Hybrid physical optics and deep learning models for speckle evolution

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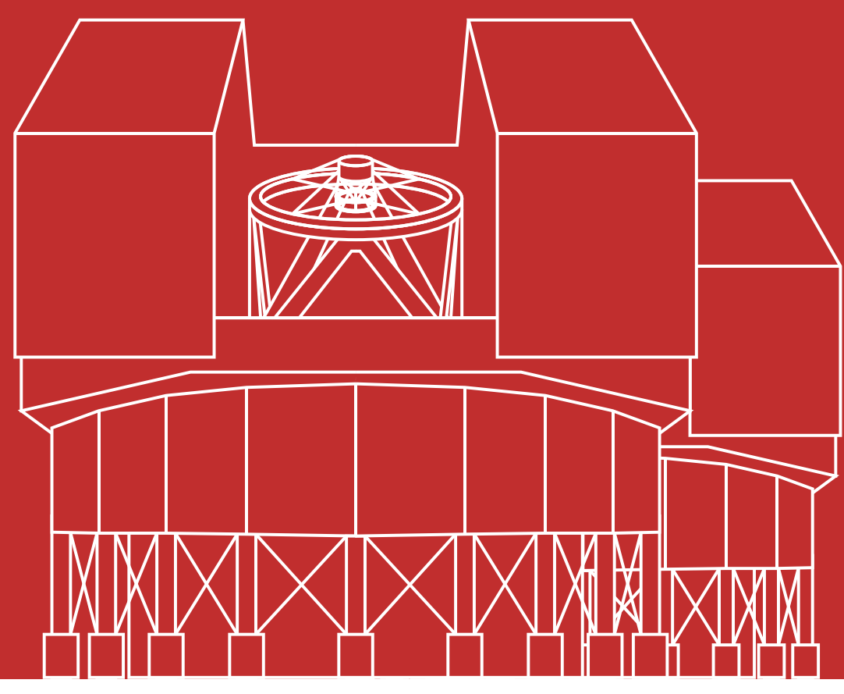


SPECKLE EVOLUTION

The much-despised speckle frustrates direct imaging of small-angular separation features like exoplanets we seek around stars and debris disk structure. Not content with stealing flux from the core of the point-spread function (PSF), these artifacts will also come and go on short timescales (Males *et al.*, 2021), making it difficult to construct models of the instrument PSF at the necessary fidelity for high-contrast imaging.

