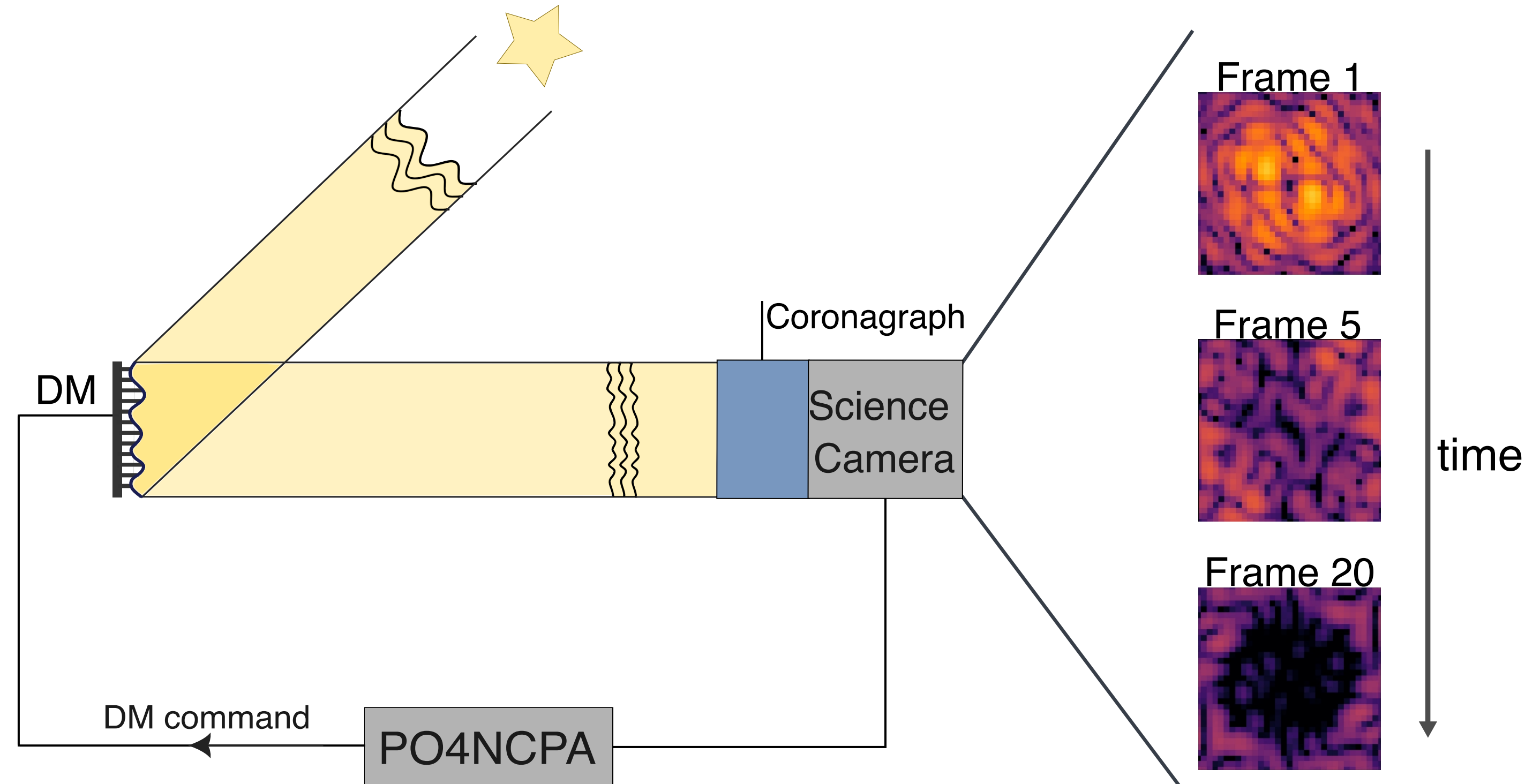


# Exploring reinforcement learning to enhance focal plane wavefront correction for vortex coronagraphs

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## 1. Introduction



**Fig 1.1:** The secondary Adaptive Optics (AO) system, fine-tuned to correct NCPAs.

### Non-common path aberrations (NCPAs)

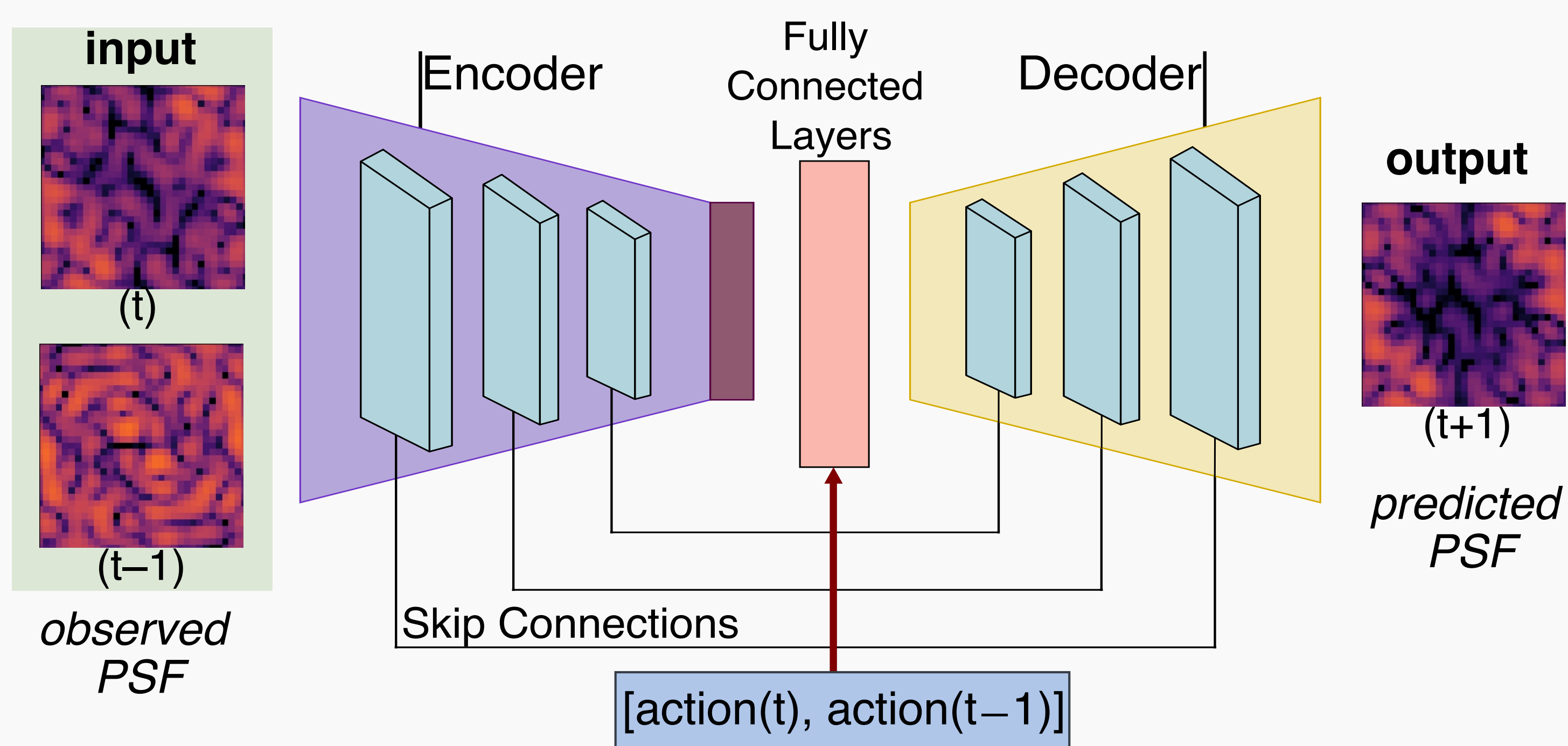
- ♦ Path difference between science camera & wavefront sensor
- ♦ Chromatic aberrations
  - **Focal plane wavefront sensing (FPWFS)**
- ♦ Nonlinear relationship between focal plane & pupil plane
- ♦ Sign ambiguities on even Zernike modes
  - **Sequential Phase Diversity + Reinforcement Learning**
- ♦ Scalar Vortex Coronagraph can lift sign ambiguities, Vector Vortex Coronagraph can not.

