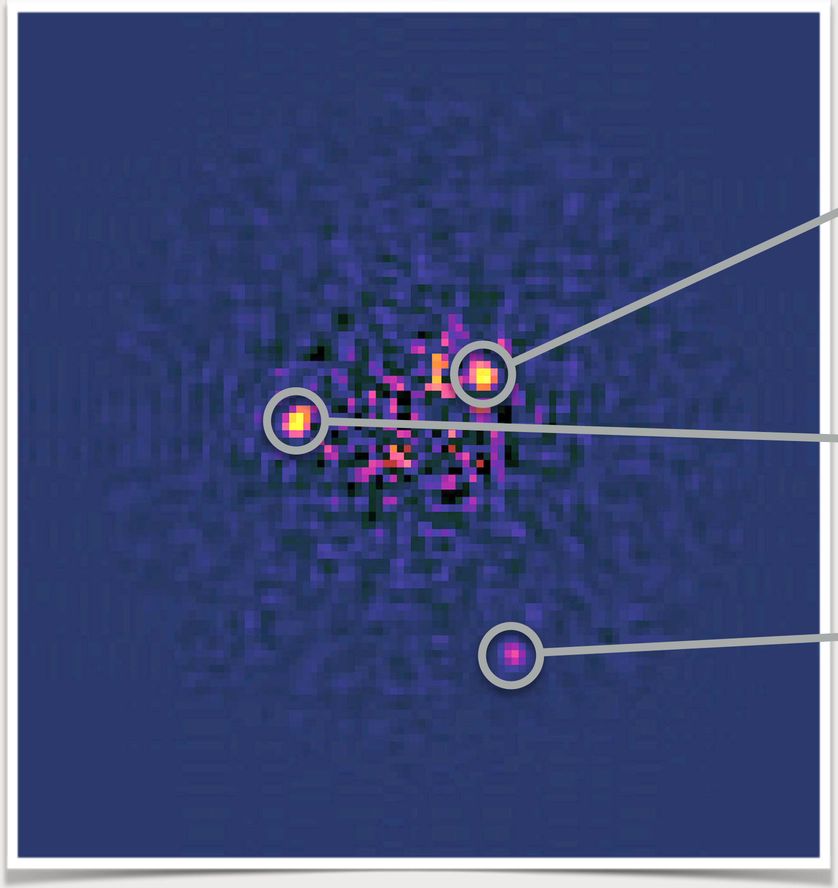
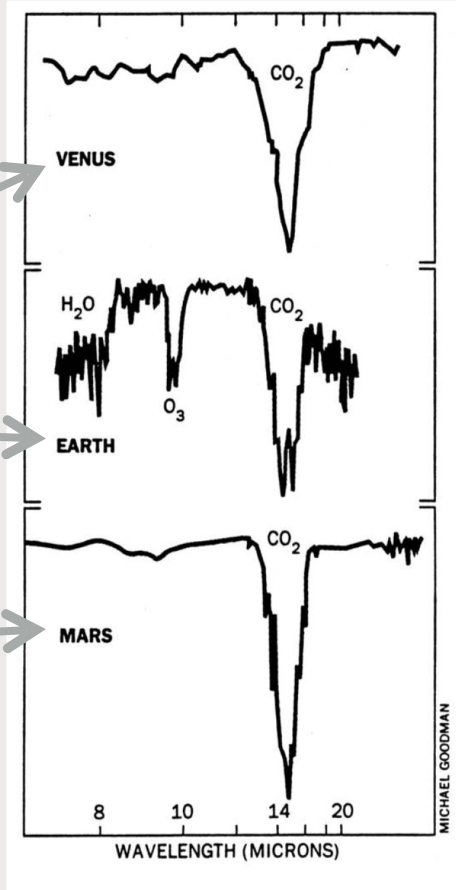
▸ Measure and control aberrations with focal-plane wavefront sensing in coronagraphs



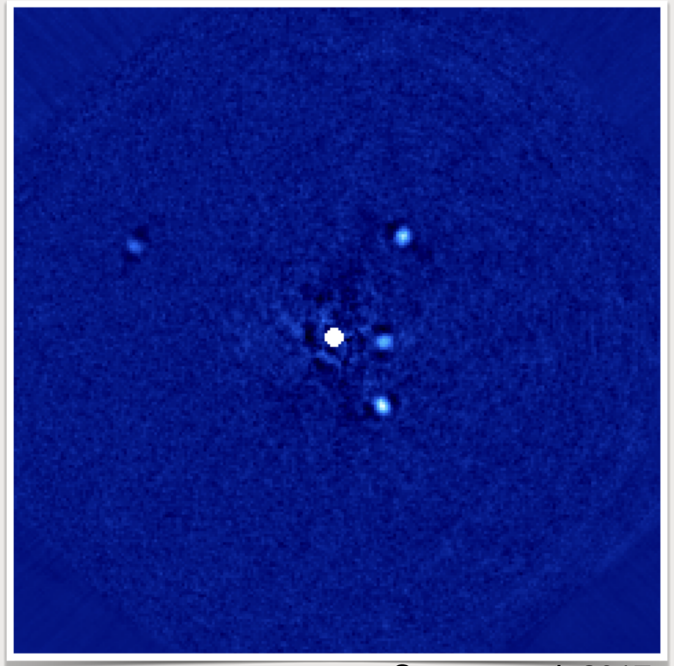


Coronagraphy

- Block star light, transmit planet light

no coronagraph

vortex coronagraph



Gomez et al. 2017

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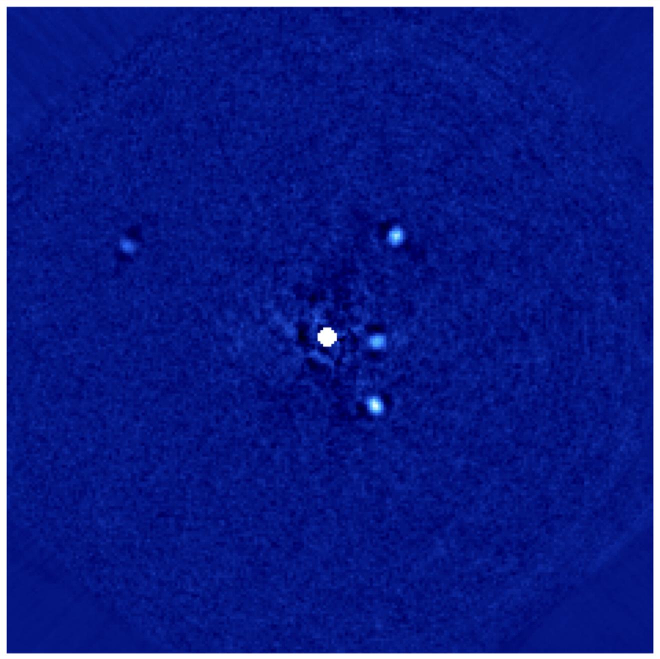
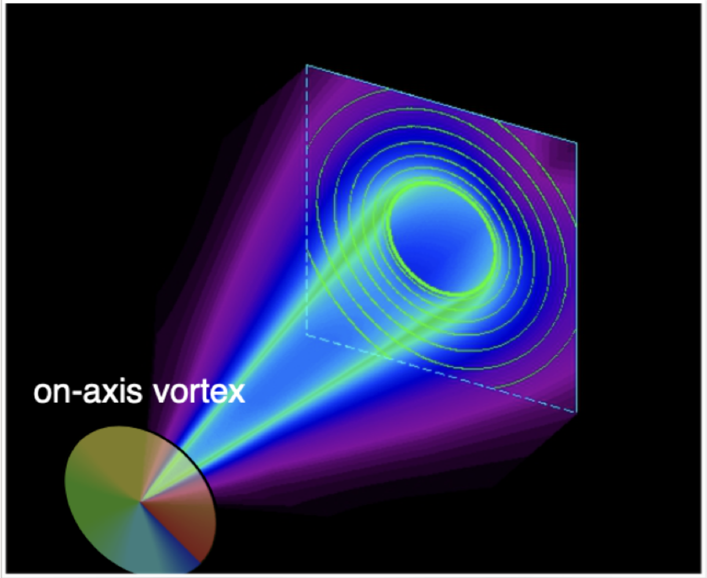
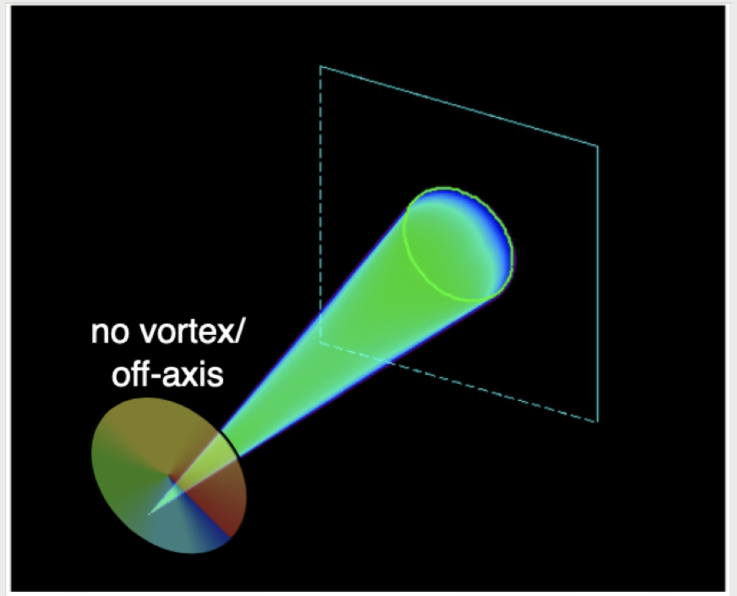


Gomez et al. 2017

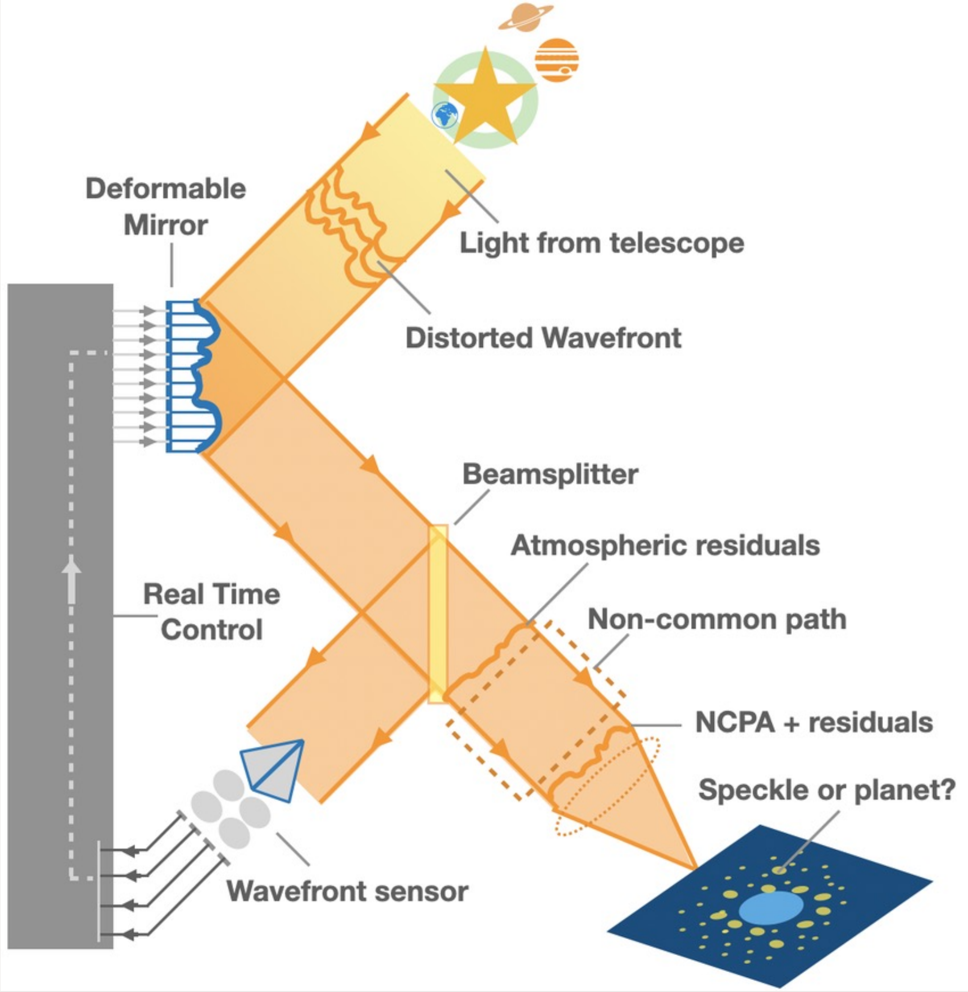
Dimitri Mawet

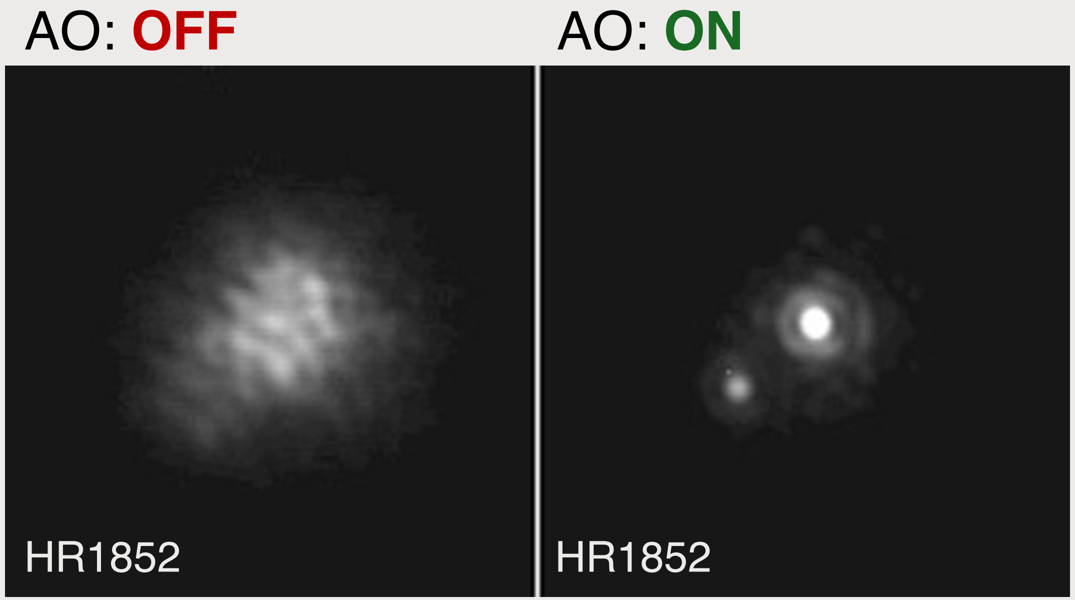




Adaptive Optics (AO)