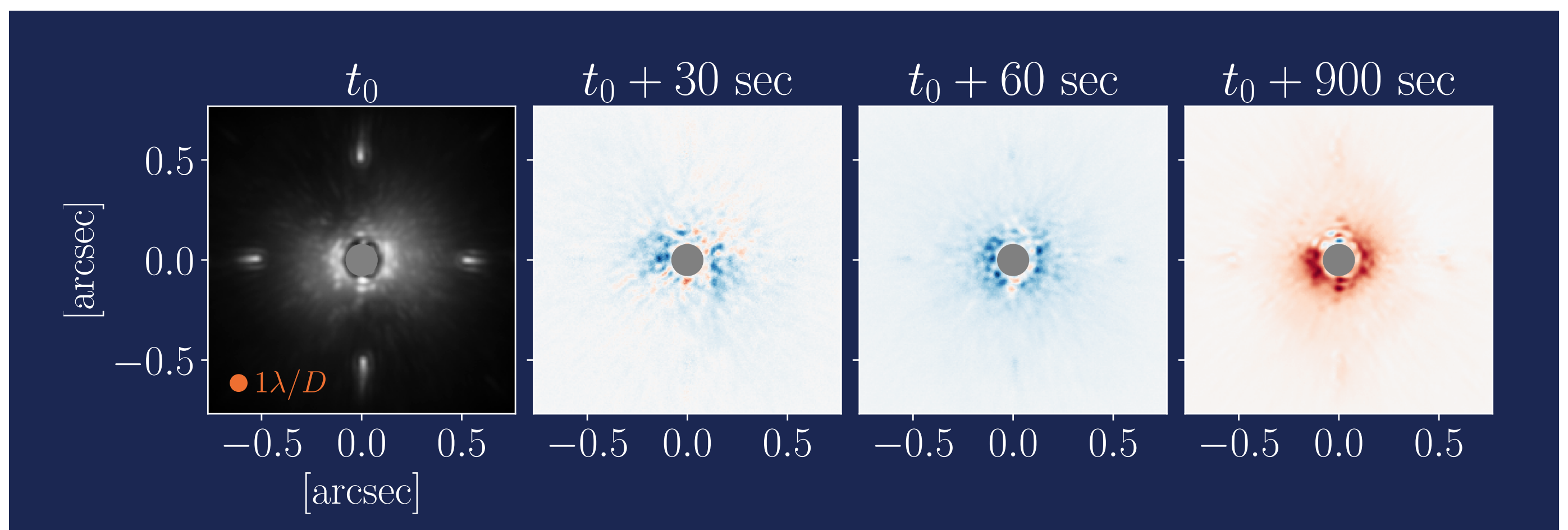
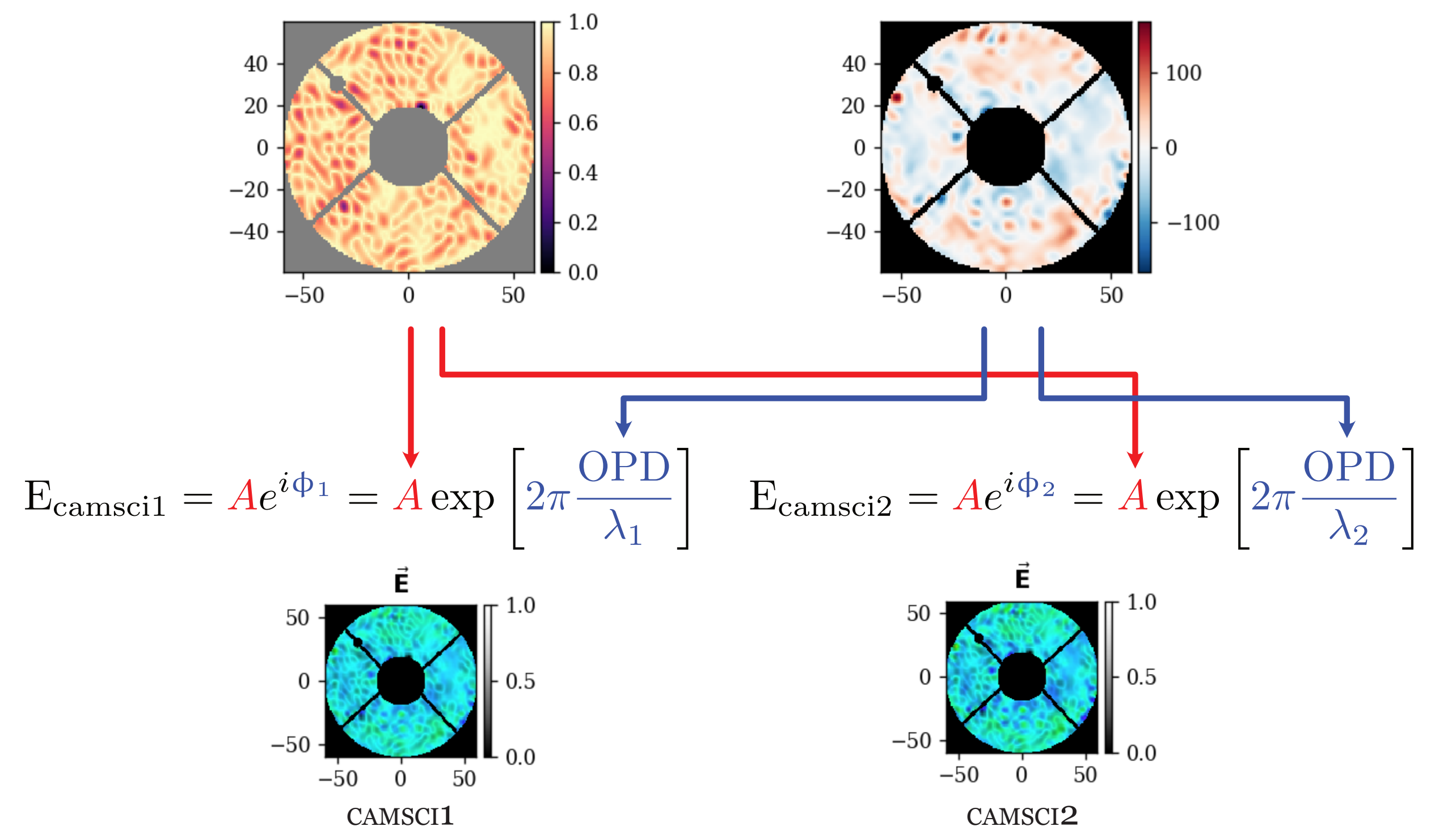