## 2. Reinforcement Learning

**PO4AO**<sup>[2.1]</sup> algorithm applied to NCPA: **PO4NCPA**

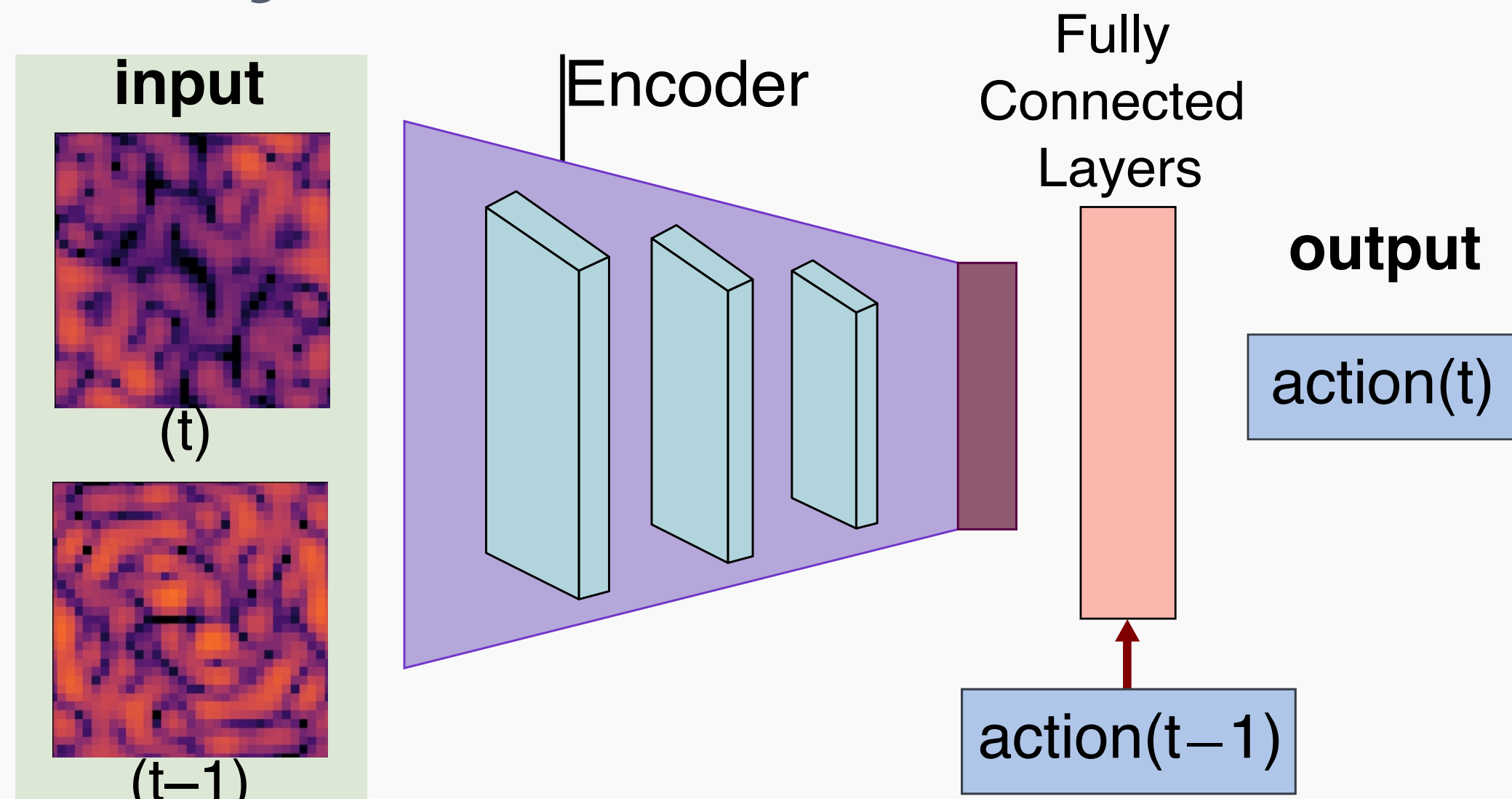
1. Running the policy by controlling DM
2. Improving the dynamics model with instrument data
3. Improving the policy by using data + dynamics model

### Dynamics Model



**Fig 2.1:** The dynamics model takes in the previous and current PSF from the science camera as inputs to predict the next PSF at the science camera. This method uses sequential phase diversity.

### Policy



**Fig 2.2:** The policy uses the current PSF and the previous PSF observed by the science camera to predict the appropriate action.