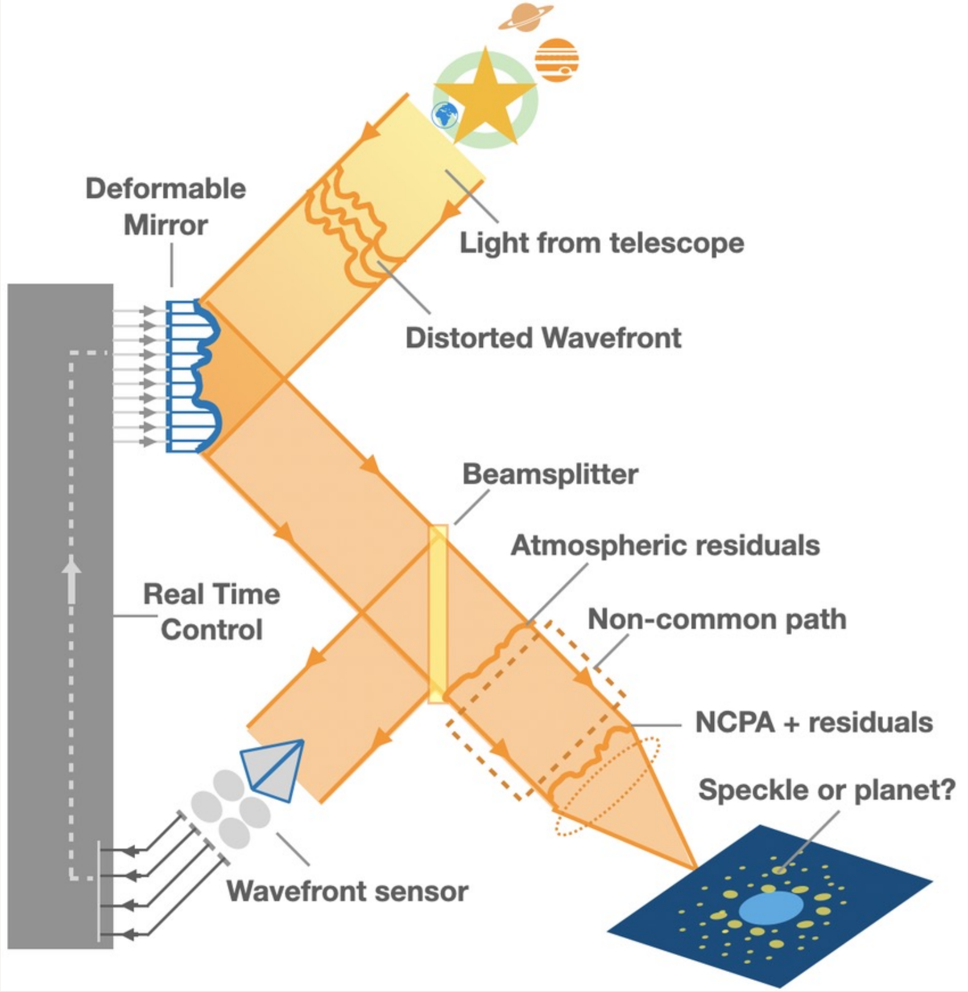
Skaf et al. 2022



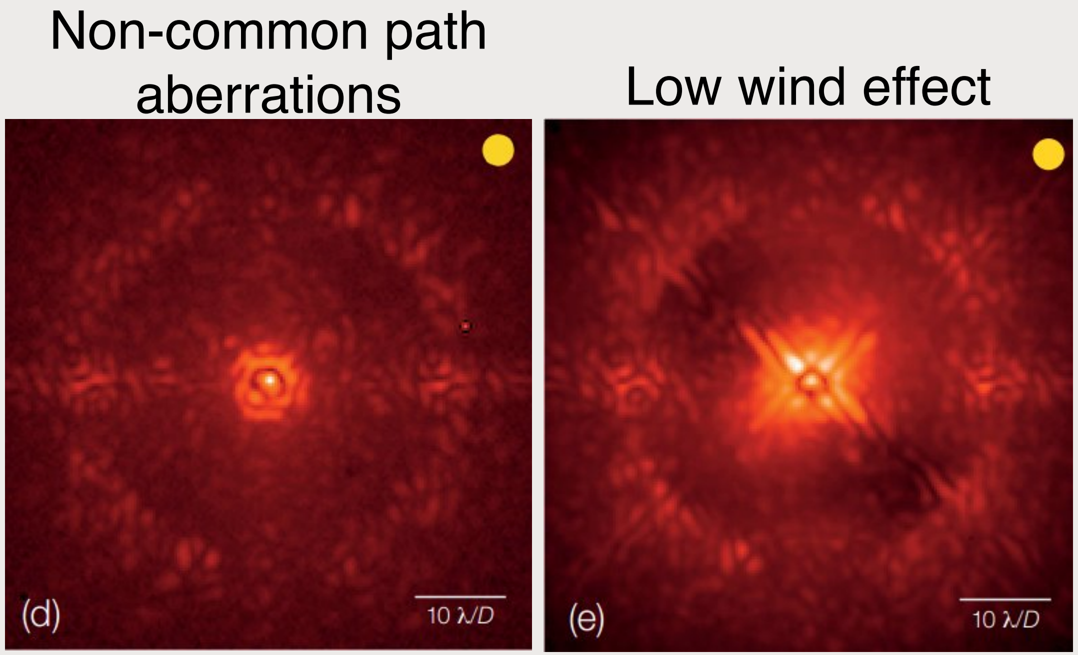


Subaru Telescope, Hawai'i

Adaptive Optics (AO)



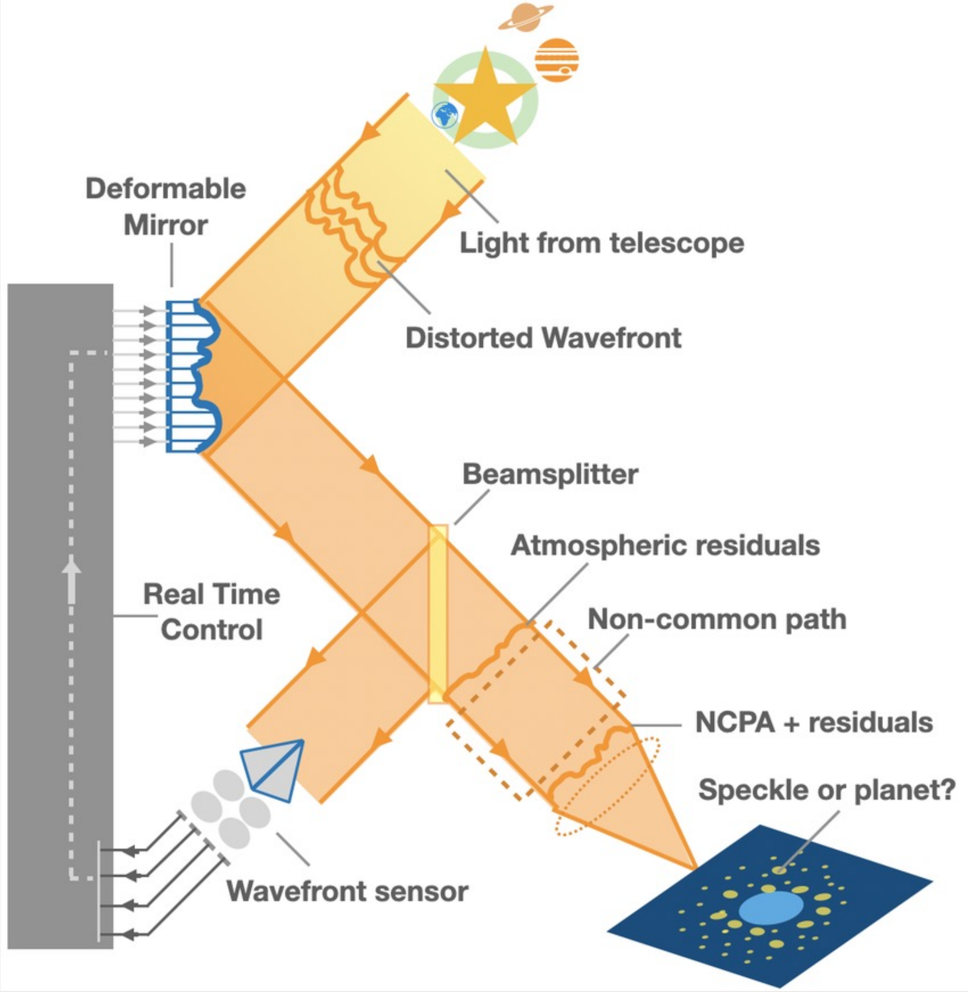
Skaf et al. 2022



SPHERE, Cantalloube et al. 2019

Non-Common Path Aberrations (NCPA)

Skaf et al. 2022



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

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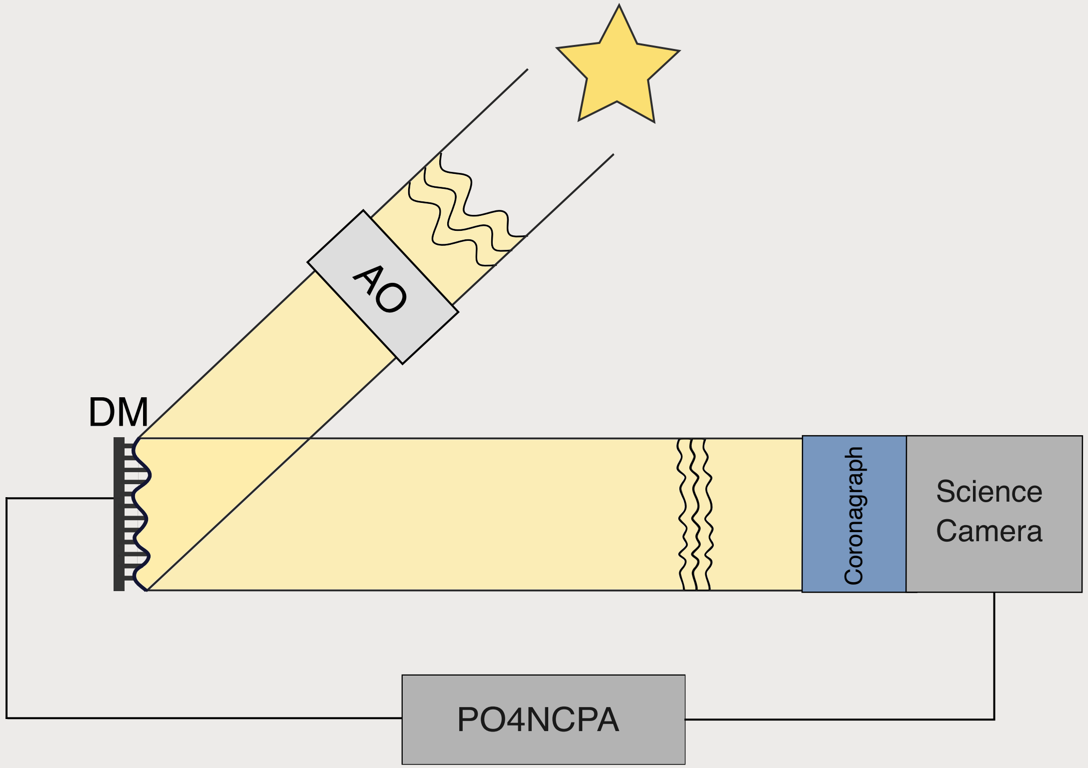
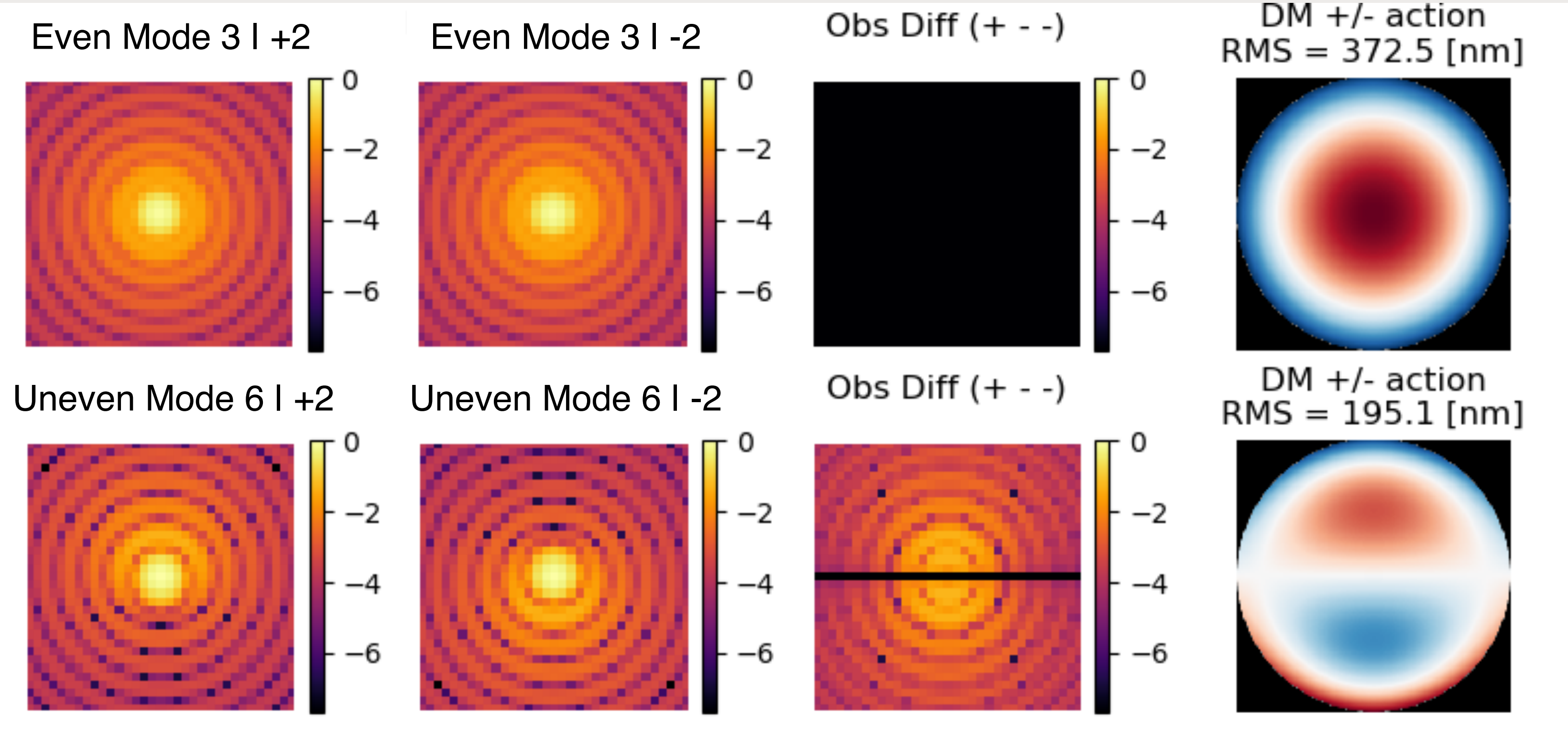