Figure 1: Coronagraphic imaging data in z' from MagAO-X, coadded in 30-second chunks. The first panel shows a single coadded frame and the others show speckle patterns in the differences with subsequent frames.

NON-COMMON-PATH ABERRATIONS

Science cameras see aberrations that wavefront sensor cameras don't: non-common-path aberrations, or NCPA.

Wavefront sensor data alone cannot capture NCPA, science detector effects, filter bandpass, target spectral energy distribution, or rotation of the science focal plane. For these, we have a "bootstrap" model that fits to a median PSF in each science channel.



$$E_{\text{camsci1}} = Ae^{i\phi_1} = A\exp\left[2\pi\frac{\text{OPD}}{\lambda_1}\right] \qquad E_{\text{camsci2}} = Ae^{i\phi_2} = A\exp\left[2\pi\frac{\text{OPD}}{\lambda_2}\right]$$

MagAO-X typically images in two filters simultaneously, using two detectors and a beamsplitter. When the center wavelengths are sufficiently different, this can break the degeneracy arising from the intensity measurement (I = |E|²).

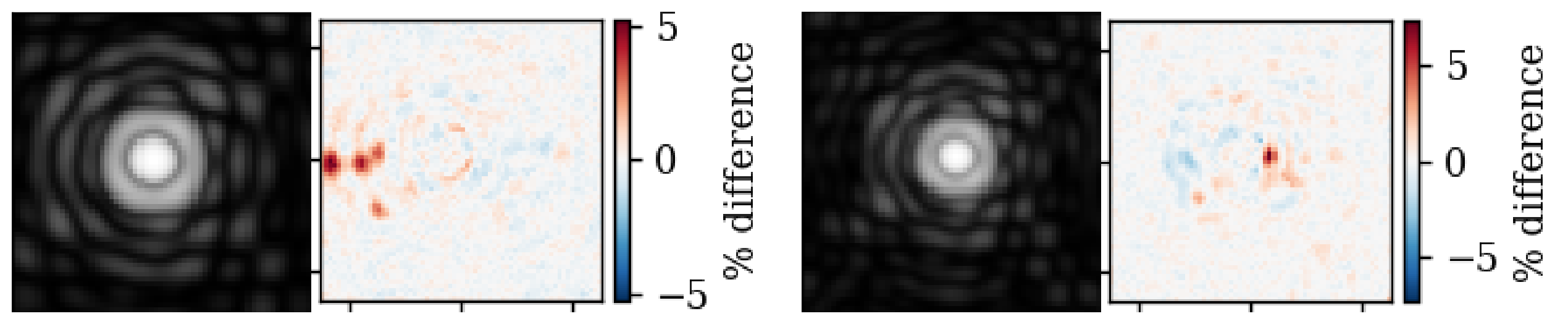


Figure 2: Comparison of simulation to median PSF from both bands after convergence (lab data, 875 nm and 656 nm narrowband filters).

