



Machine Learning Wavefront Reconstruction: On-sky Results with SPIDERS

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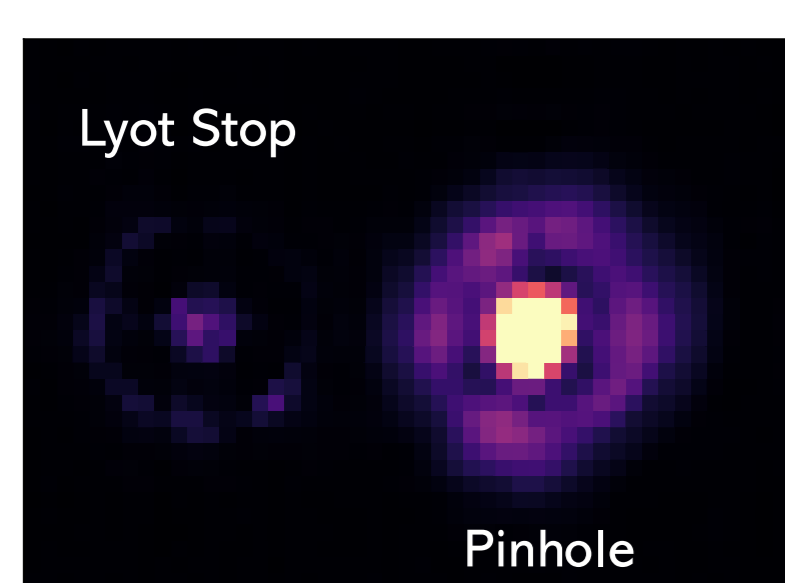
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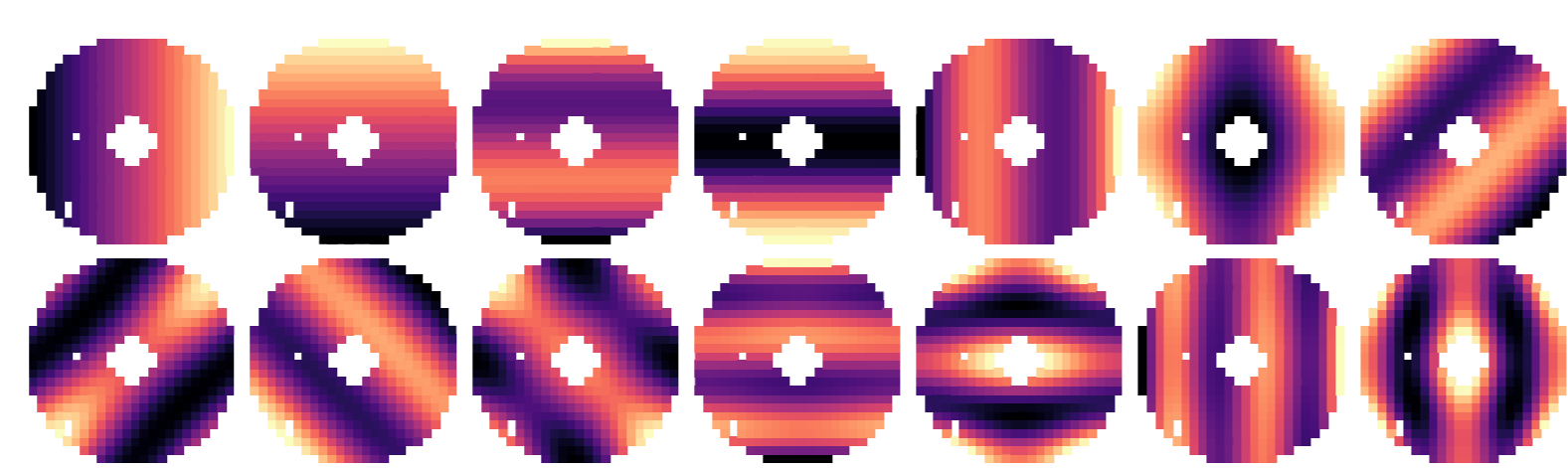
SPIDERS and Wavefront Sensing