- Wavefront propagating to detectors ≠ wavefront measured by wavefront sensor
  - ➞ Optics located after the beamsplitting, **chromatic aberrations**
- Focal plane wavefront sensor (FP-WFS)
  - Intensity measured at focal plane
  - Estimation of the aberrations on the complete optical path → images taken 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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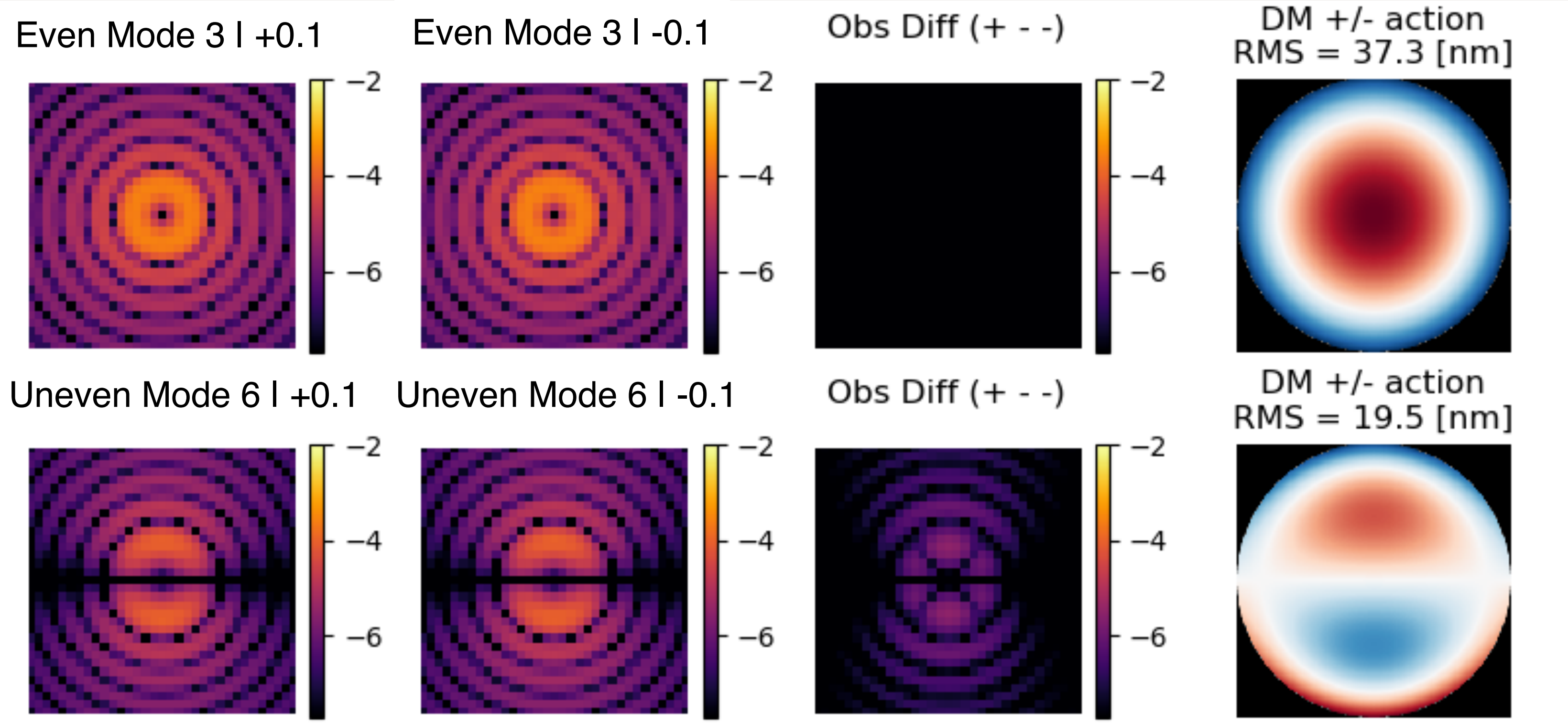
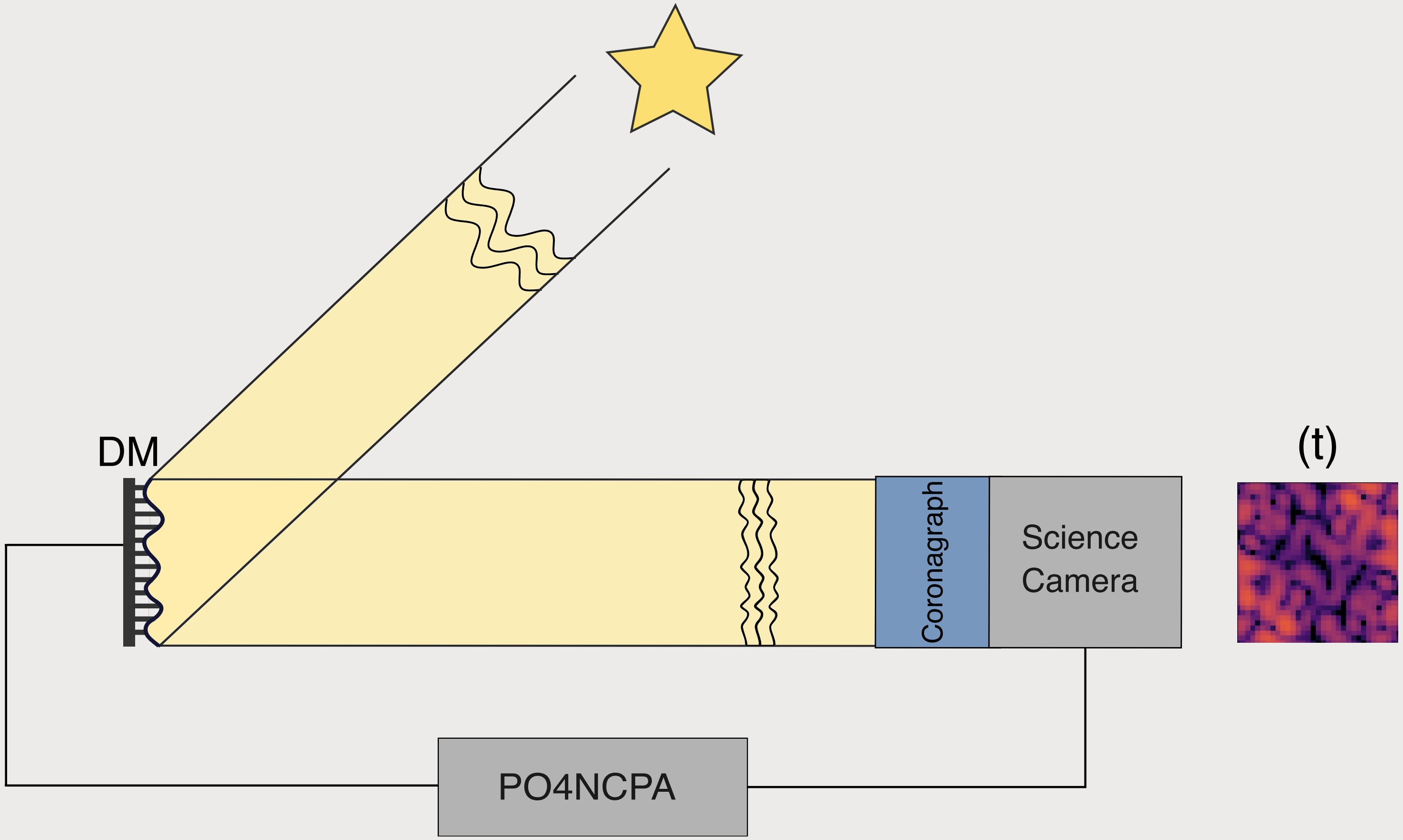
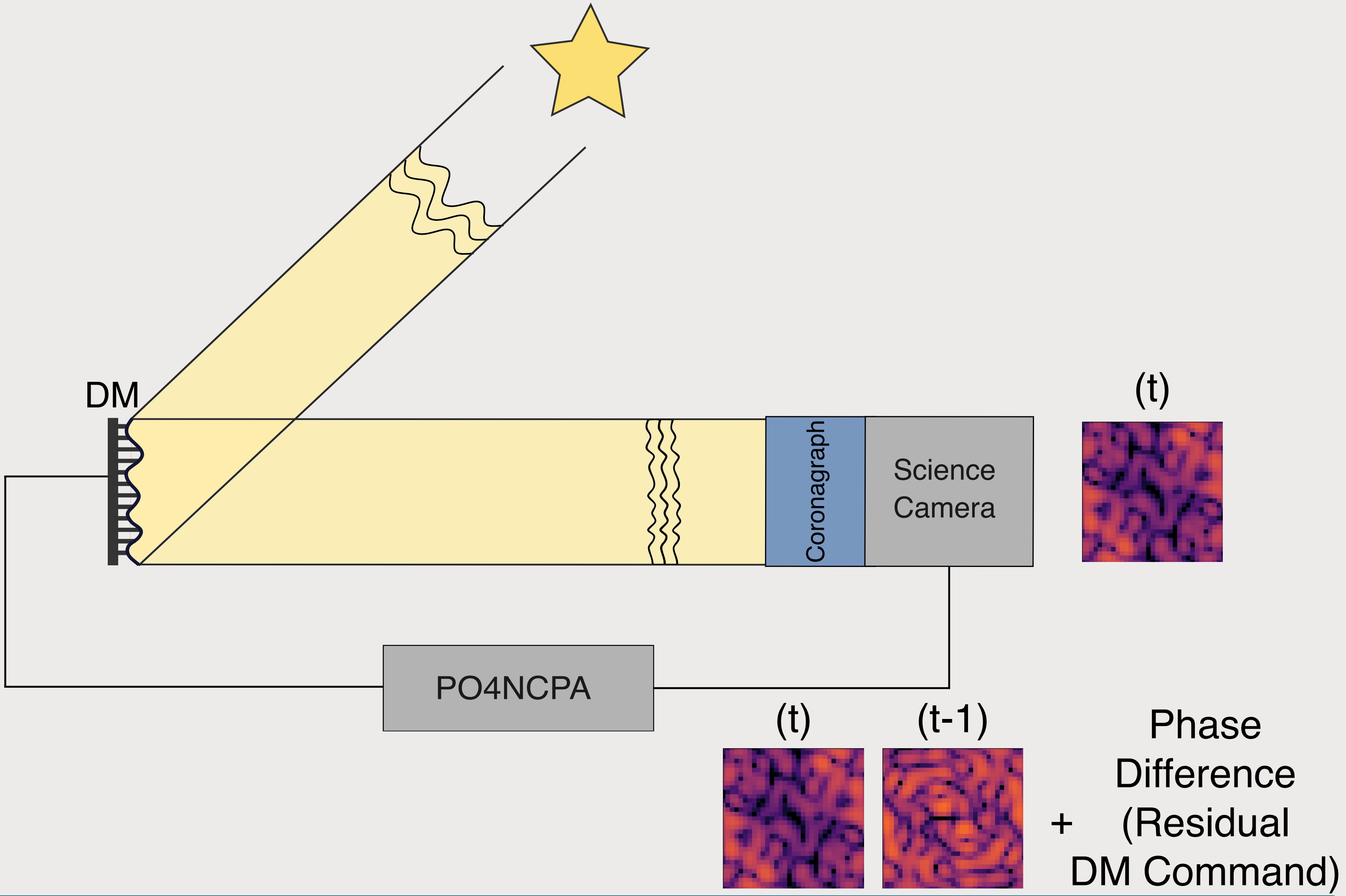
Perfect Coronagraph



Sequential Phase Diversity



Sequential Phase Diversity



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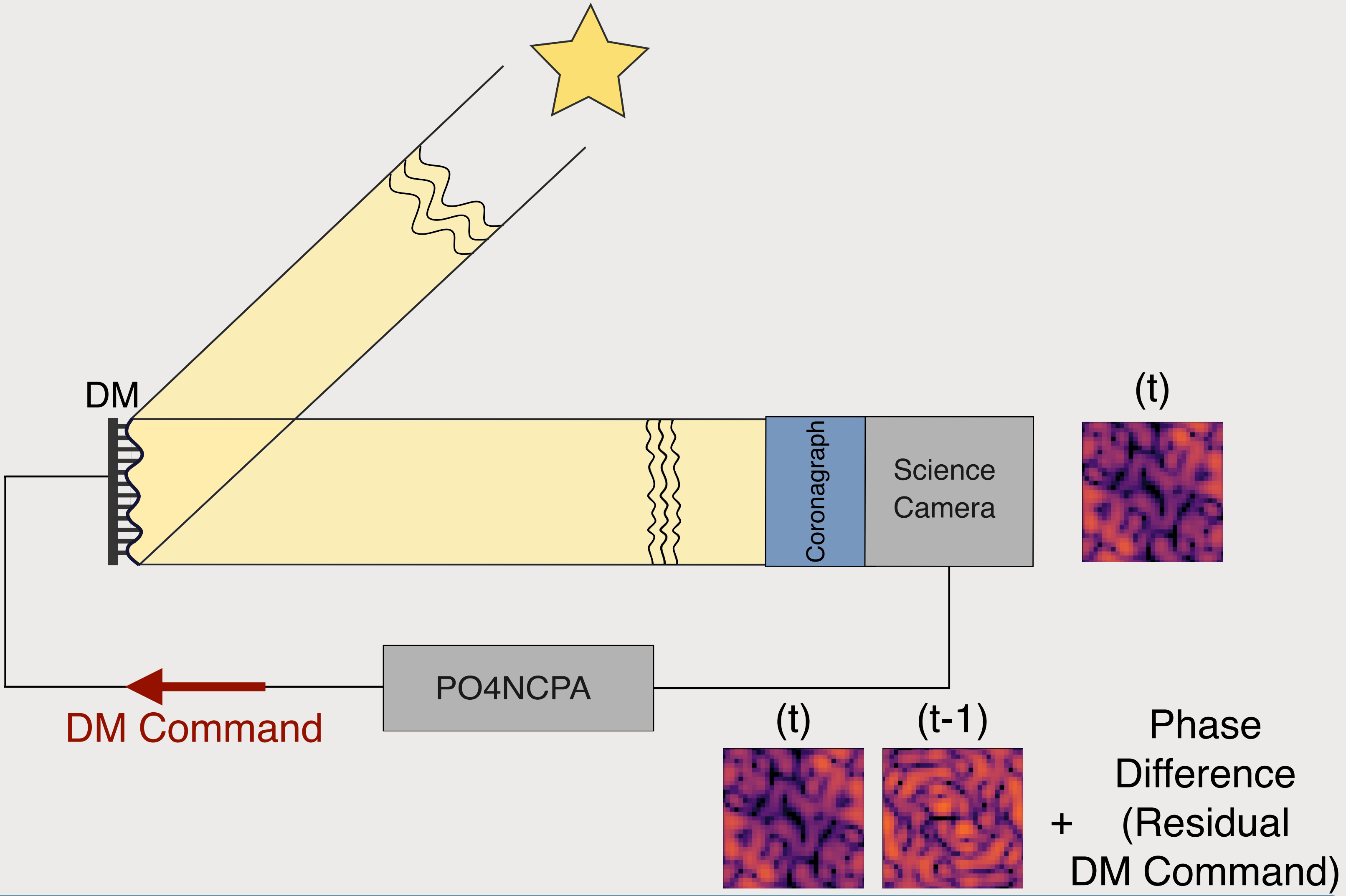
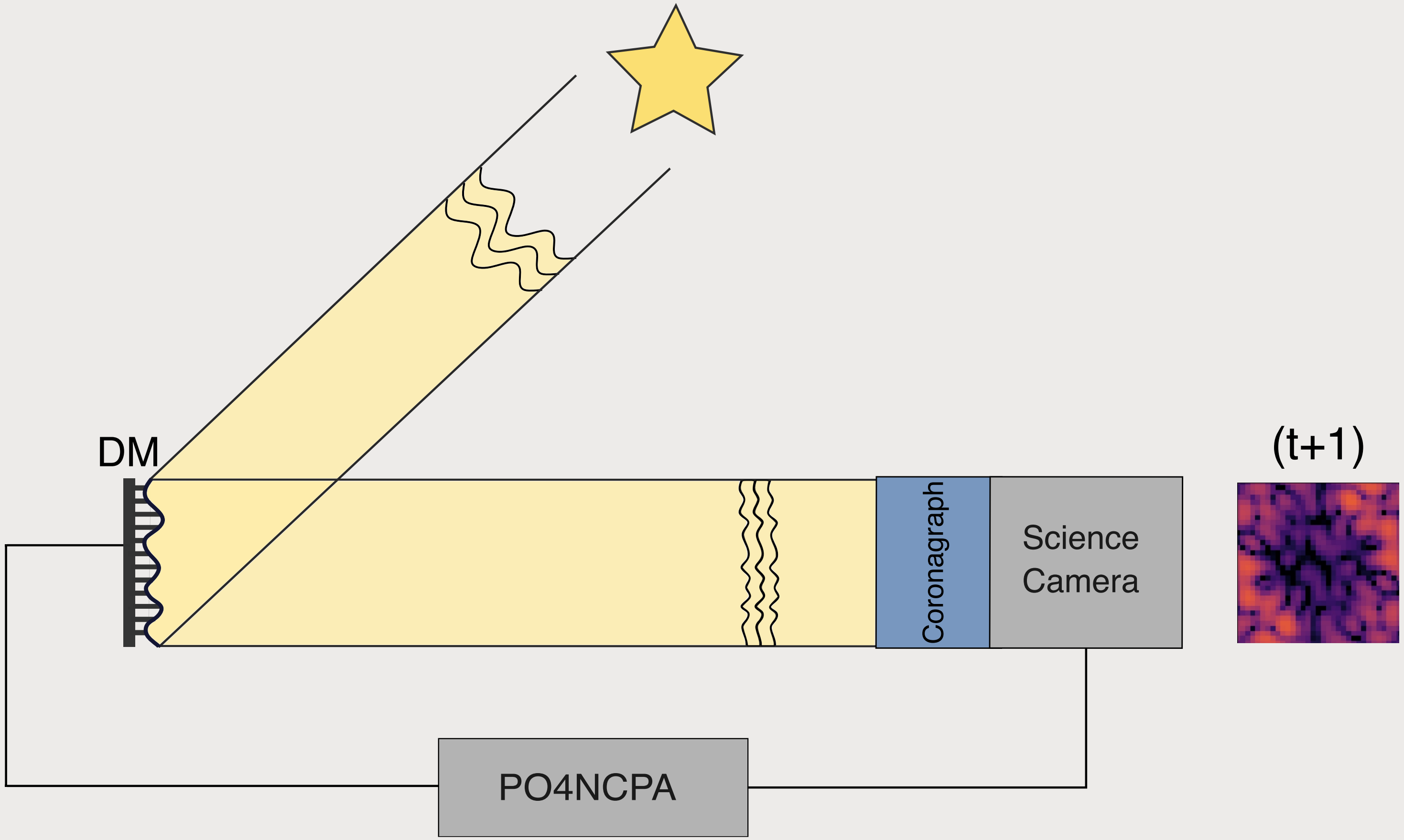
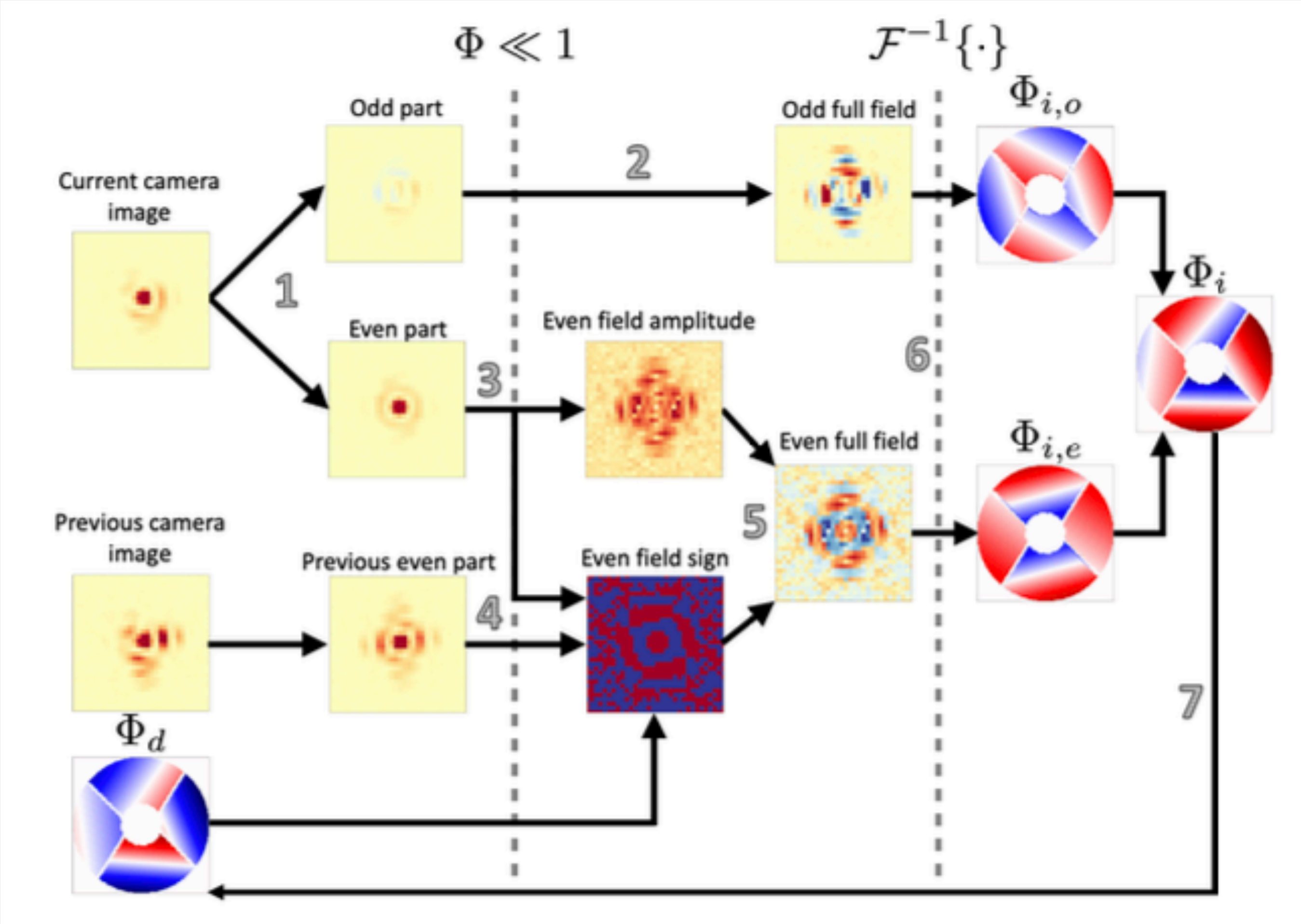