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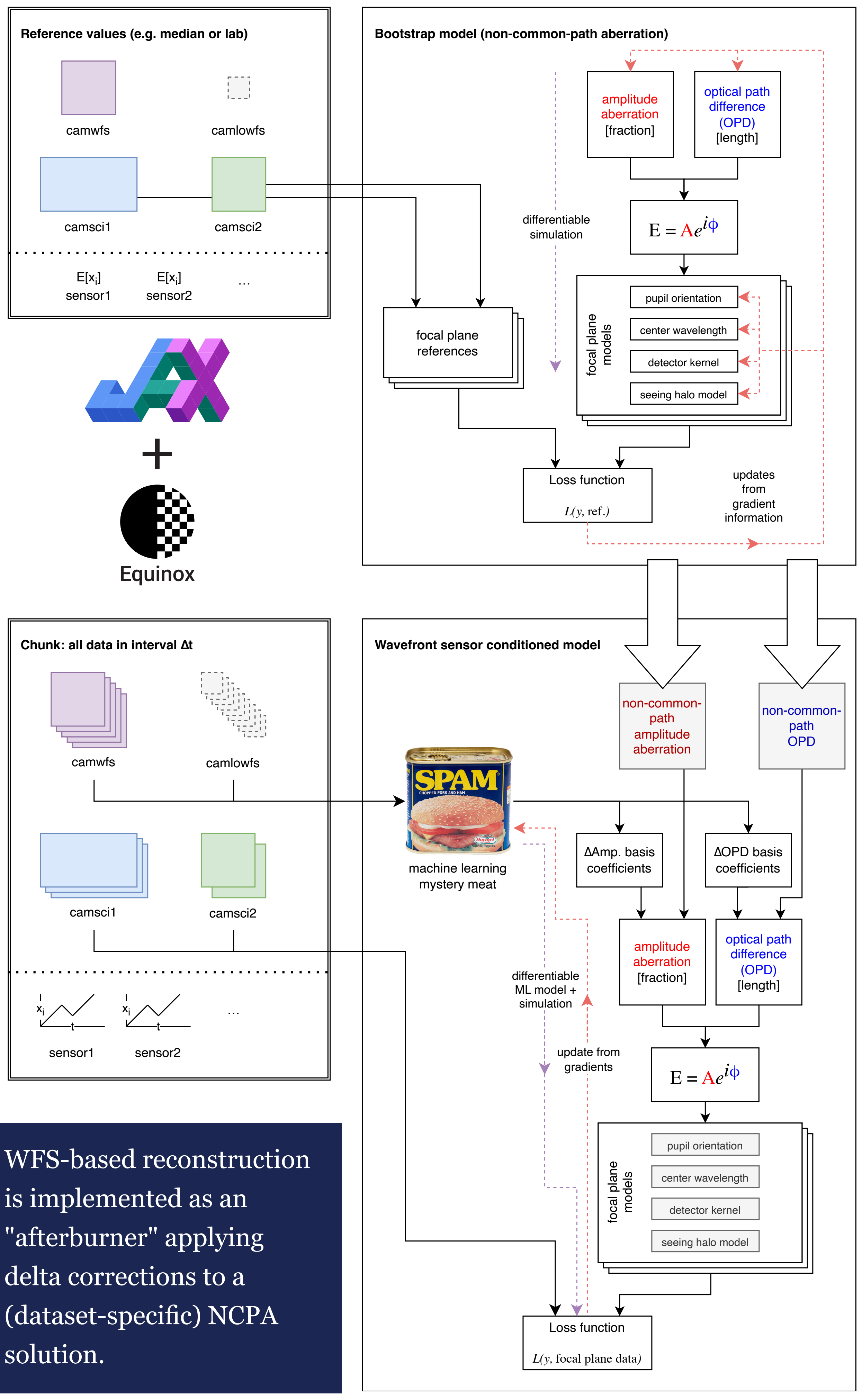
DIFFERENTIABLE HYBRID MODEL

Using JAX, we have implemented a model for MagAO-X science focal plane PSFs that produces gradient information for numerical optimization. We implement wave optics propagation to multiple focal planes to preserve physical plausibility of output PSFs (similar to Desdoigts *et al.* 2025).