- Subaru Pathfinder Instrument for Detecting Exoplanets and Retrieving Spectra (SPIDERS) is a pathfinder instrument for the Fast Atmospheric Self-Coherent Camera Technique to be used on the GPI 2.0 CAL2 system and future AO for ELT systems¹
- Lyot-based Low Order Wavefront Sensor (LLOWFS) detects and controls low spatial frequency aberrations in the pupil plane²
- SPIDERS control modes are orthogonal over circular aperture
- From LLOWFS image reconstruct first 14 modes to apply correction via deformable mirror → single image phase diversity estimation
- Linear matrix reconstructor suffers from non-linearity and modal crosstalk²
- Solution: machine learning-based wavefront reconstructor

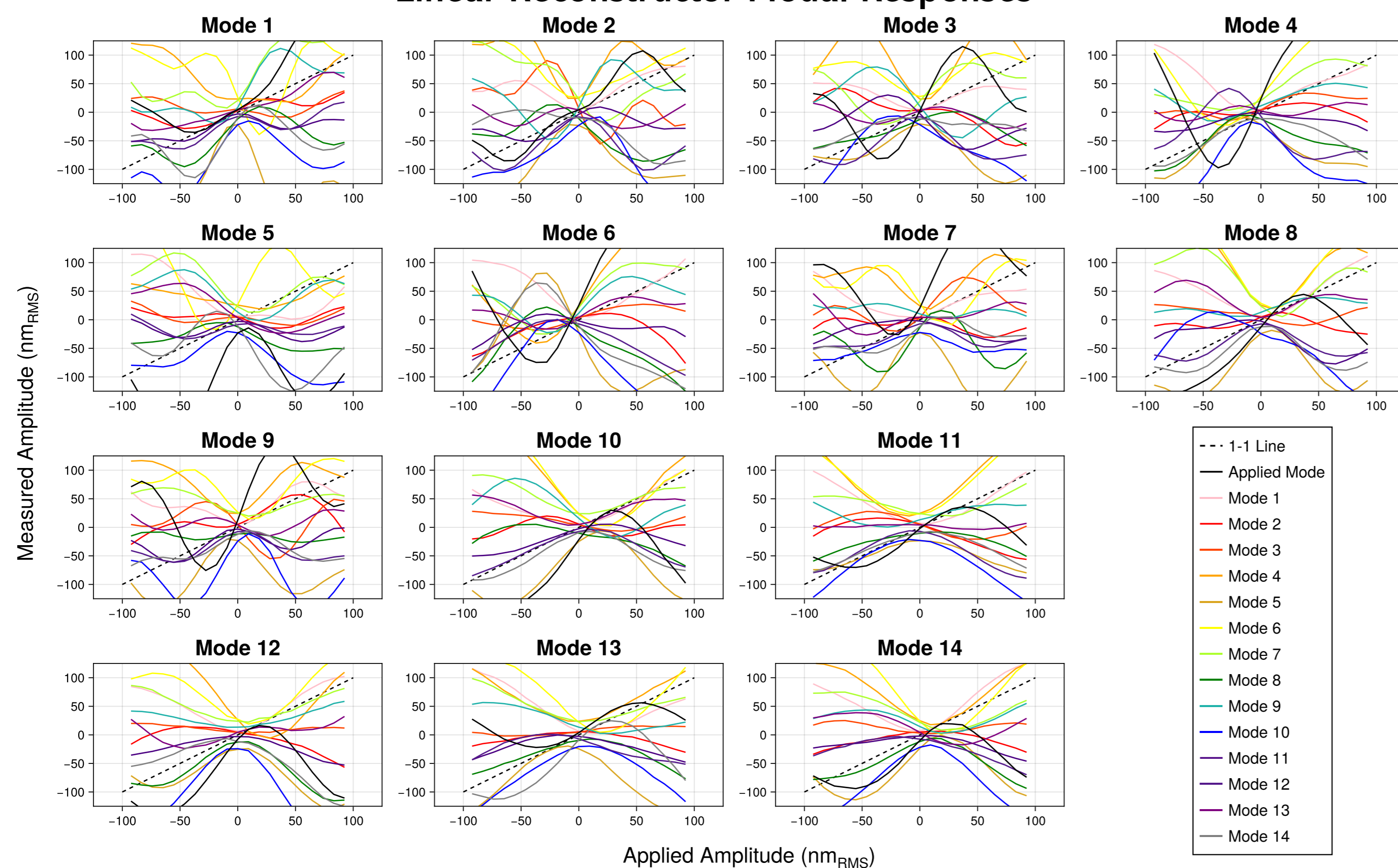
Sample LLOWFS Image



First 14 SPIDERS Spatial Modes

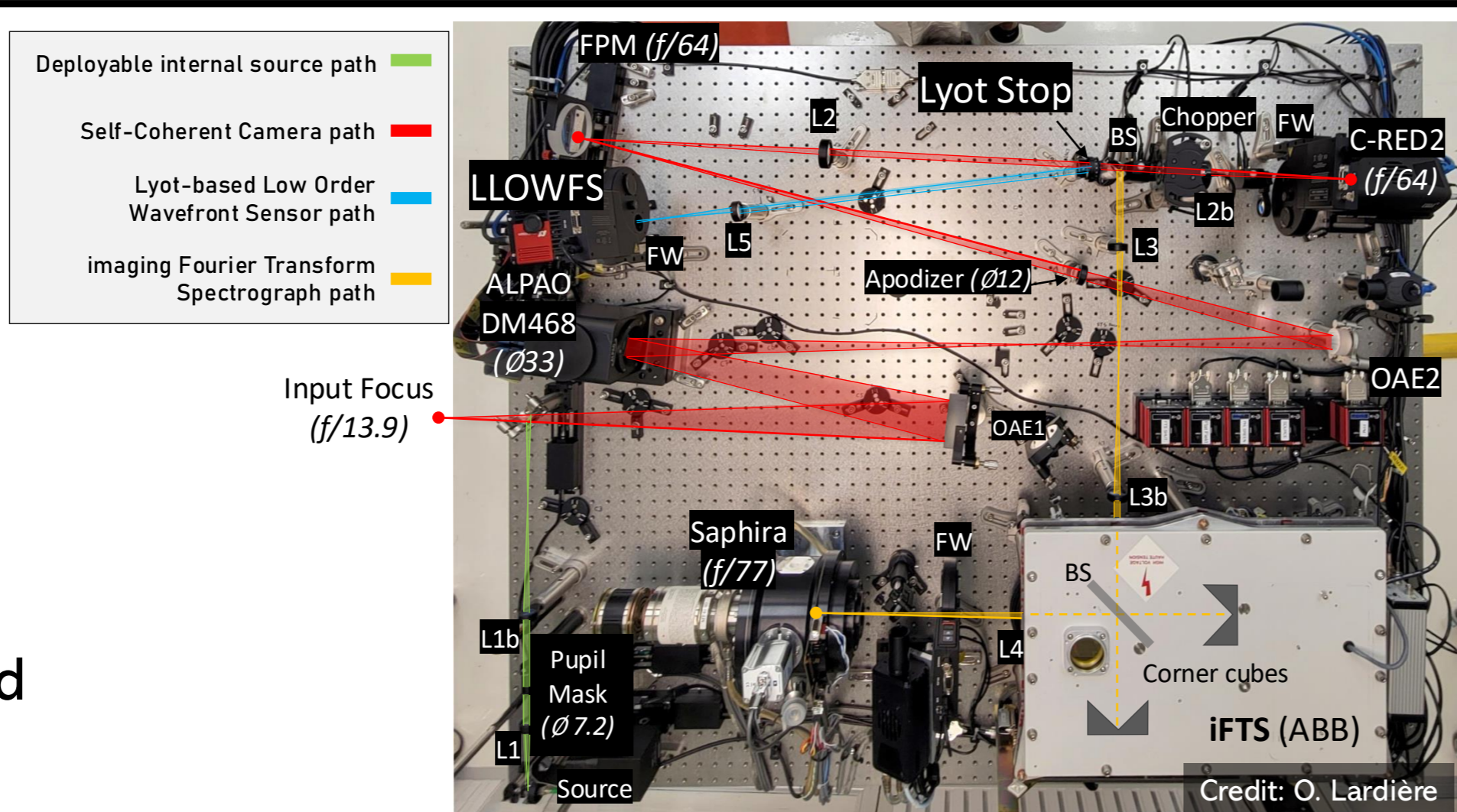


Linear Reconstructor Modal Responses



SPIDERS Design

- Uses Fast Atmospheric Self-Coherent Camera Technique³
- Low order loop runs at 1 kHz
- SCC loop runs at 1-10 Hz
- iFTS extracts full-field spectra
- On-sky contrast of 4.0×10^{-6} !
- See talks and posters by K. Hessel, C. Marois, C. Mann and W. Thompson for more!