Sequential Phase Diversity

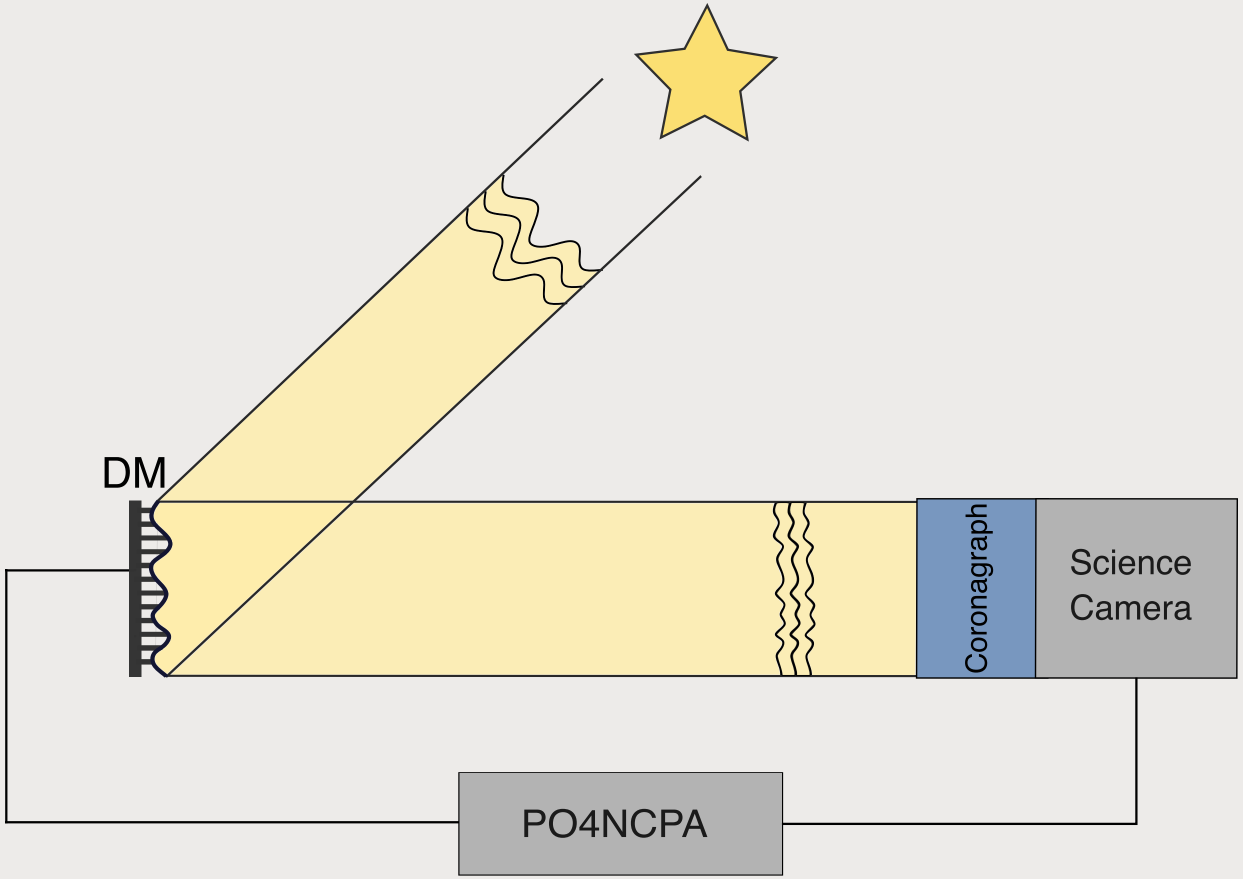


Fast and Furious



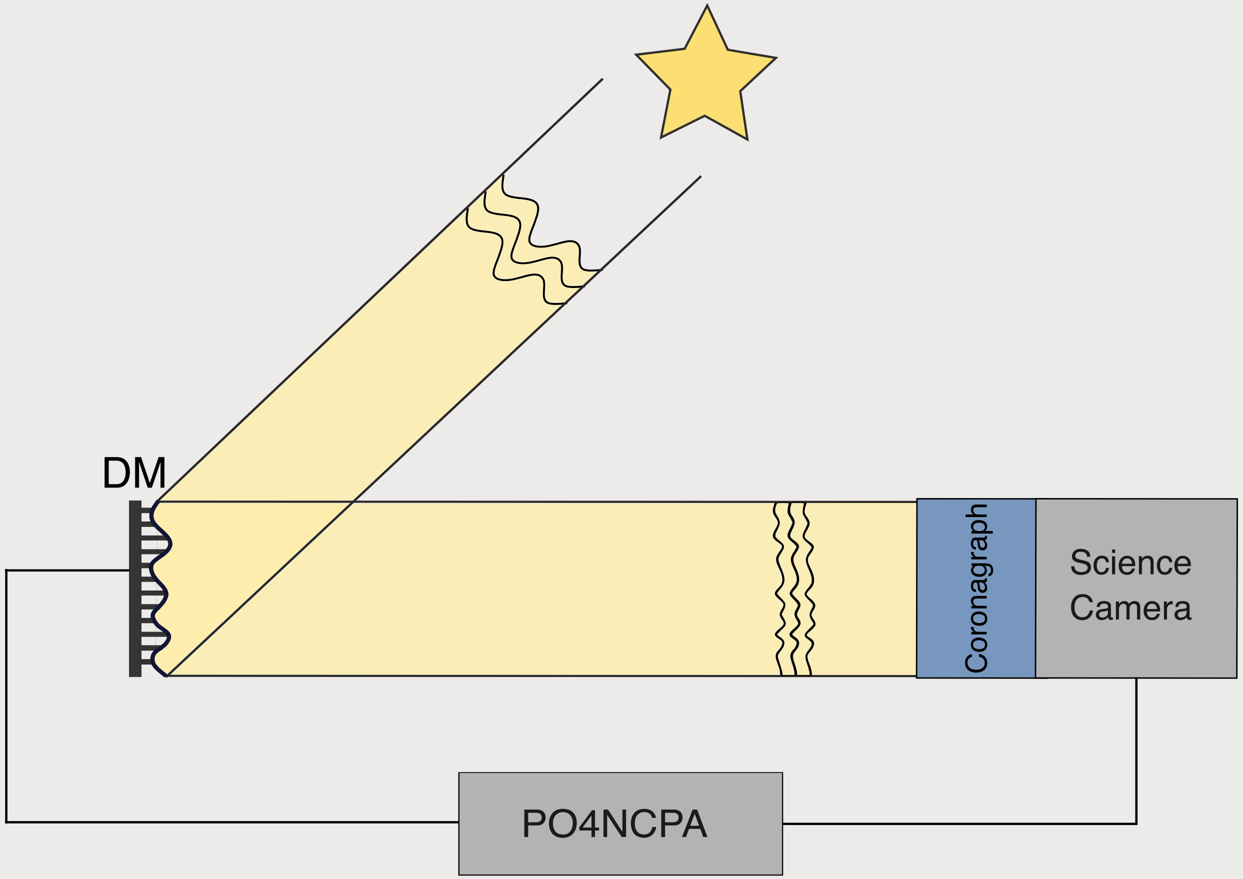
- Low wind effect
- Iteratively minimise focal plane aberrations
- On-sky testing (Keck & Subaru)
- Not compatible with coronagraphs

PO4NCPA



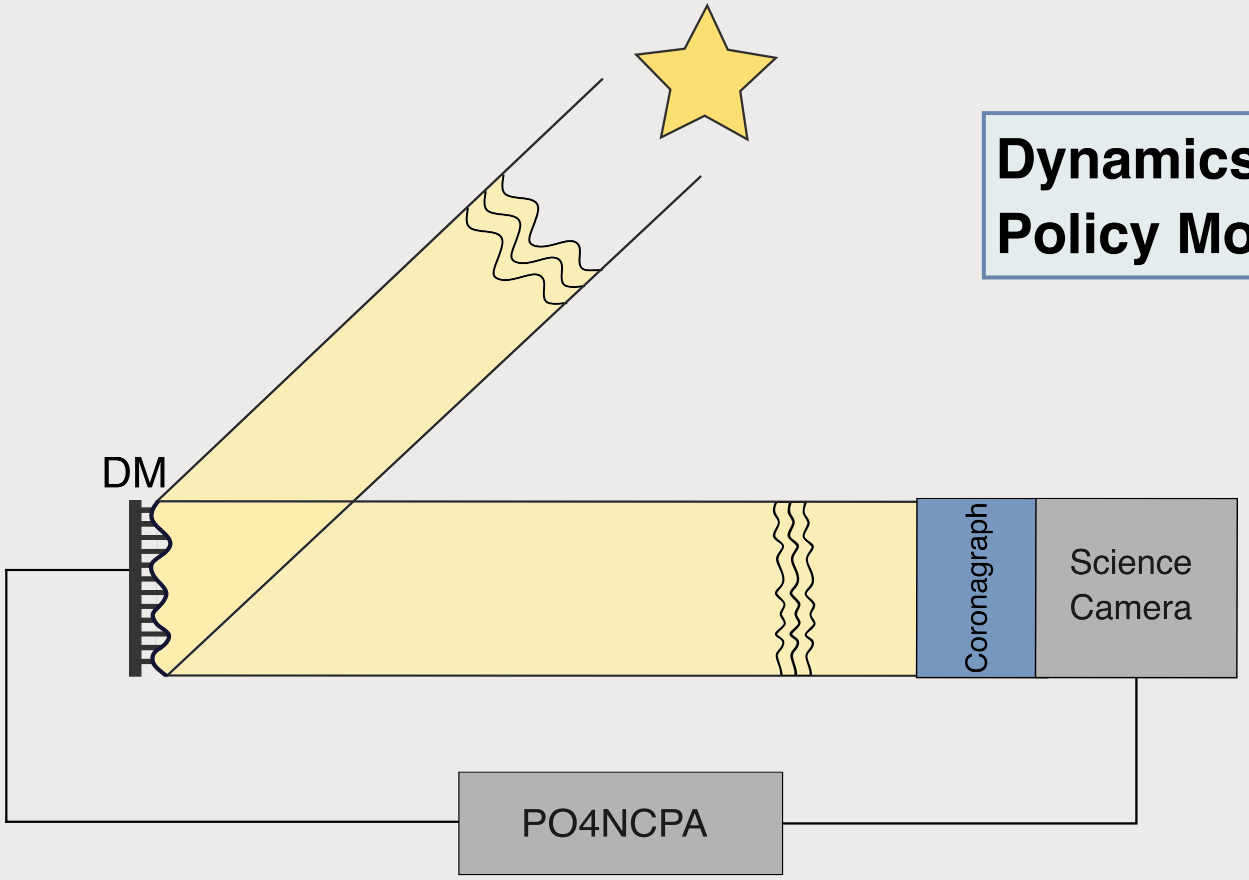
$$\arg\max_{\theta} \mathbb{E}_{p_\theta(s_0,\ldots,s_T)}\left[\sum_{t=0}^{T} r(\boldsymbol{s}_t, \pi_\theta(\boldsymbol{s}_t))\right]$$

PO4NCPA



obtain desired image

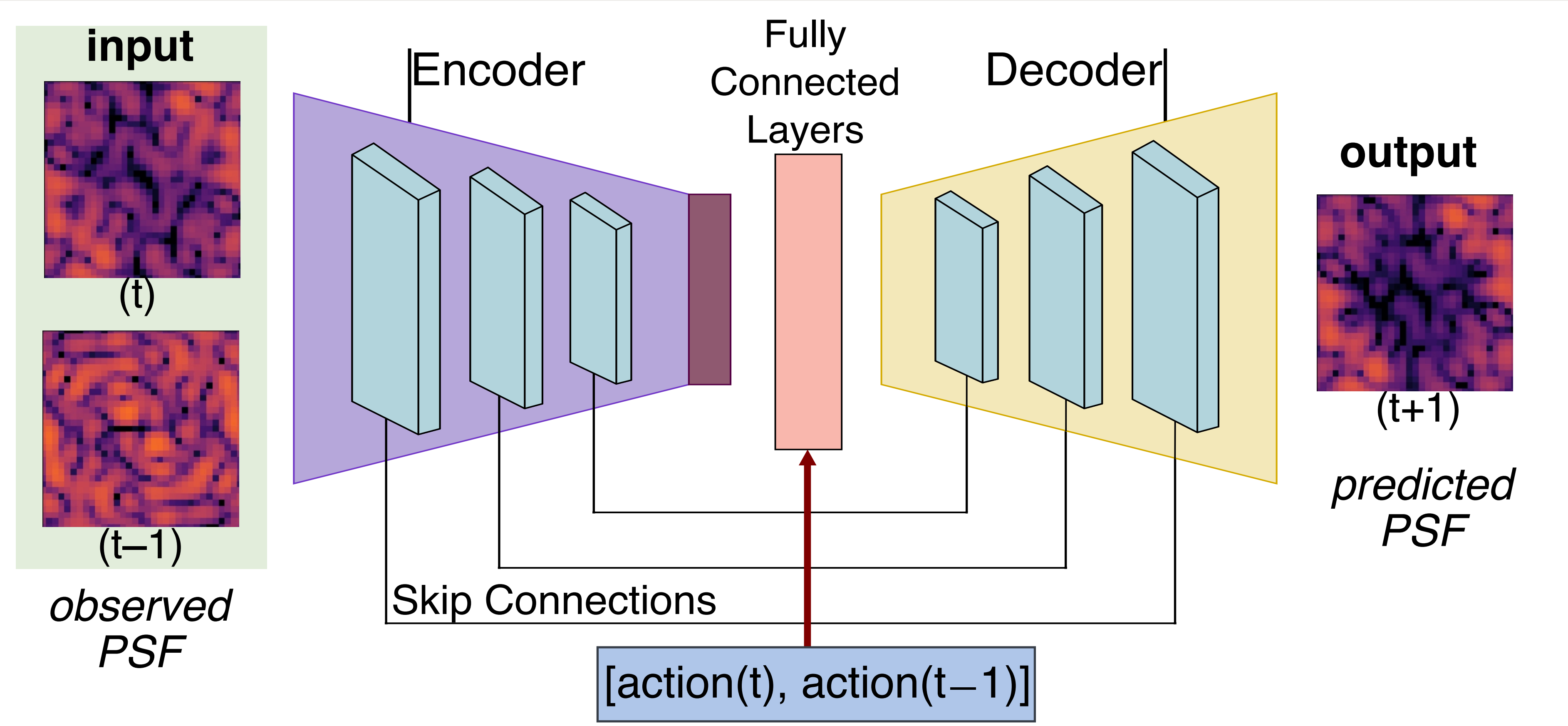
PO4NCPA



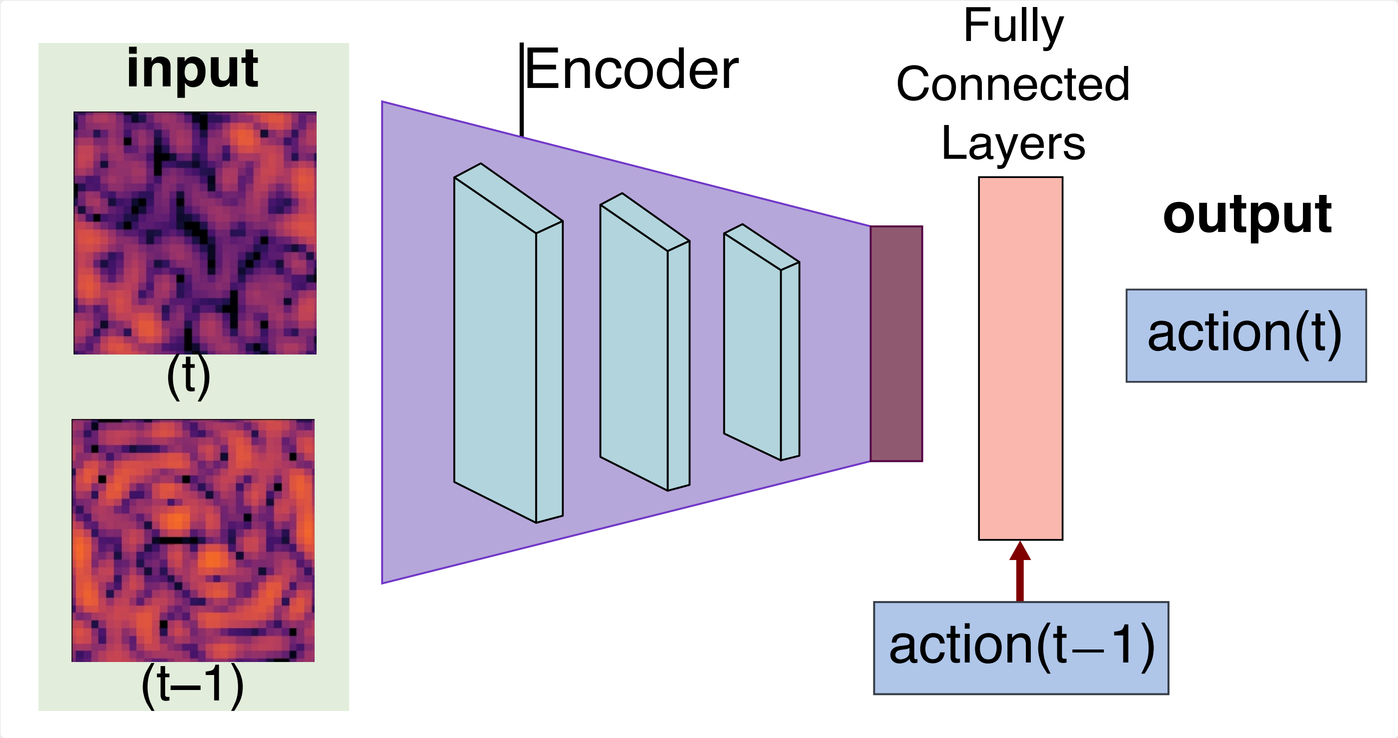
Dynamics Model: environment model
Policy Model: control algorithm