## 3. Results

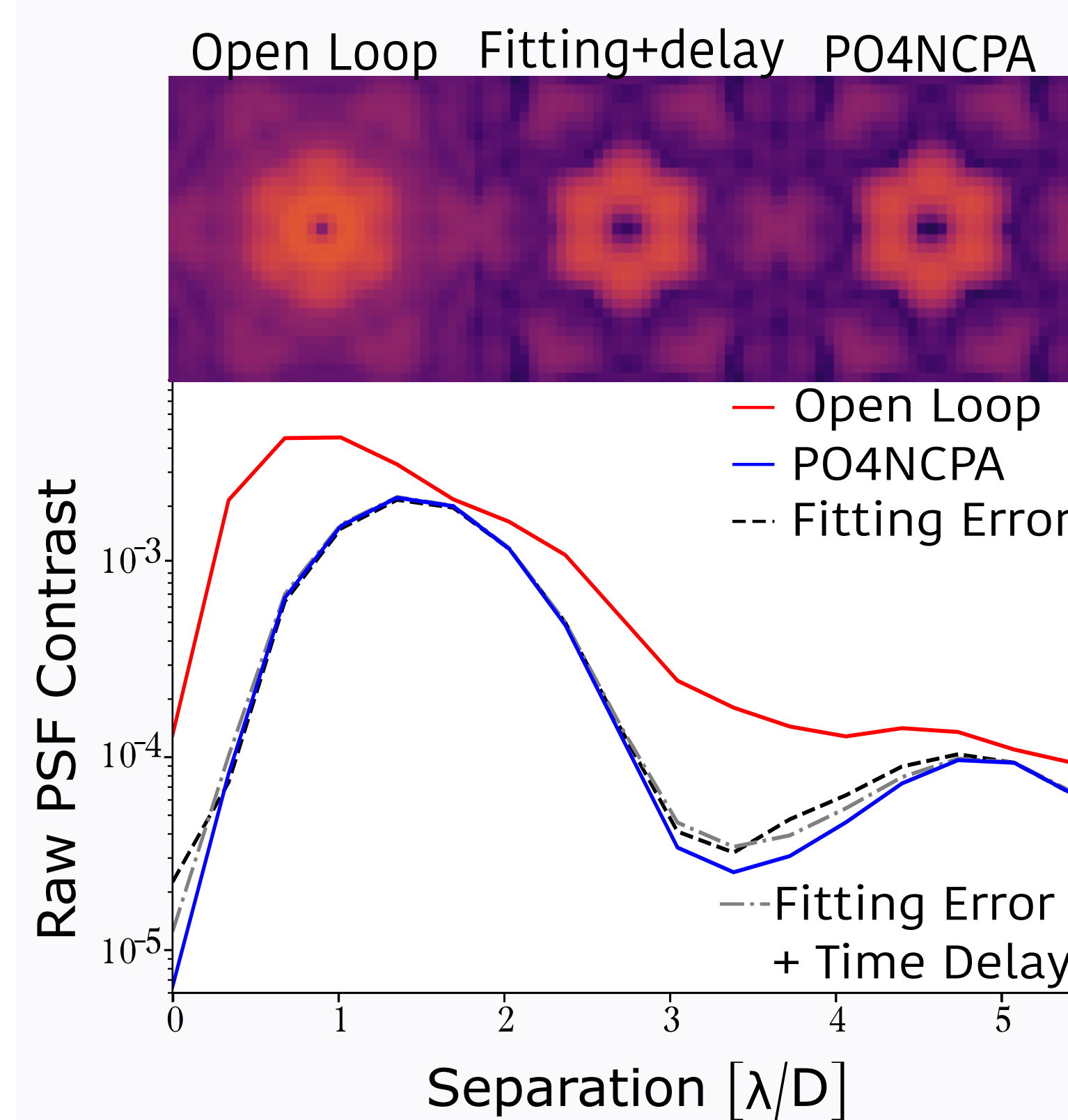
|                    |                             |
|--------------------|-----------------------------|
| Telescope Diameter | 39.3 m                      |
| Observation Band   | Mid-IR ( $11 \mu\text{m}$ ) |
| # Modes Corrected  | 55                          |
| Frame Rate         | 10 Hz                       |
| Mean NCPA RMS      | $266 \pm 9 \text{ nm}$      |

**Tab 3.1:** METIS-like PO4NCPA simulation parameters.

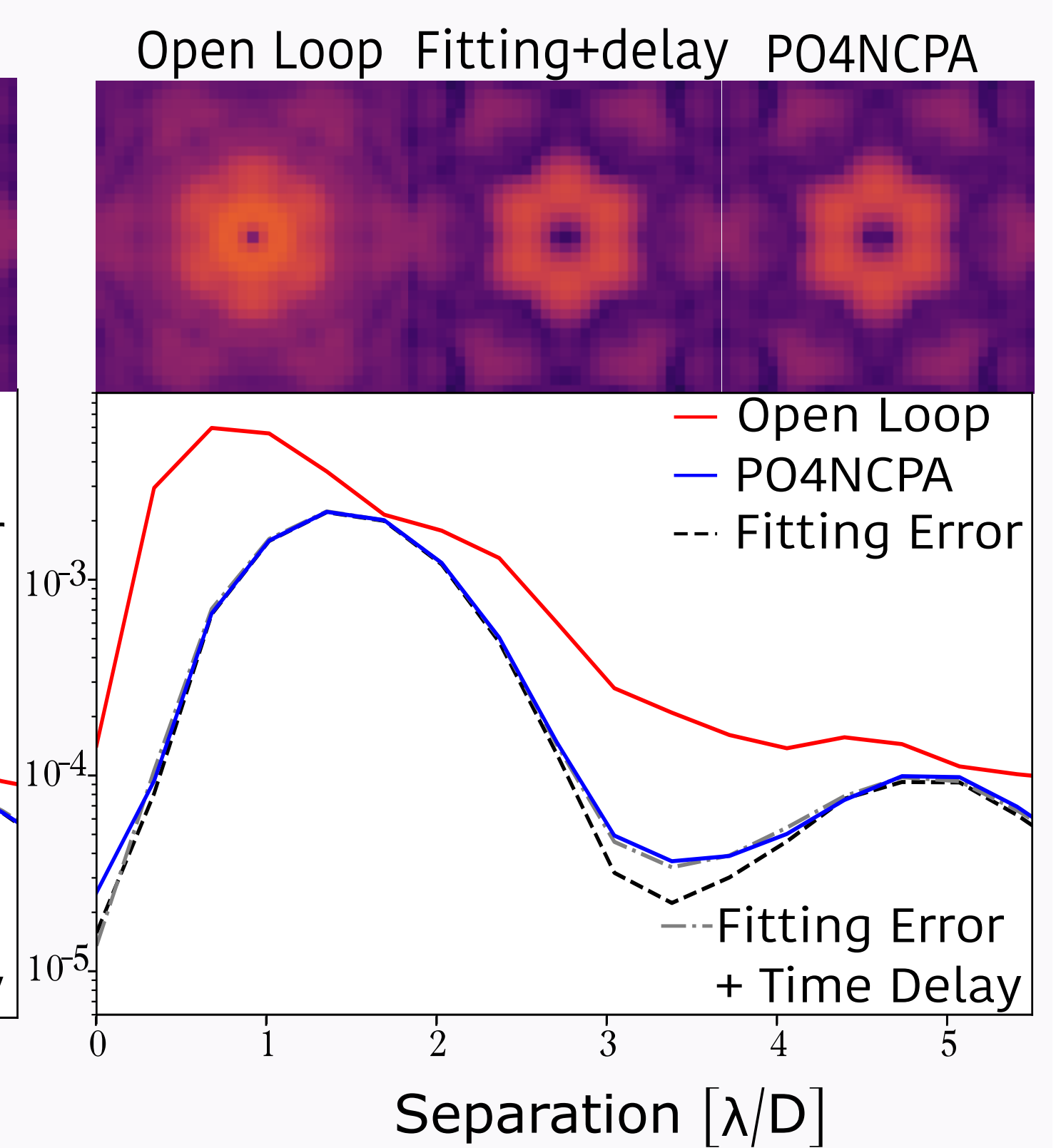
**Dynamic NCPA:** Water vapor<sup>[3.1]</sup> effects for METIS, evolving throughout the simulation.

### Vortex Coronagraph

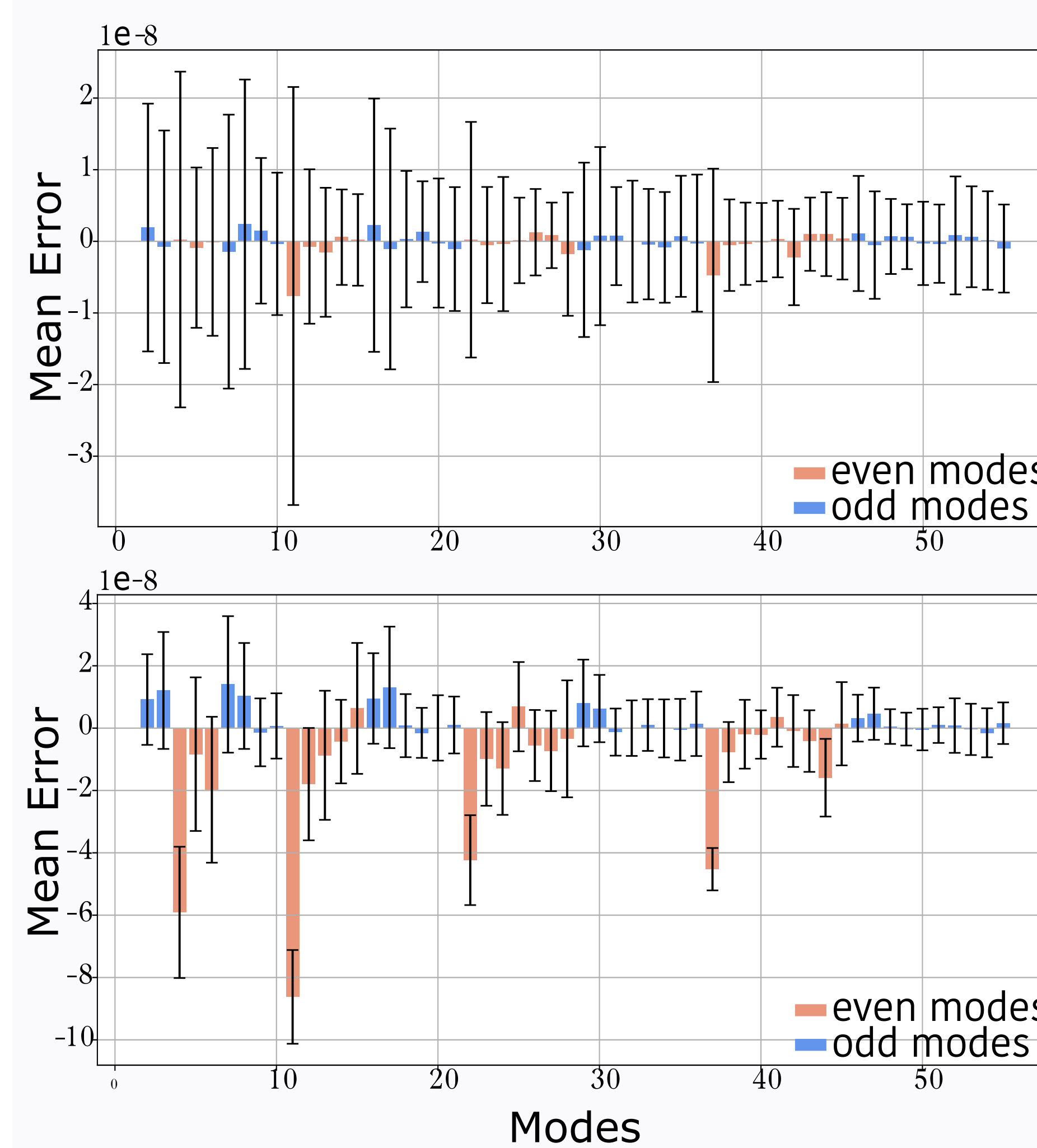
#### Scalar Vortex Coronagraph



#### Vector Vortex Coronagraph



**Fig 3.1:** The performance of PO4NCPA for Scalar Vortex Coronagraph (SVC) and Vector Vortex Coronagraph (VVC). The curves display the radial PSF contrast. In certain separations for SVC, PO4NCPA is able to obtain slightly better contrast than fitting error.



**Fig 3.2:** Mean modal command error per mode for SVC (top) and VVC (bottom). The bars represent the standard deviation. The pure radial modes' mean error (1st orange bar of each radial order) exceed their standard deviation. This points to the policy introducing a fixed phase diversity in an attempt to lift the phase ambiguity on even modes<sup>[3.2]</sup>.

**For further results and videos please check the QR code.**

## 4. Conclusions

- ♦ Can compensate dynamic NCPA such as water vapor aberrations in various imaging types (normal imaging, perfect coronagraph, vortex coronagraphs) & instruments
- ♦ Current work: Asymmetric Lyot stop (METIS) vs sequential phase diversity, Dark-hole digging
- ♦ Next steps: Laboratory tests on GHOST bench, ESO and on-sky testing with SCEXAO instrument, Subaru