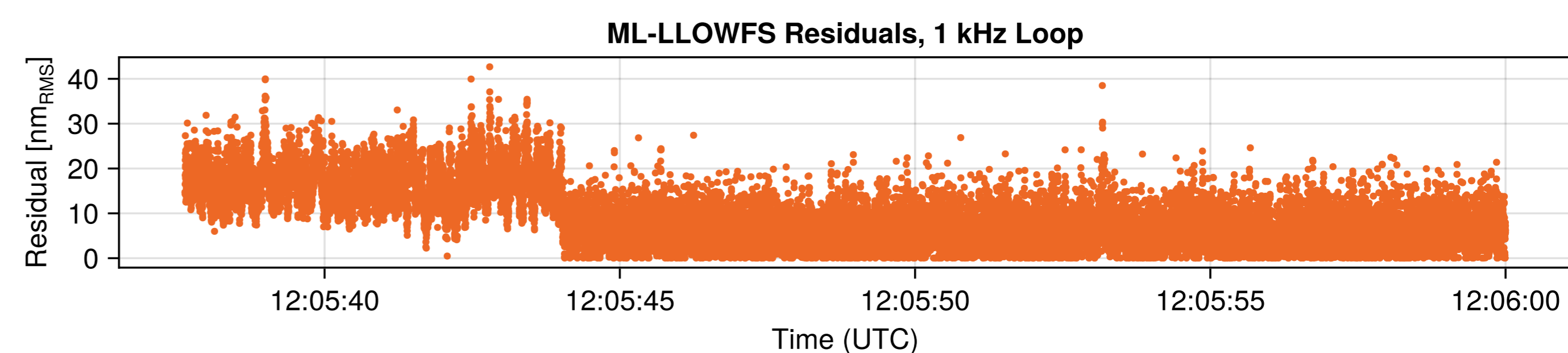
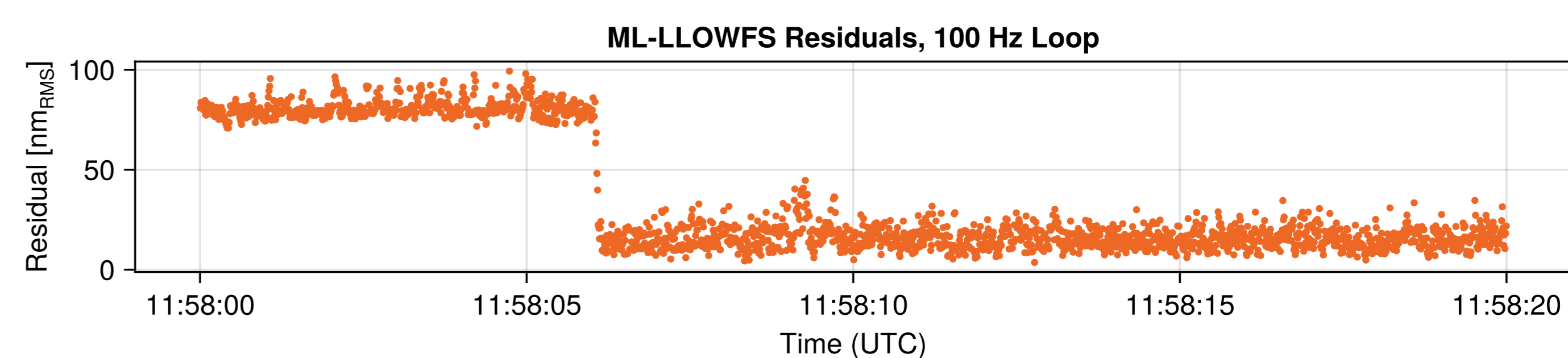