obtain desired image

PO4NCPA: Dynamics Model



PO4NCPA: Policy Model



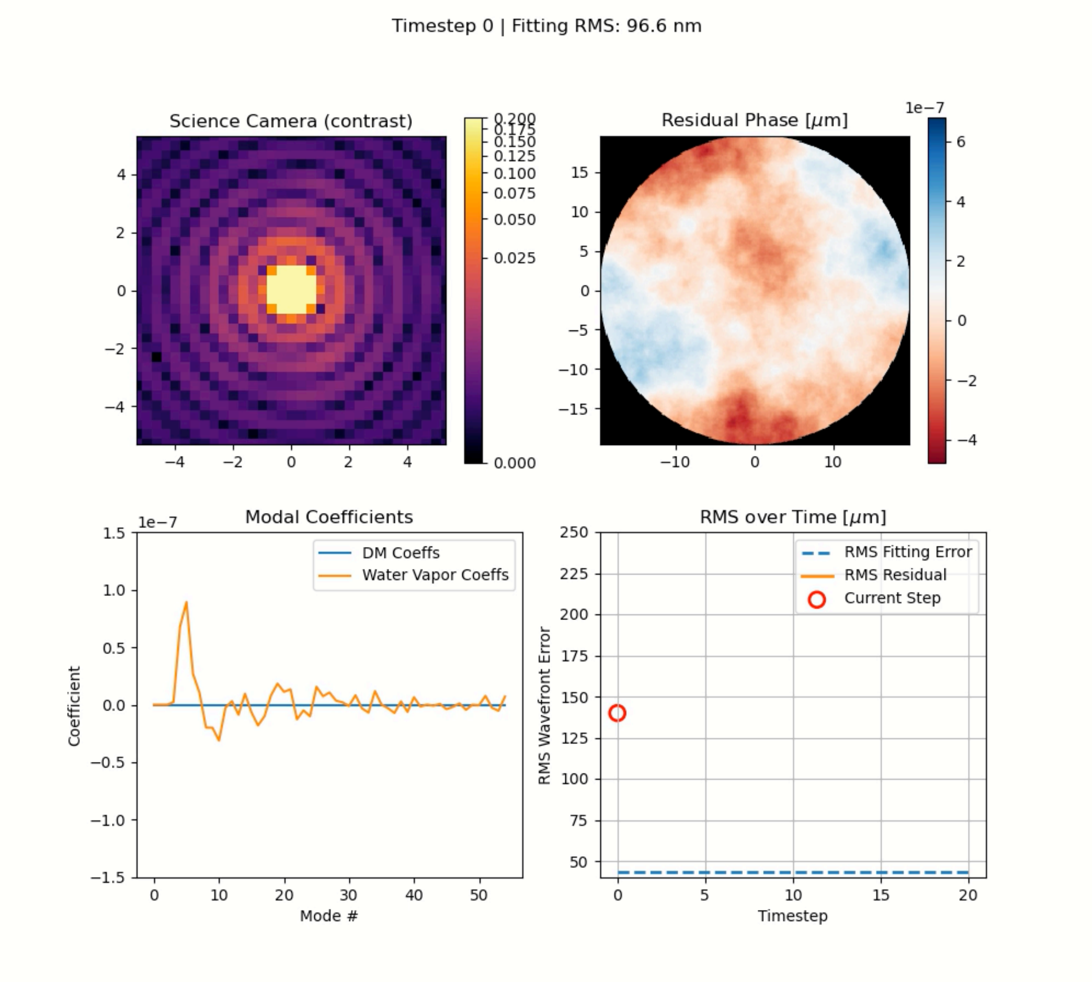
PO4NCPA: Simulation

- **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*

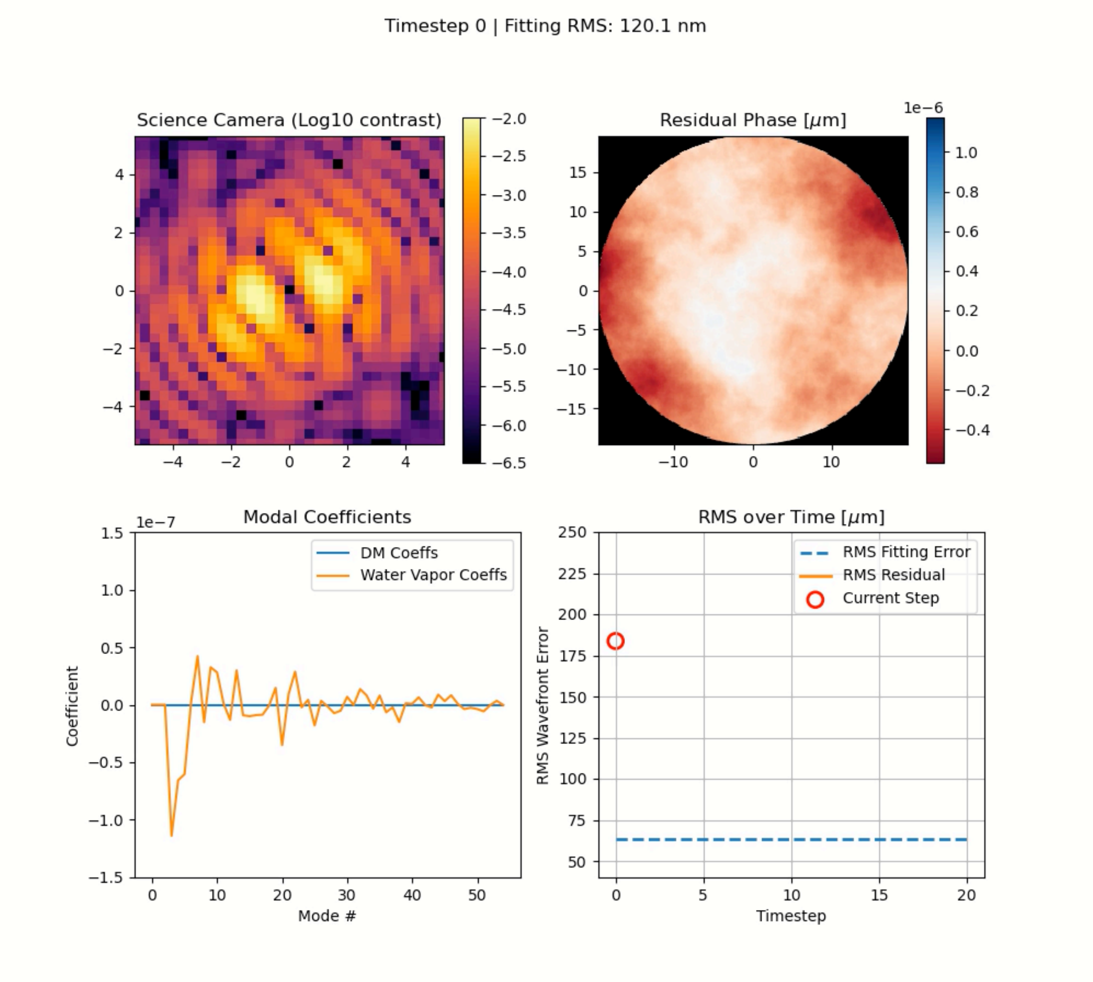
Telescope Diameter	39.3 m
Observation Band	Mid-IR (11 μm)
# Modes Corrected	55
Frame Rate	10 Hz
Median NCPA RMS	286 nm
Fried Parameter	95 m (at 11 μm)
Wind Speed	10 m/s

PO4NCPA: Static NCPA

Standard Imaging



Perfect Coronagraph



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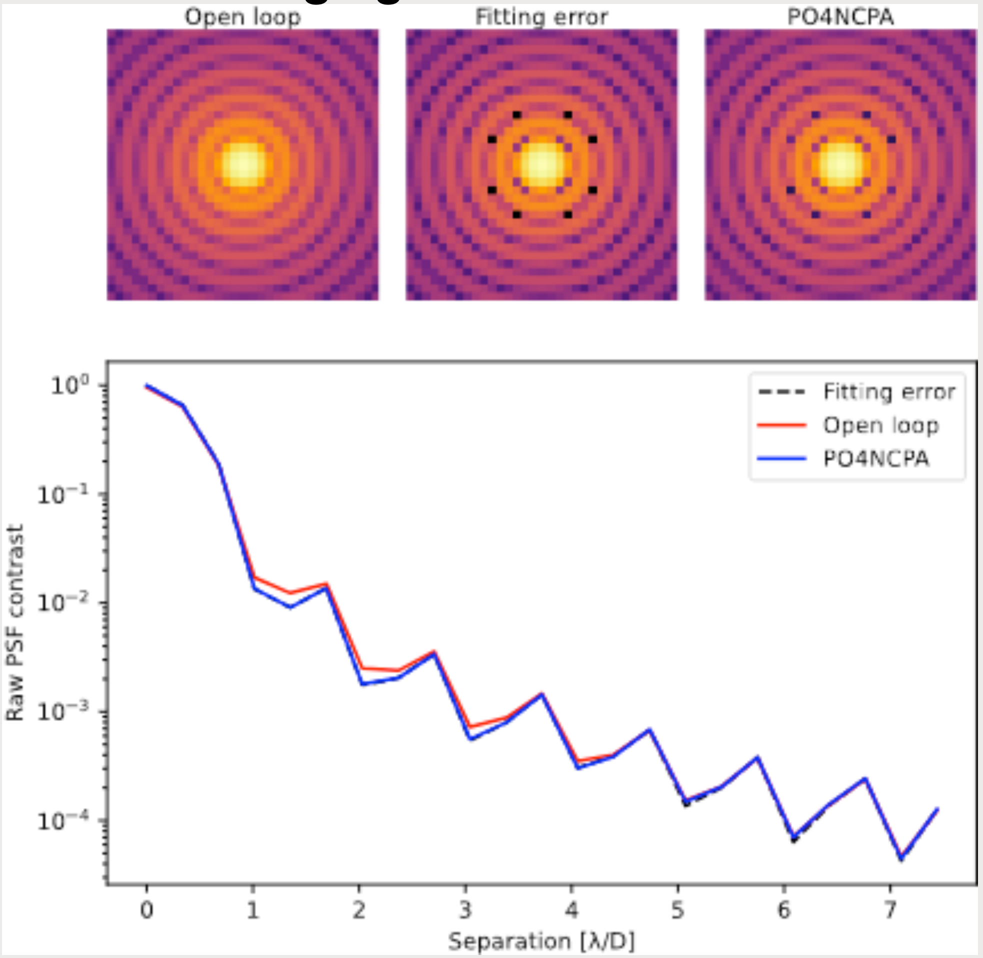

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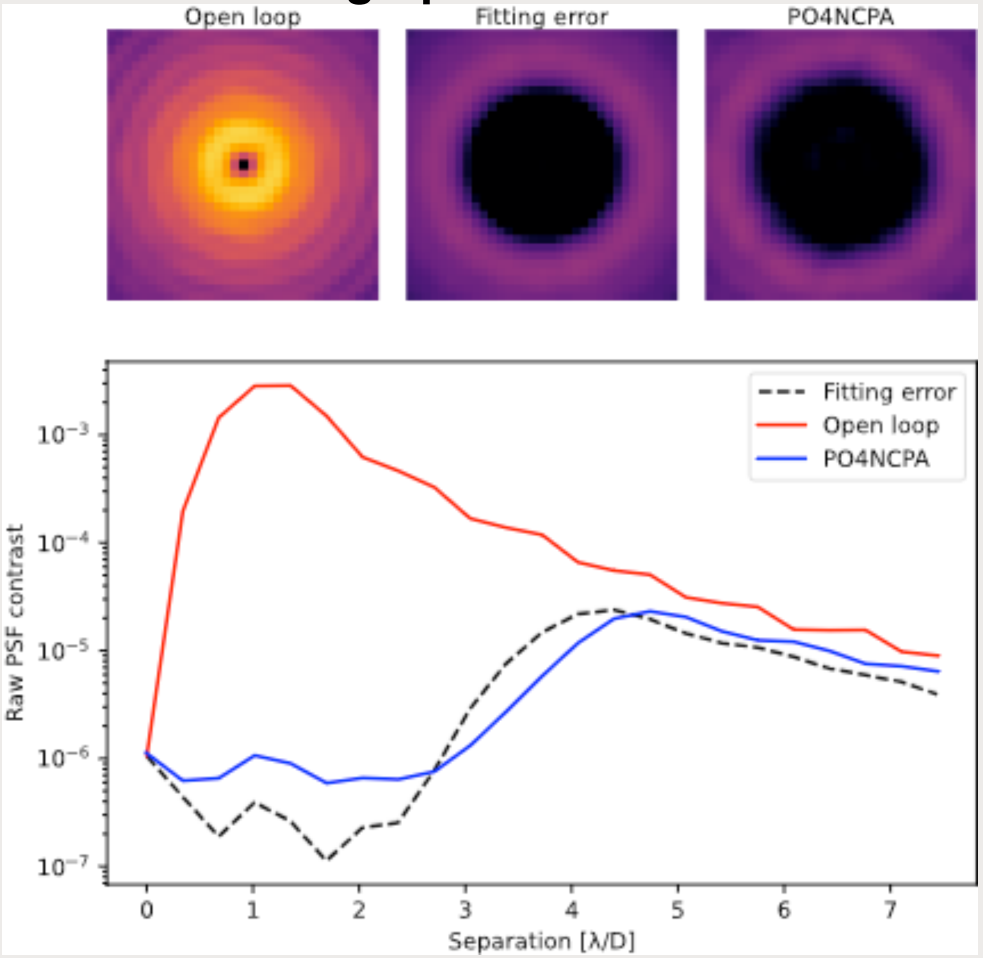