While developed for MagAO-X, the model architecture makes minimal assumptions about the system and should be adaptable to other instruments with simultaneous wavefront sensing signals.



WFS-based reconstruction is implemented as an "afterburner" applying delta corrections to a (dataset-specific) NCPA solution.

GENERATING TRAINING DATA

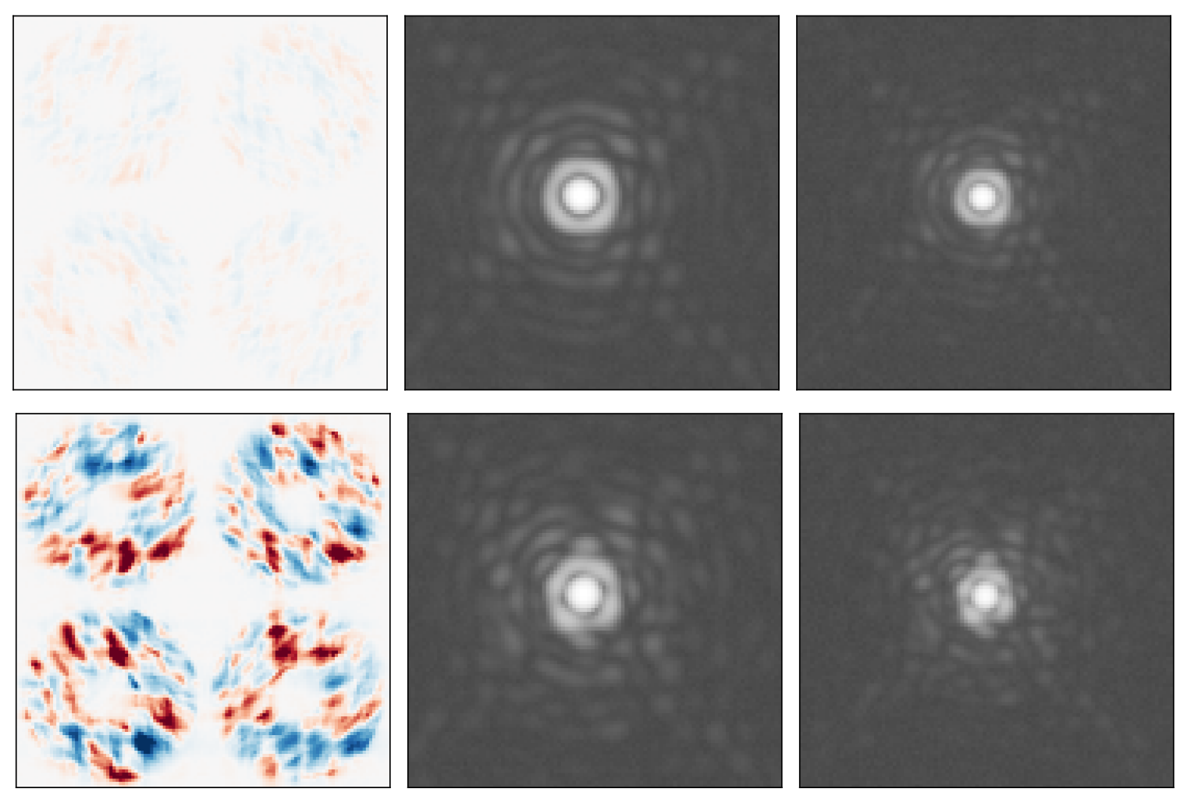


Figure 3: CAMWFS image minus reference (left), CAMSCI1 image (middle), and CAMSCI2 image (right) for two realizations of random aberrations in training data from MagAO-X .

Similarly to calibrating the AO system itself, we need to probe the response of the wavefront sensor to known wavefront error. Using the MagAO-X Python scripting interface and internal calibration source, we randomly generate and apply DM commands while holding the AO loop correction off—both so that they are not removed, and to integrate longer. This gives us more signal than we could get on-sky from a single frame.