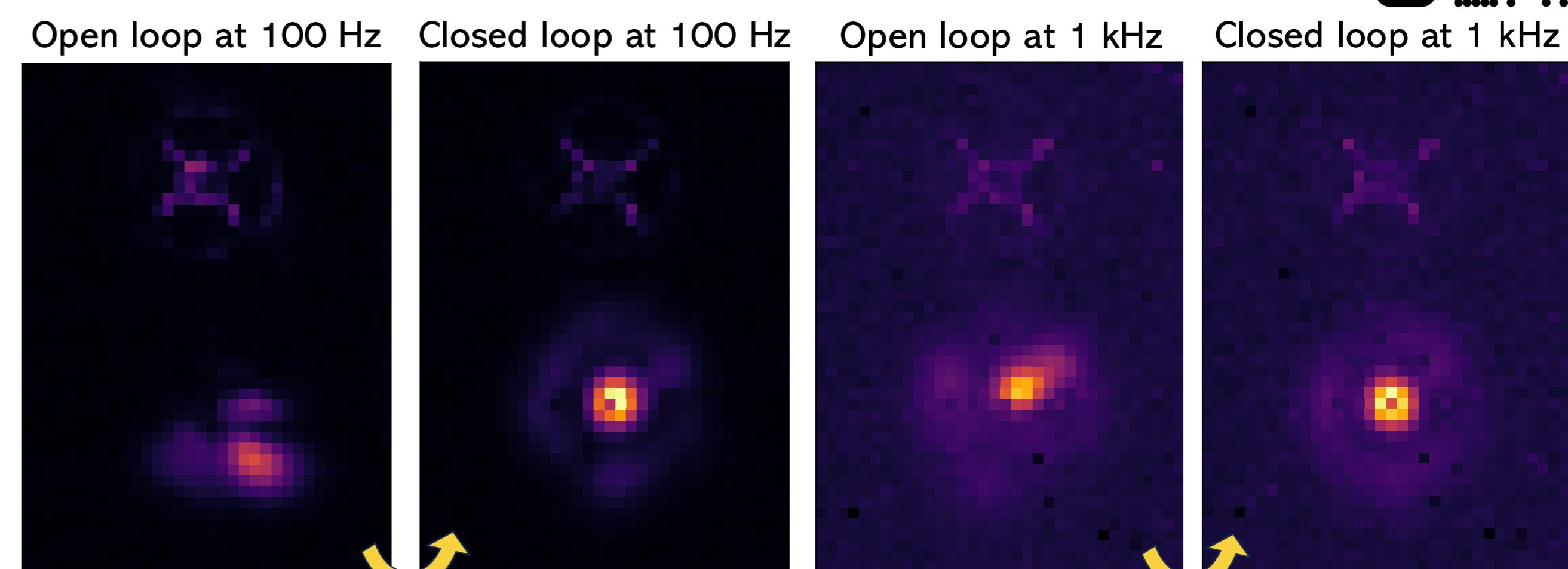
Model Training/Generalizing