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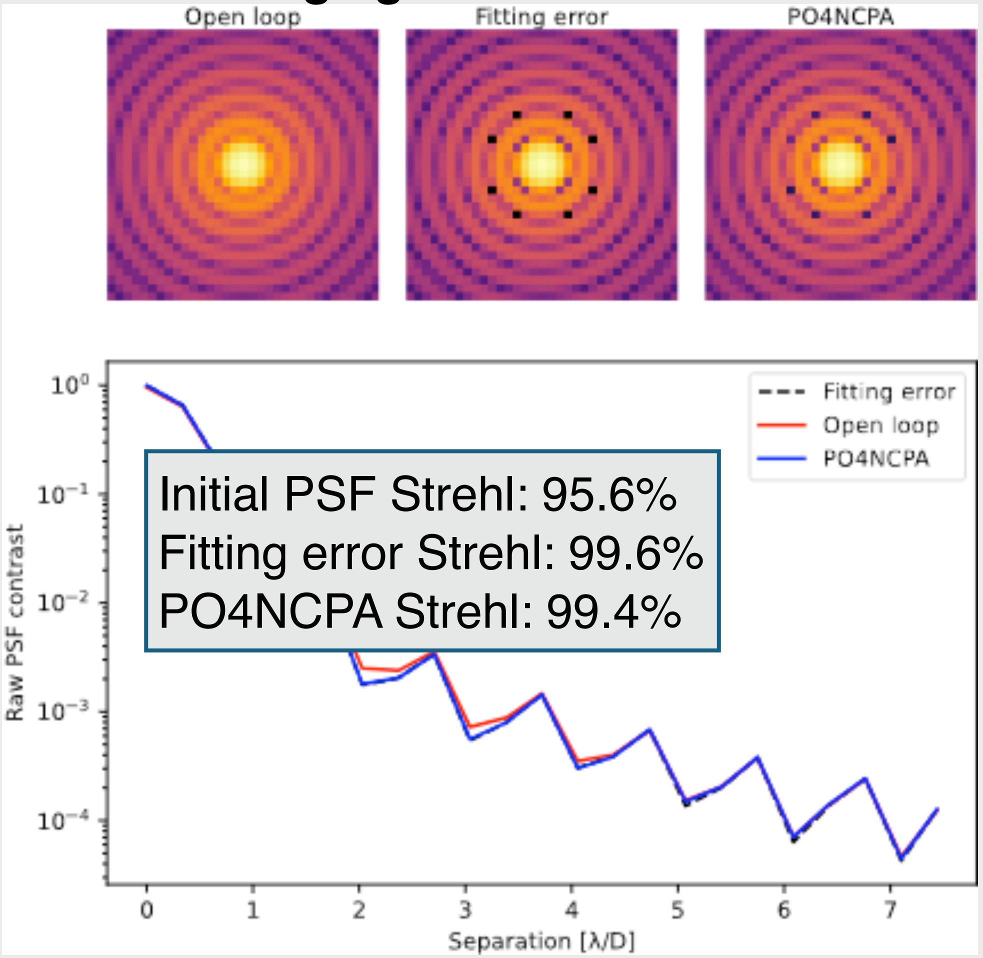
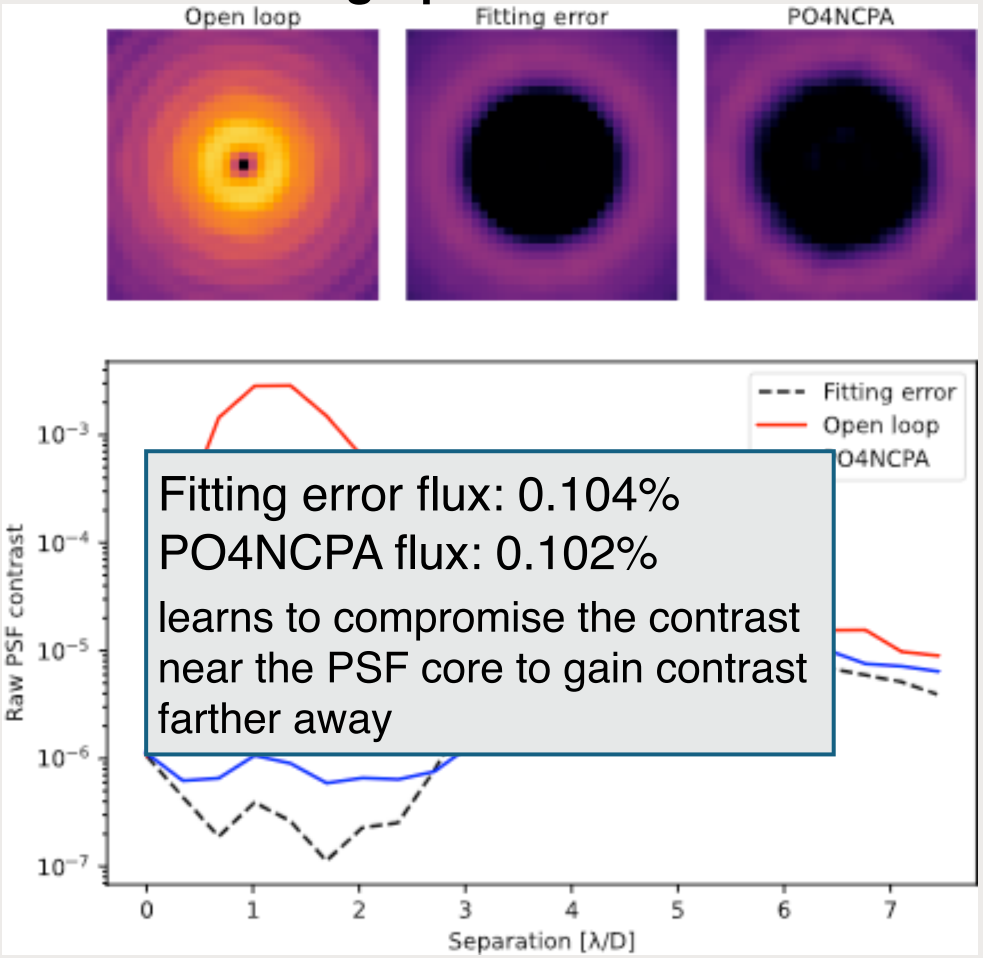


Initial PSF Strehl: 95.6%
Fitting error Strehl: 99.6%
PO4NCPA Strehl: 99.4%

Perfect Coronagraph

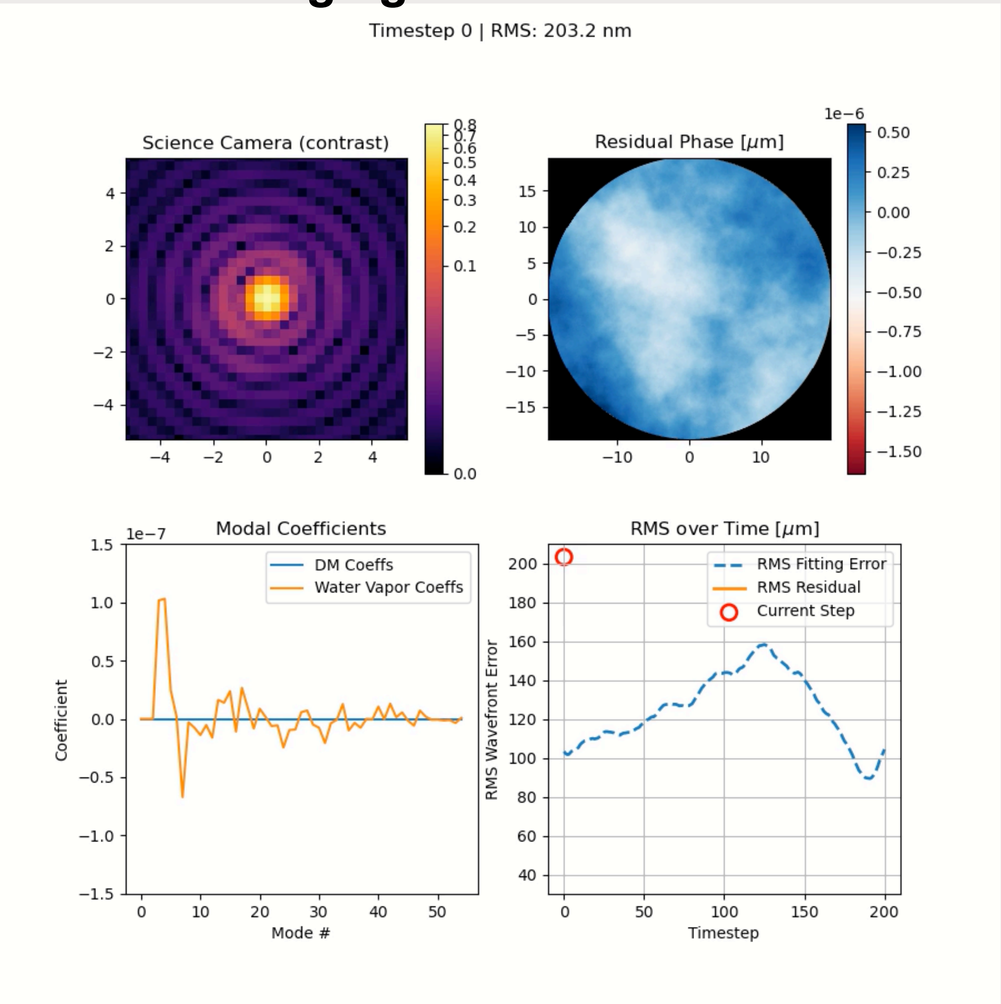


Fitting error flux: 0.104%
PO4NCPA flux: 0.102%

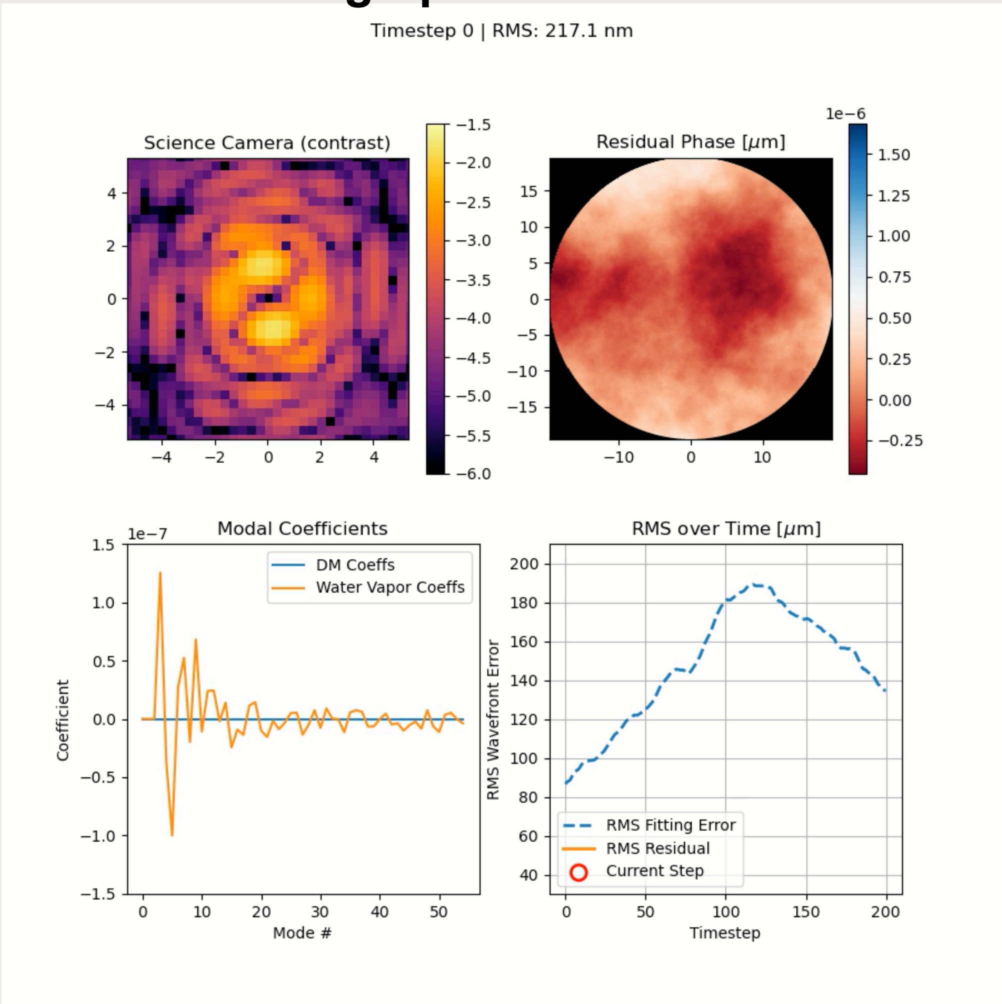
learns to compromise the contrast near the PSF core to gain contrast farther away

PO4NCPA: Dynamic NCPA

Standard Imaging

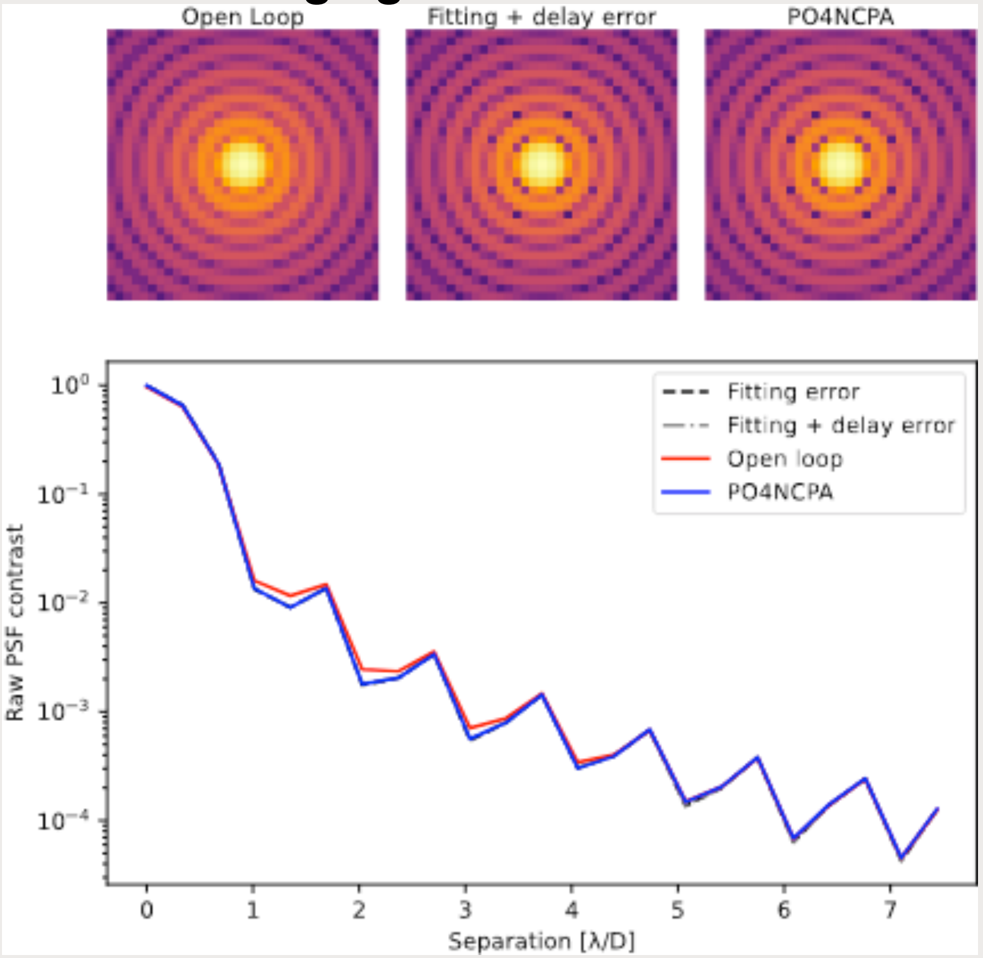


Perfect Coronagraph



PO4NCPA: Dynamic NCPA

Standard Imaging



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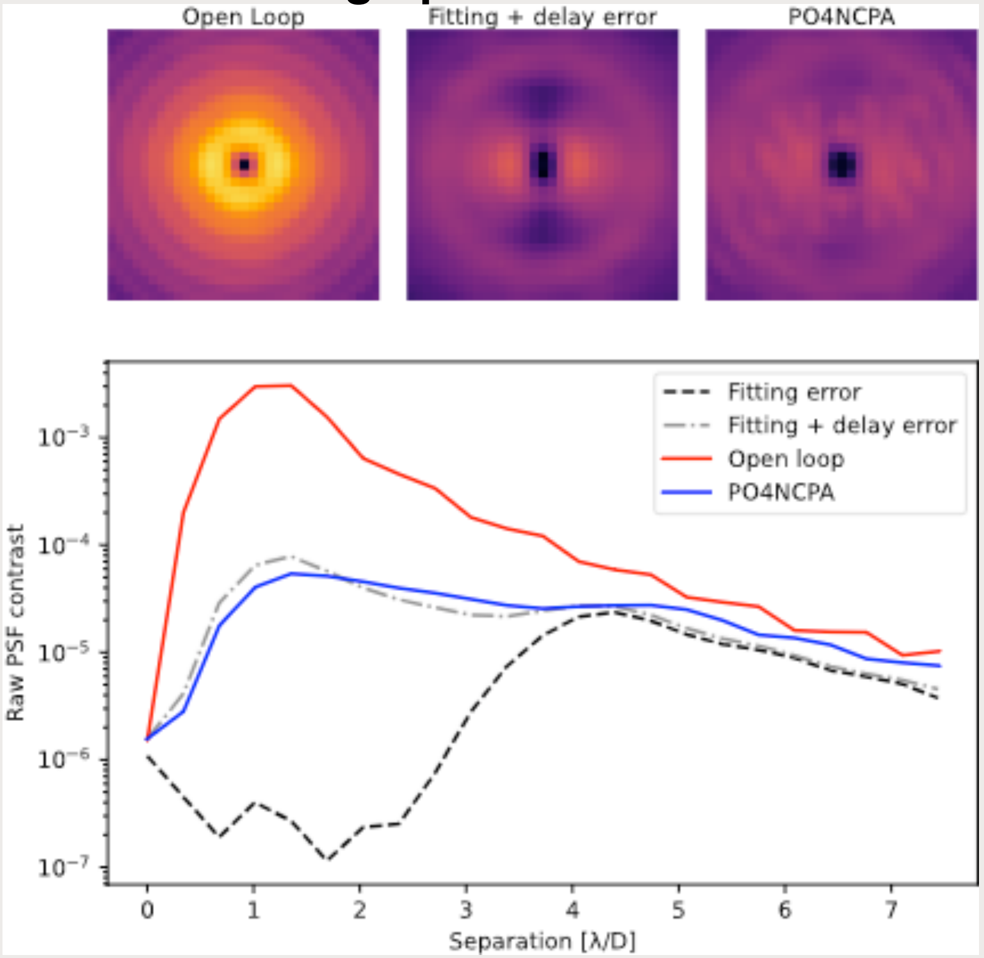