TEMPORAL CORRELATIONS IN WAVEFRONT SENSOR DATA

Wavefront sensor (WFS) data are **high-dimensional** (one frame has 14 400 pixels) and **high-cadence** (one science frame has many WFS frames). To make analysis tractable with current hardware, we need to distill the WFS data into a **lower-dimensional representation**.

Our experiments revealed that individual WFS frames are effctively full-rank and **impossible to compress** any better than simply masking non-illuminated pixels.

To find a lower-dimensional representation, we use chunks of WFS frames and exploit **temporal correlation**.

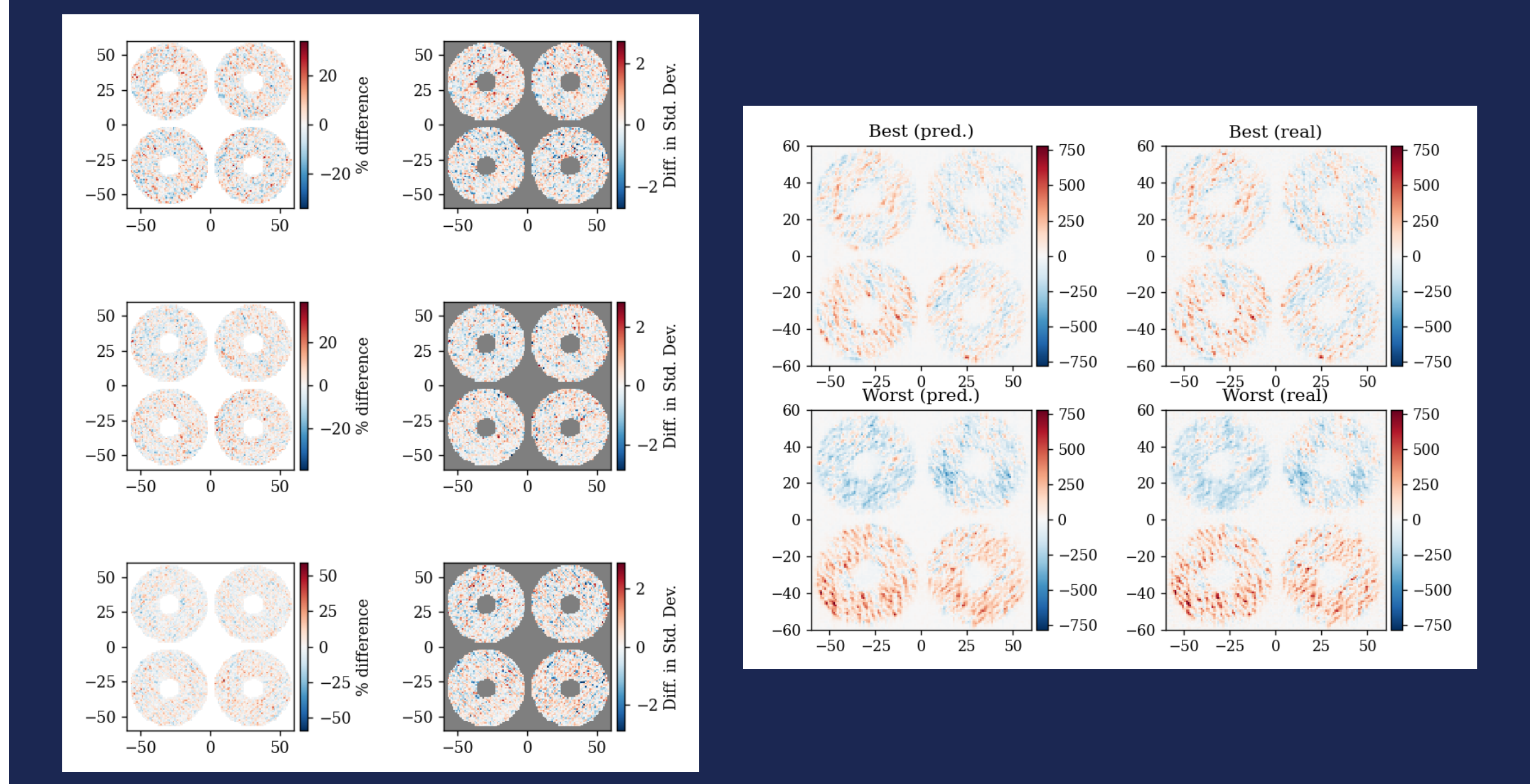


Figure 4: *Left:* Residuals of reconstructed frames from a convolutional neural network. *Right:* Example WFS frames from the best and worst held-out interval in the test set from on-sky data on alpha Cen . This network reconstructs 16 x 120 x 120 = 230400 pixels using vectors of length 12168, approximately 20:1 compression or 5% of the input dimension.

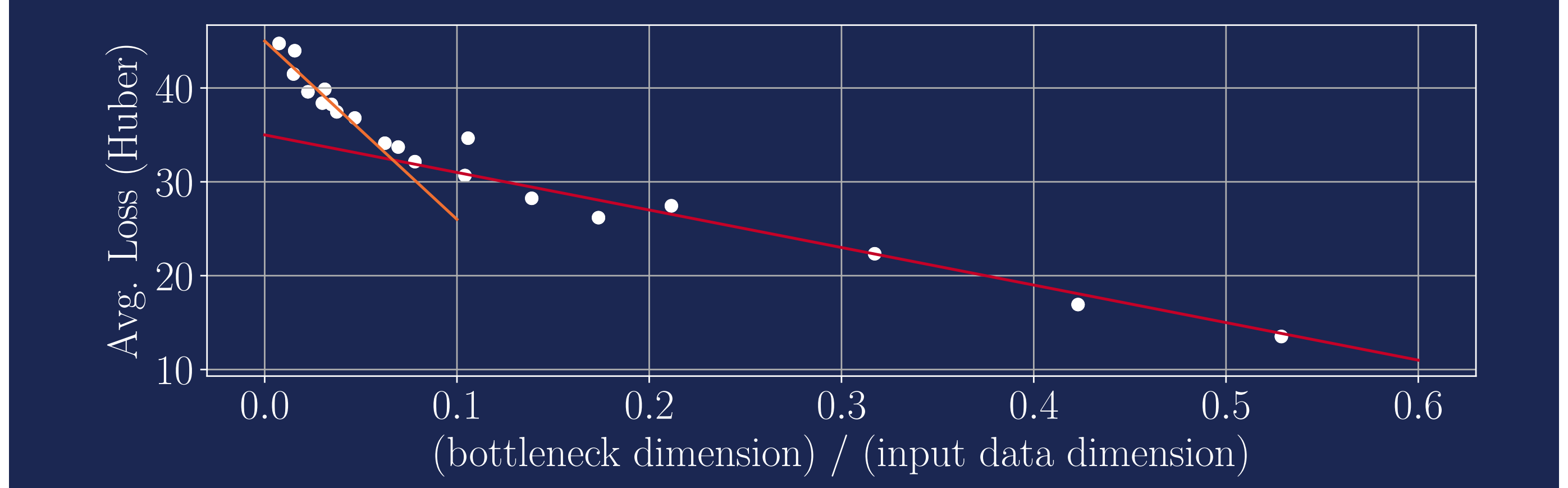


Figure 5: Sampling a variety of hyperparameter values reveals a point of diminishing returns when compressing wavefront sensor data nonlinearly. Going from 10% of the input dimension to 20% provides only a marginal improvement.

FUTURE WORK

With a credible architecture to achieve 20:1 reduction of WFS frame data, coupled with a sufficiently flexible NCPA model, we can isolate and train the WFS to residual WFE stage in a way that should generalize from lab data to on-sky data. However, we still need to investigate the ability of this architecture to handle differences in WFS readout modes.

ACKNOWLEDGEMENTS

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