- Loss function from Landman et al. 2024⁴ equally weights small aberrations with large aberrations, focusing on full range of amplitudes instead of only large aberrations
- Bench training: applied known signal to DM composed of SPIDERS modes, record LLOWFS image for training pair
- Injected simulated detector noise to mimic dim targets on sky
- Trained on 100,000 images with random combinations of modes + 100,000 copies with various levels of added noise

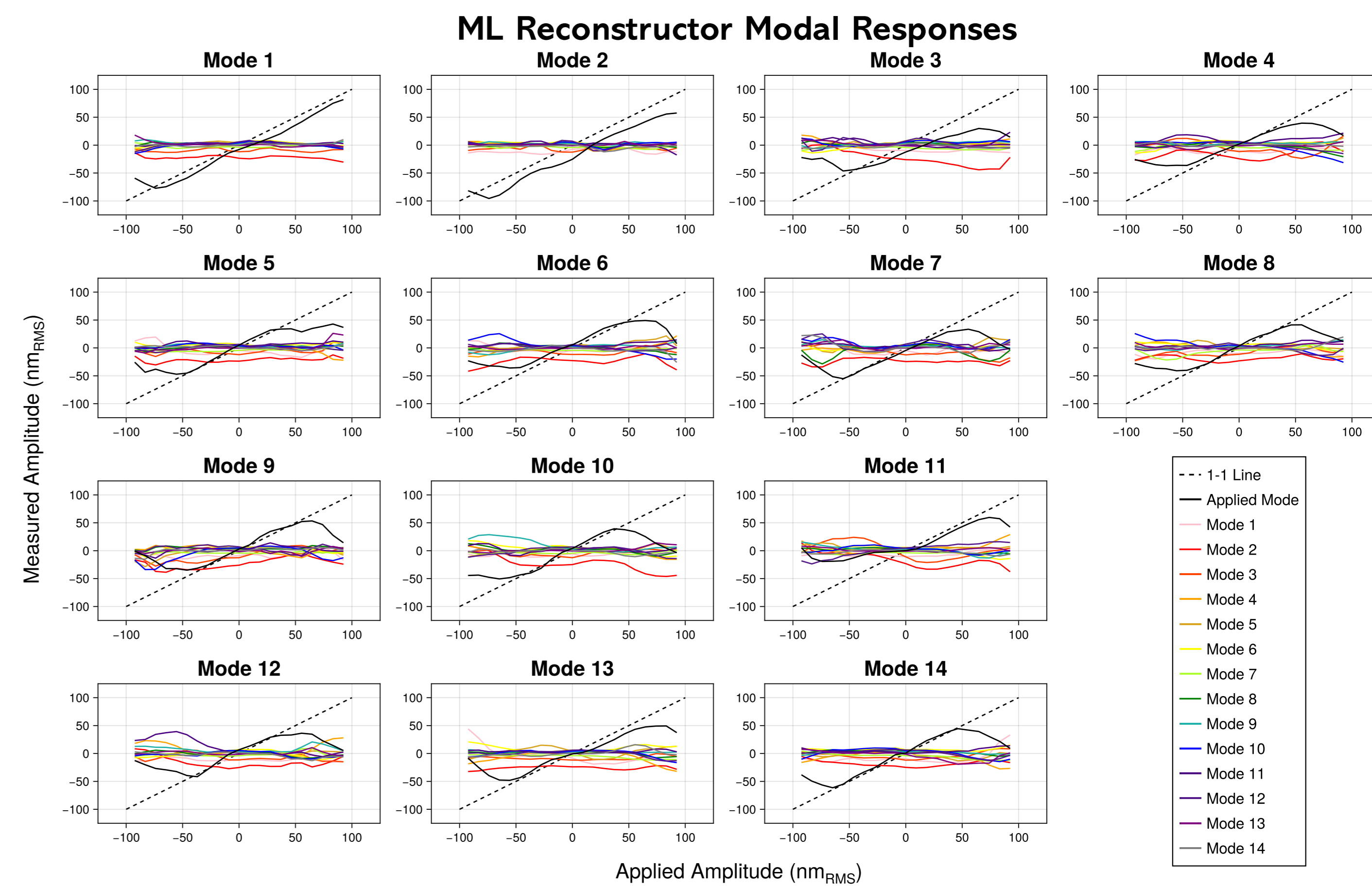
On-sky Performance

- Closed loop on-sky in poor conditions (~1" seeing, 40 m/s winds)
- 100 Hz slightly too slow to fully control low orders, 1 kHz better control over 14 modes → low order modes are evolving rapidly
- Observing in May/June, hoping for better conditions to go further!

Scan for observing videos!



Lab Reconstruction Performance



- Huge improvement to cross-talk, better linearity
- Fast predictions allow for closed loop at 1 kHz or faster

Outlook and Next Steps

- Successful results even in relatively poor conditions, promising for better conditions
- Potentially switch GoldEye detector with CRED2 for lower detector noise, run faster
- Experiment with controlling up to 24 low order modes, tweak architecture as needed

References

1. Lardière, Olivier et al. (June 2023). "Design, integration & tests of SPIDERS: a Subaru Pathfinder Instrument for Detecting Exoplanets & Retrieving Spectra". In: *Adaptive Optics for Extremely Large Telescopes 7th Edition*. Avignon, France. doi: 10.13009/AO4ELT7-2023-093.
2. Singh, G. et al. (2022). "Pupil-plane LLOWFS simulation and laboratory results from NEW-EARTH's high-contrast imaging testbed". In: *Adaptive Optics Systems VIII*. Ed. by Laura Schreiber, Dirk Schmidt, and Elise Vernet. Vol. 12185. International Society for Optics and Photonics. SPIE, p. 1218553.
3. Gerard, Benjamin L. et al. (2019). *The Fast Atmospheric Self-Coherent Camera Technique: Laboratory Results and Future Directions*. arXiv:1910.04554 [astro-ph.IM].
4. Landman, R., et al. (2024). "Making the unmodulated Pyramid wavefront sensor smart - Closed-loop demonstration of neural network wavefront reconstruction with MagAO-X". In: *A&A* 684, A114.