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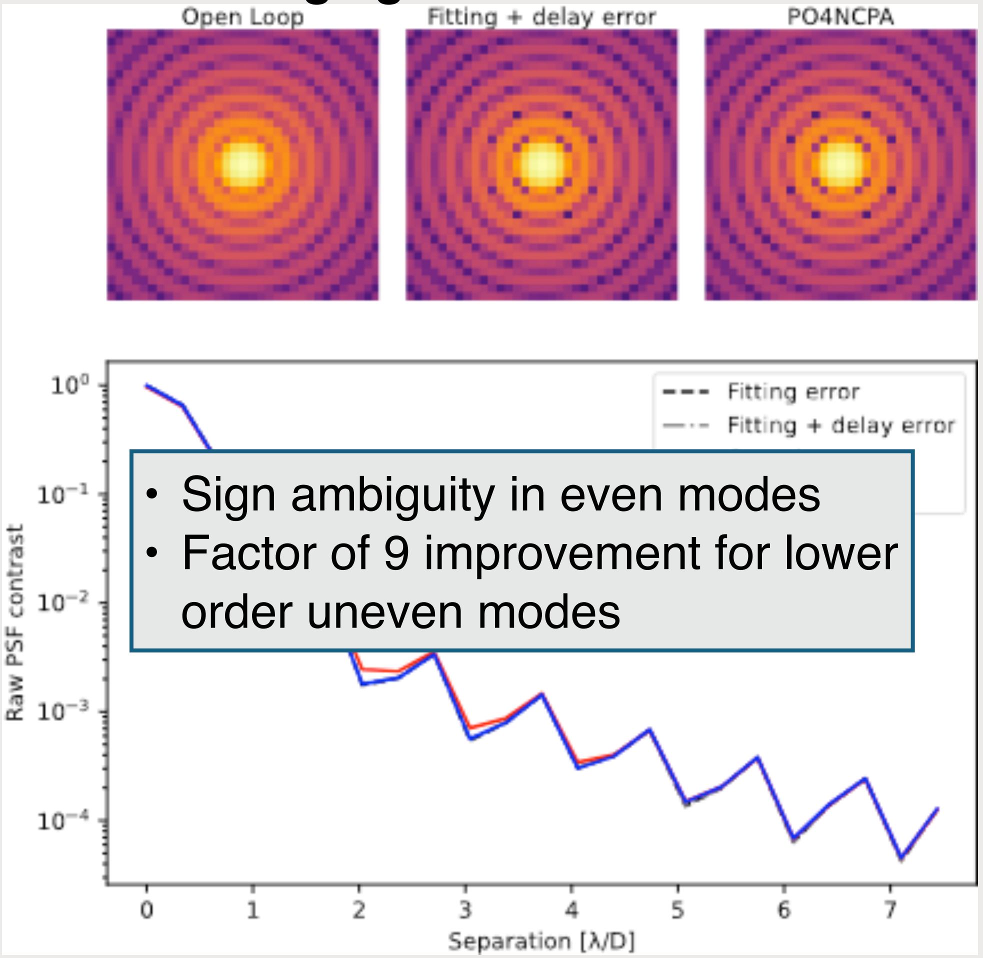
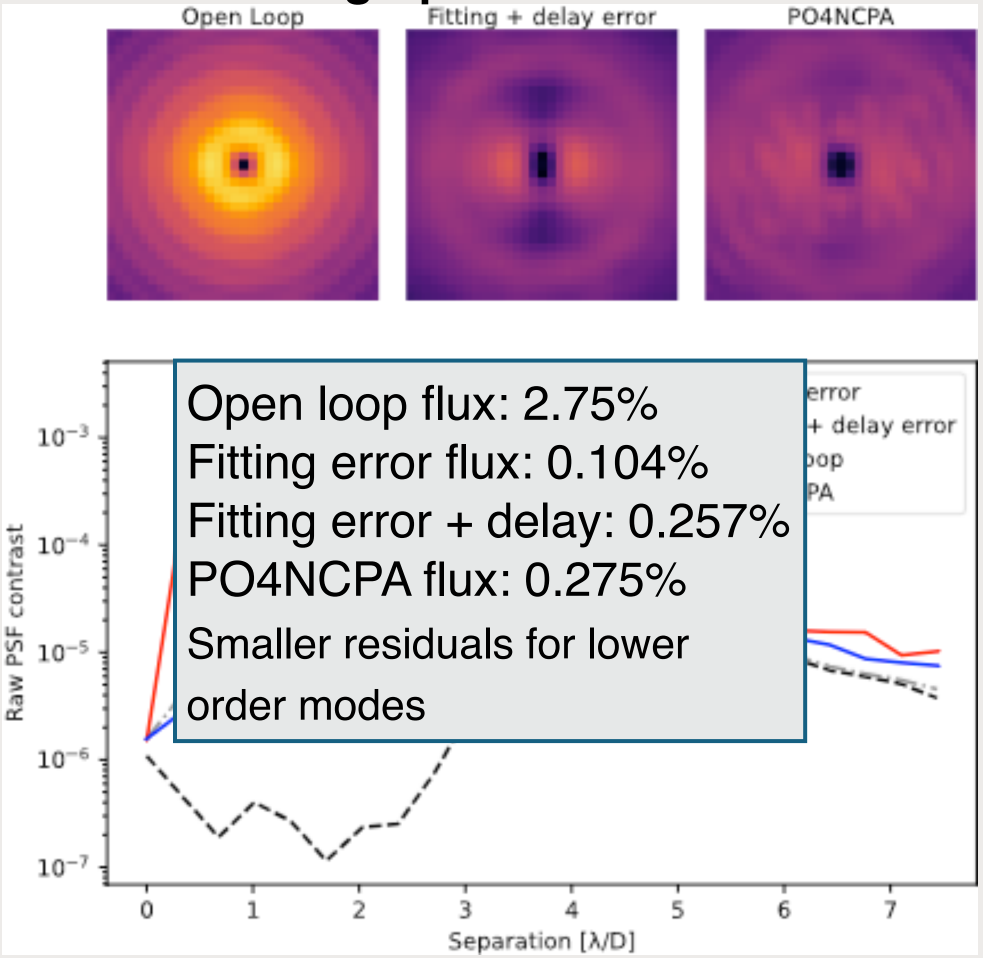


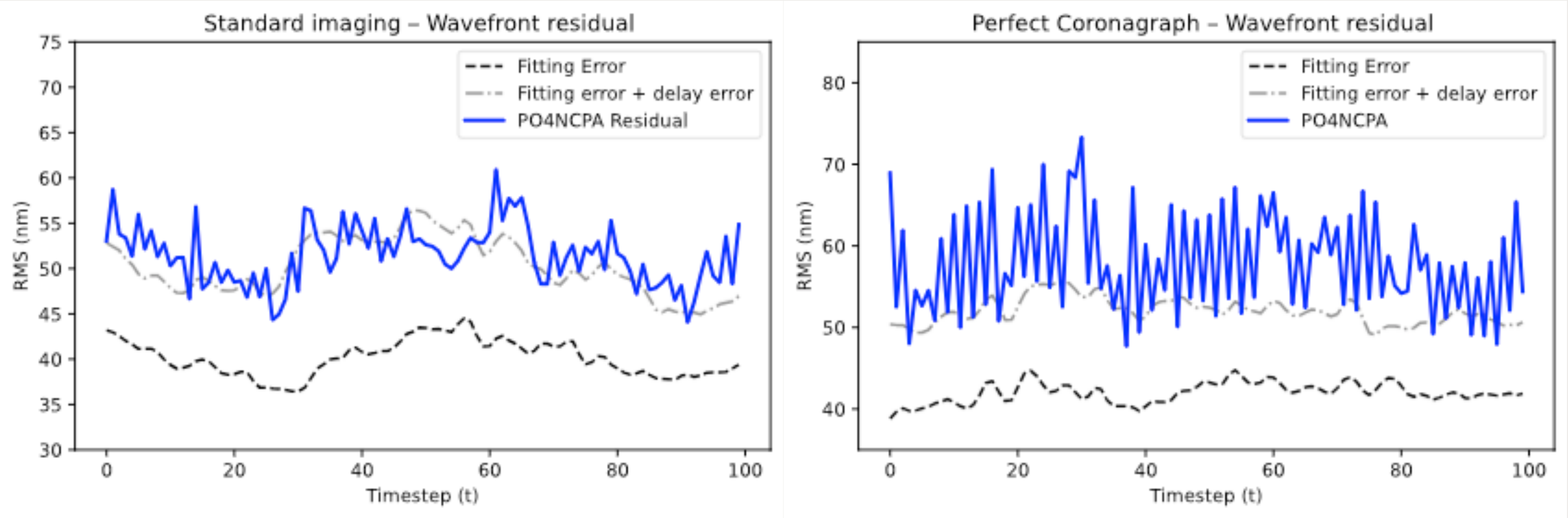
- Sign ambiguity in even modes
- Factor of 9 improvement for lower order uneven modes

Perfect Coronagraph

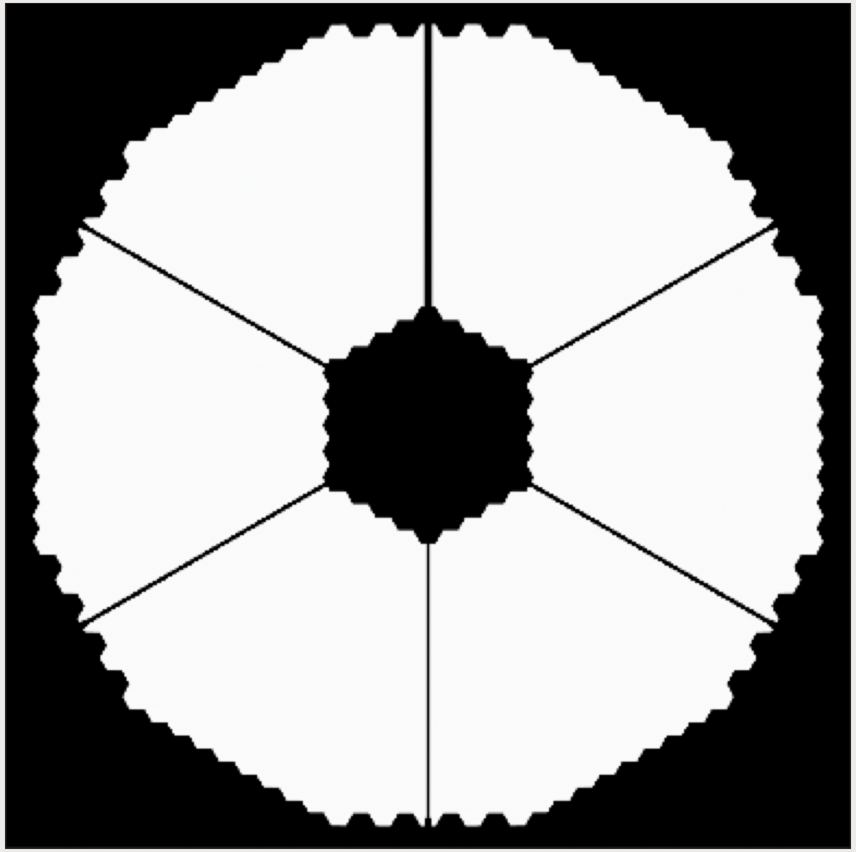


Open loop flux: 2.75%
Fitting error flux: 0.104%
Fitting error + delay: 0.257%
PO4NCPA flux: 0.275%
Smaller residuals for lower order modes

PO4NCPA: Dynamic NCPA



PO4NCPA: Vector Vortex Coronagraph



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Background noise	10e8 #/pix/frame

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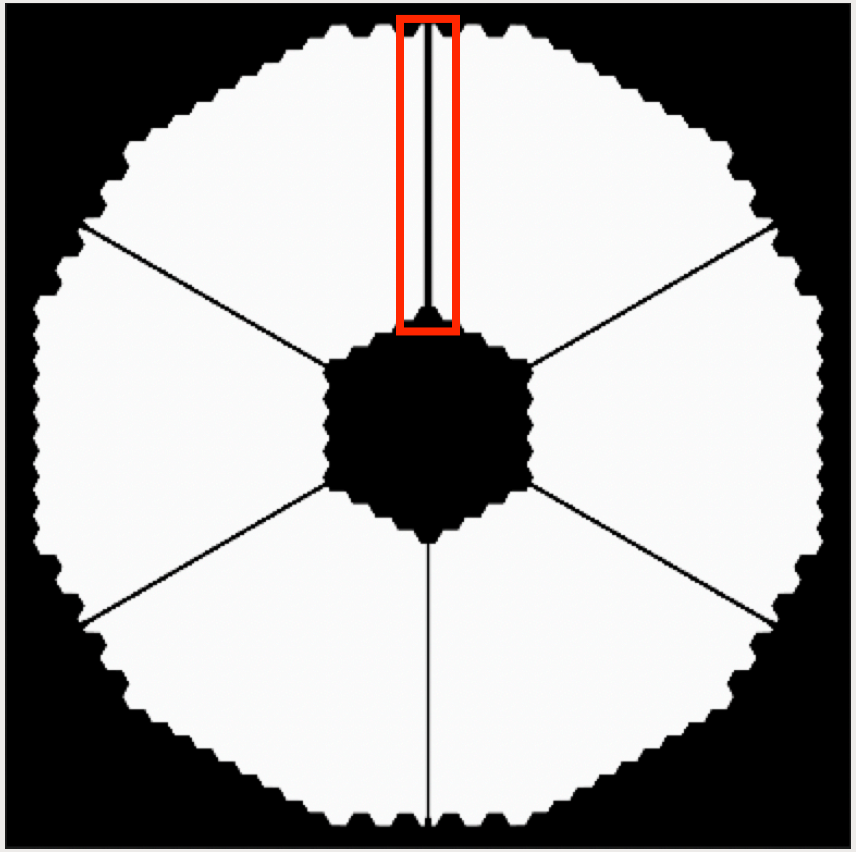

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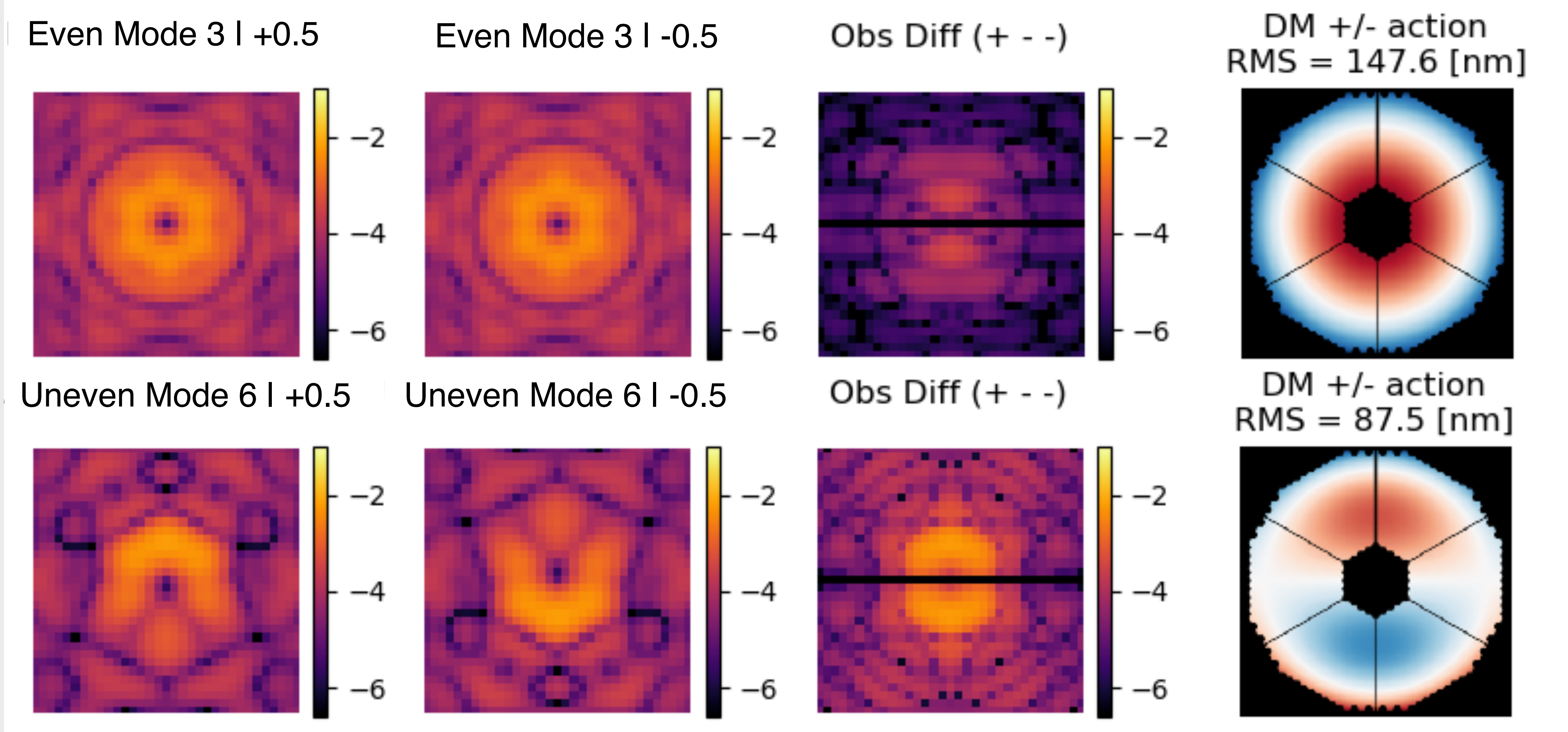

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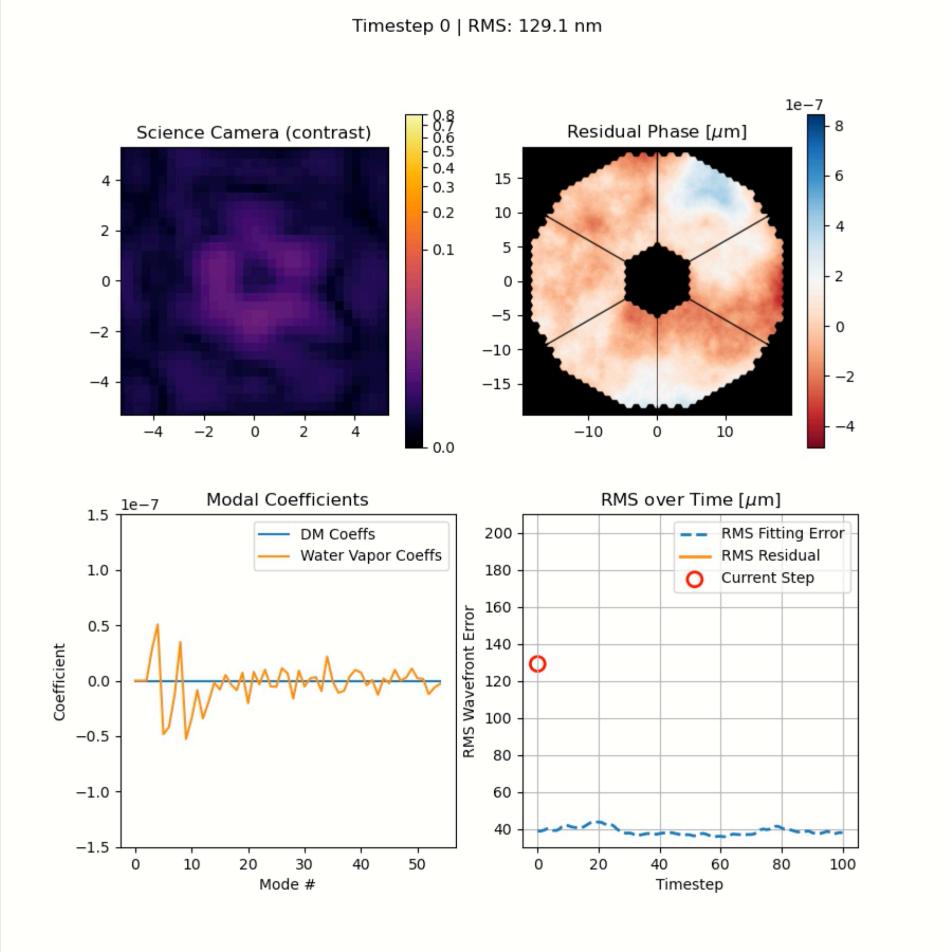

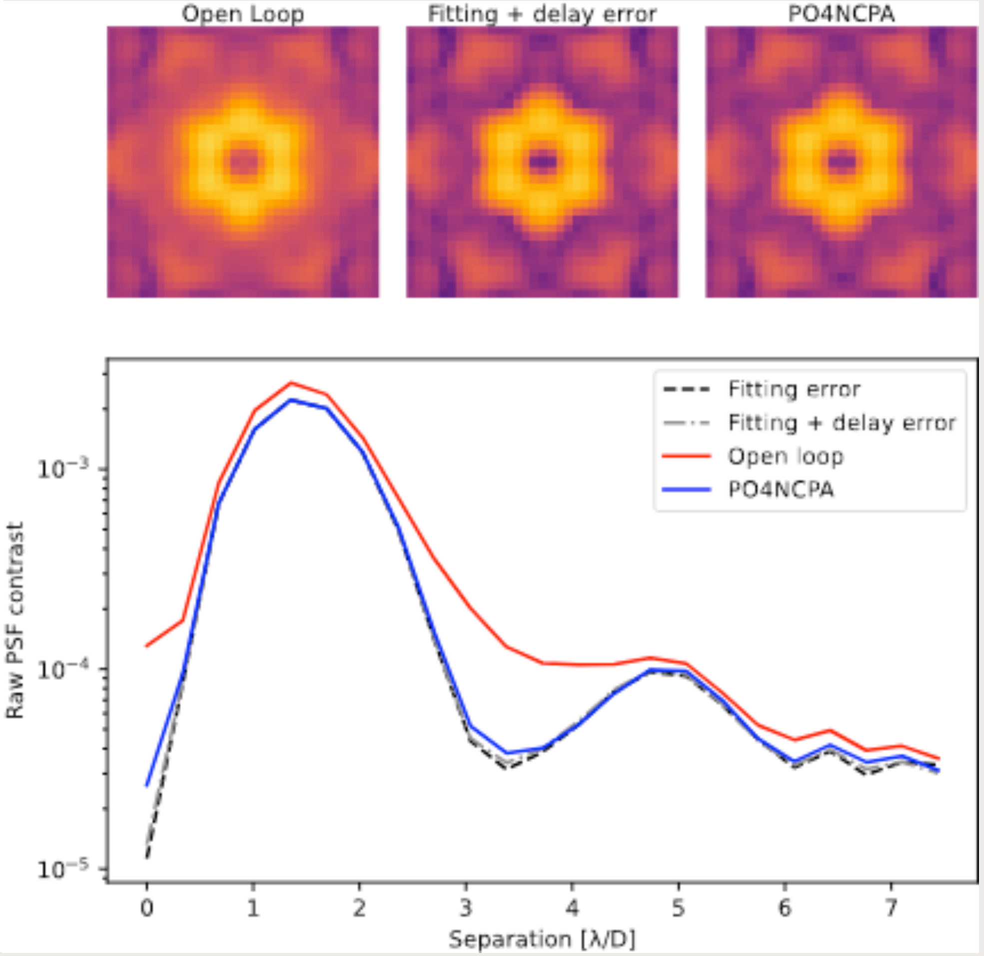

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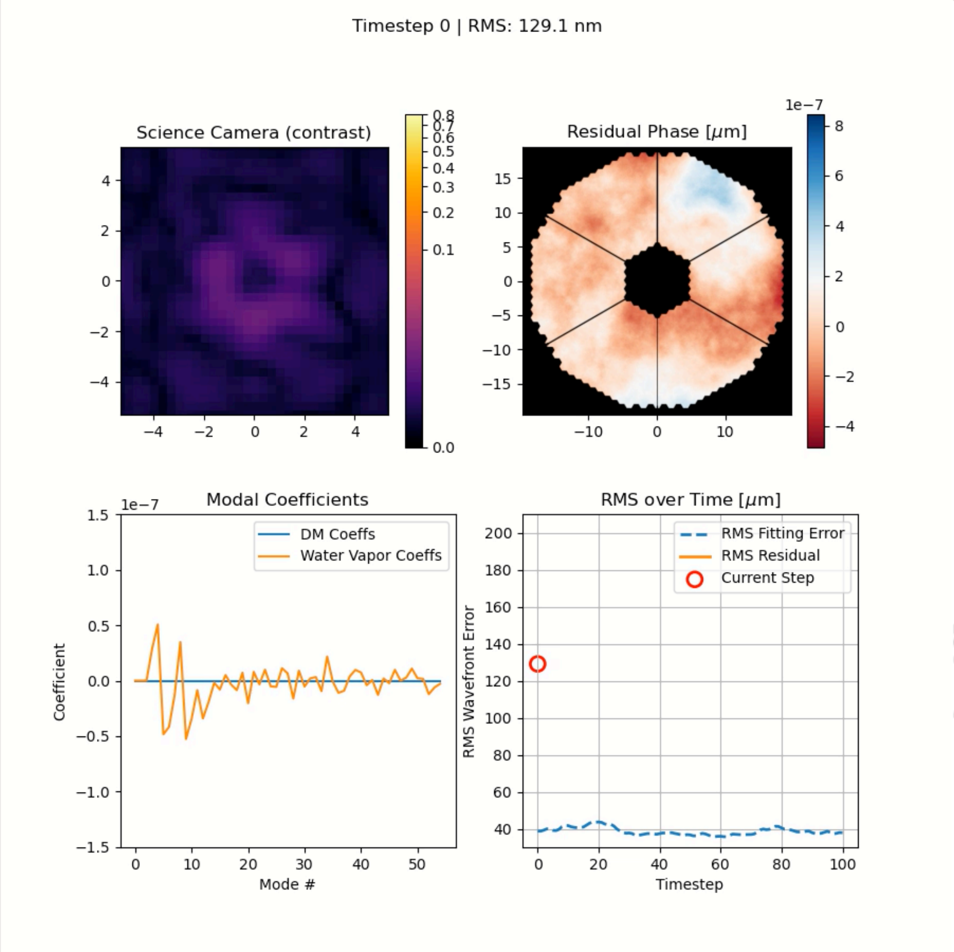
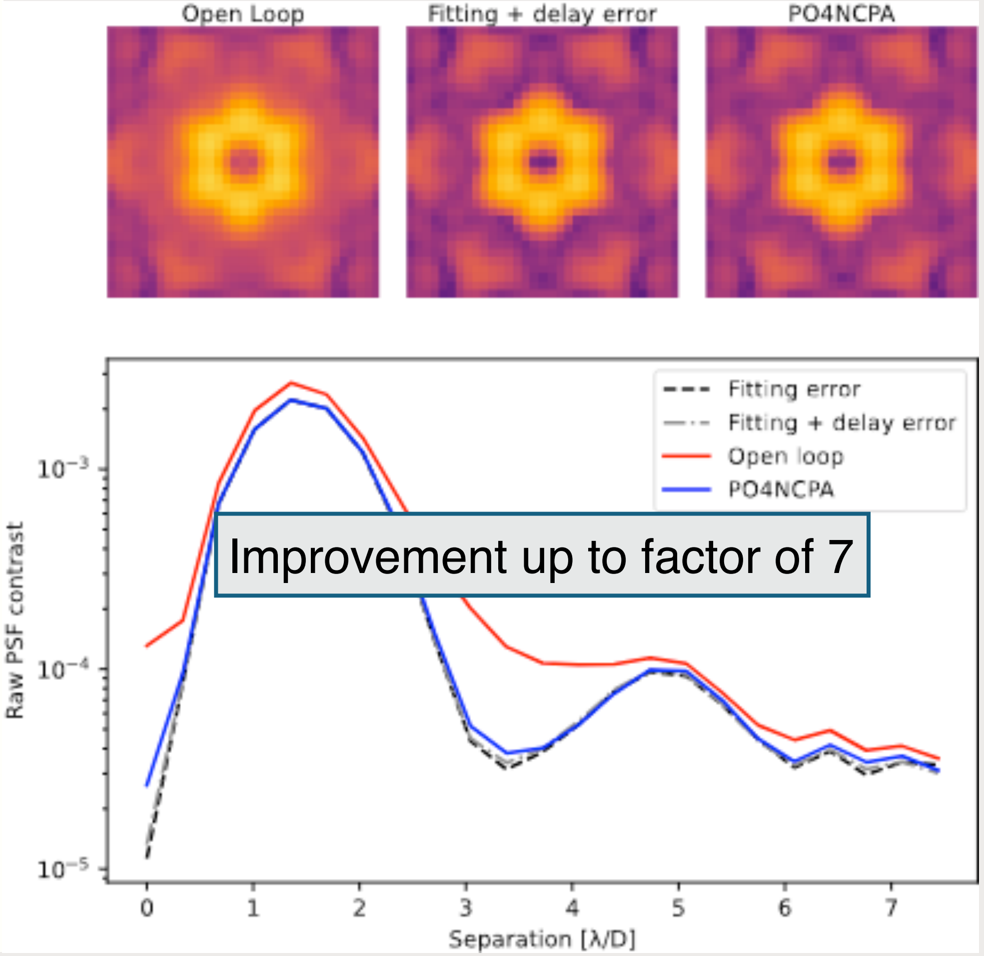
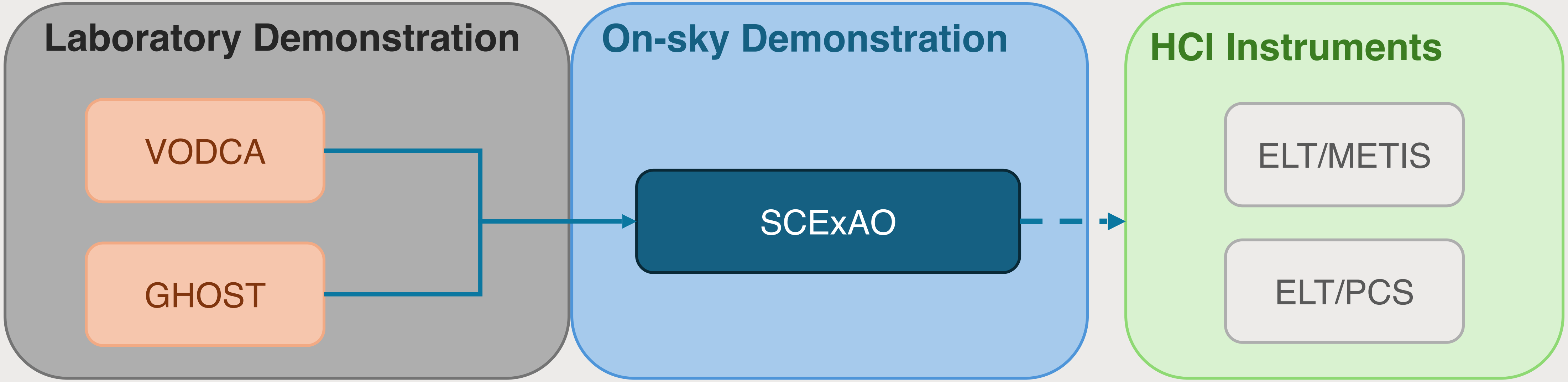




Conclusion

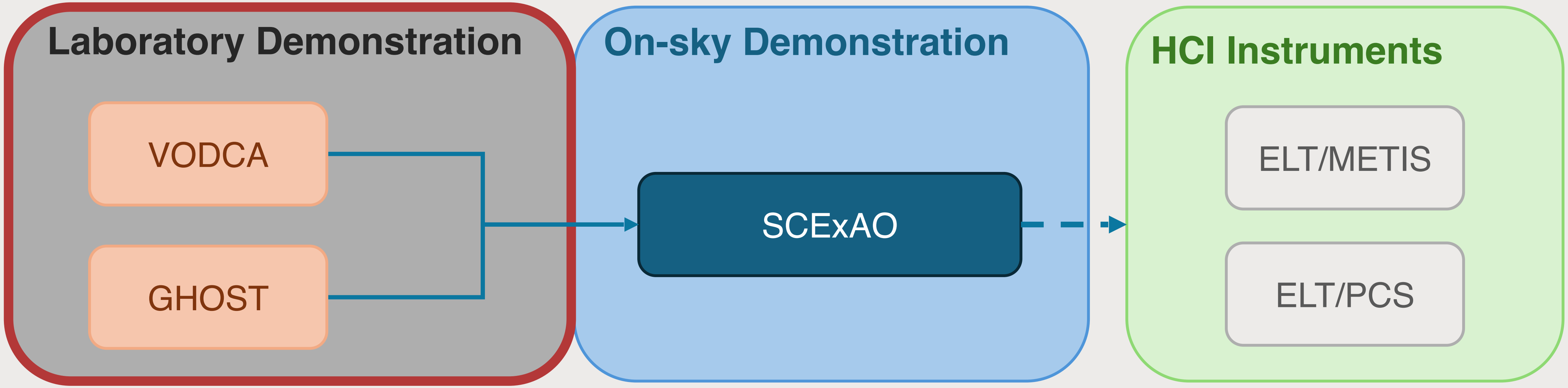
- **Model-free**
  - → Works with any aperture, coronagraph
  - → No flat reference needed
- Fast, sensorless AO adaptive to changing conditions
- Embedded **decision making**
  - → When to apply phase diversity to achieve the highest reward

Conclusion



- Simulations with AO residuals
- Dark-hole digging

Conclusion



- Simulations with AO residuals
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Focal plane wavefront control with model-based reinforcement learning

Optimizing policies with learned optical models

J. Nousiainen[1], I. Taskin[2, 1,⋆], M. Kasper[1], G. Orban de Xivry[2], and O. Absil[2,⋆⋆]

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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: