Photonic wavefront sensors for extreme AO

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Wavefront Sensing in the VLT/ELT era V & AO workshop
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THE UNIVERSITY OF SYDNEY
Institute of Photonics and Optical Science

SUBARU TELESCOPE SCExAO

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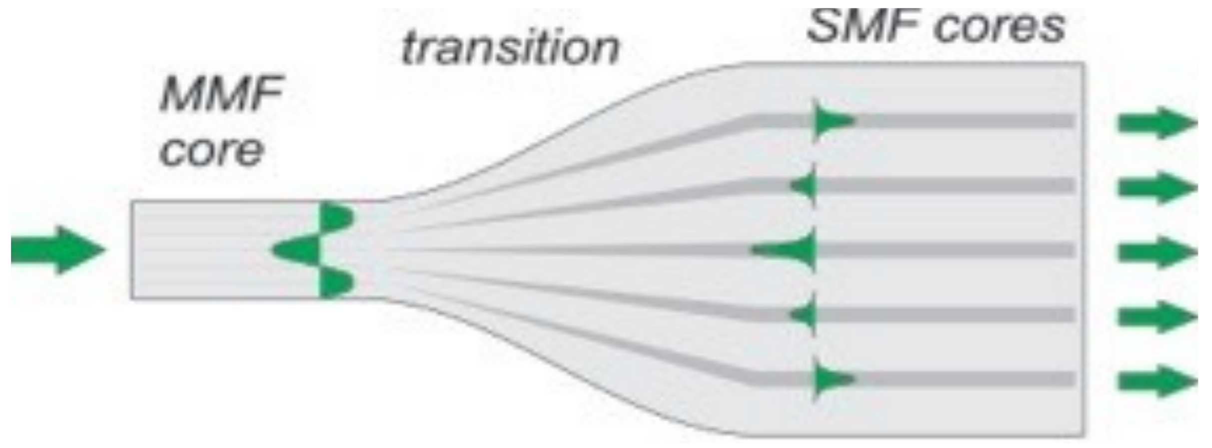
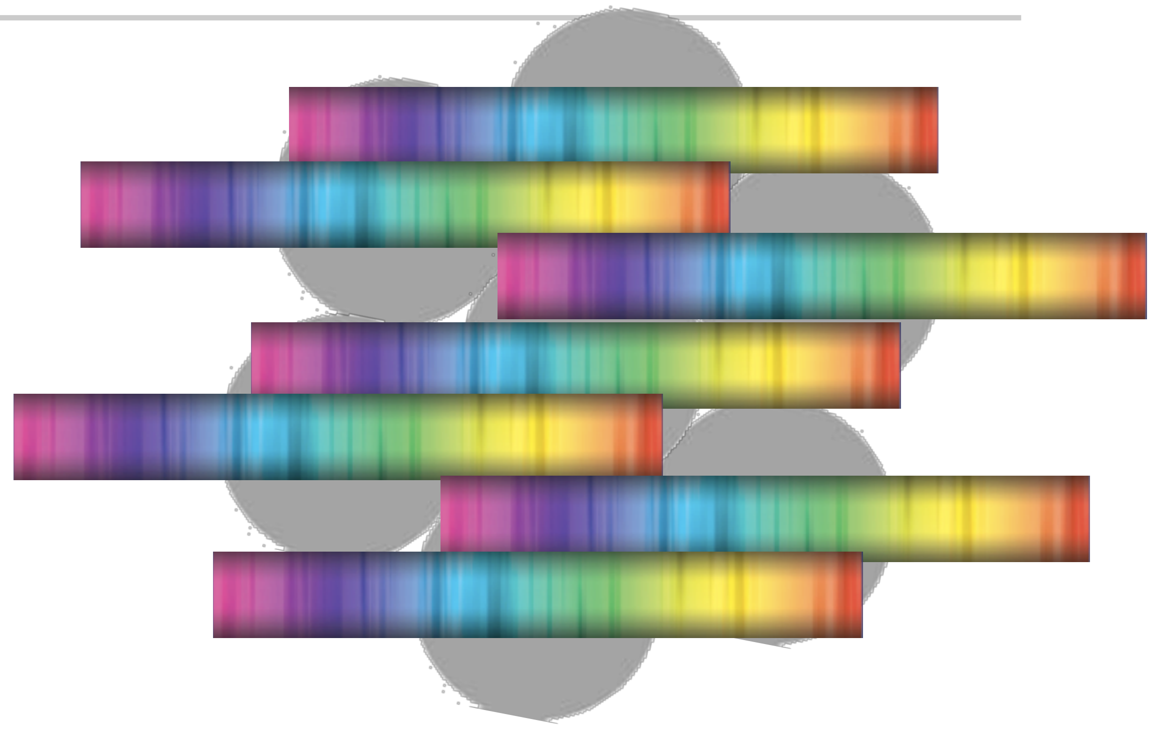
SYDNEY ASTROPHOTONIC INSTRUMENTATION LABORATORY

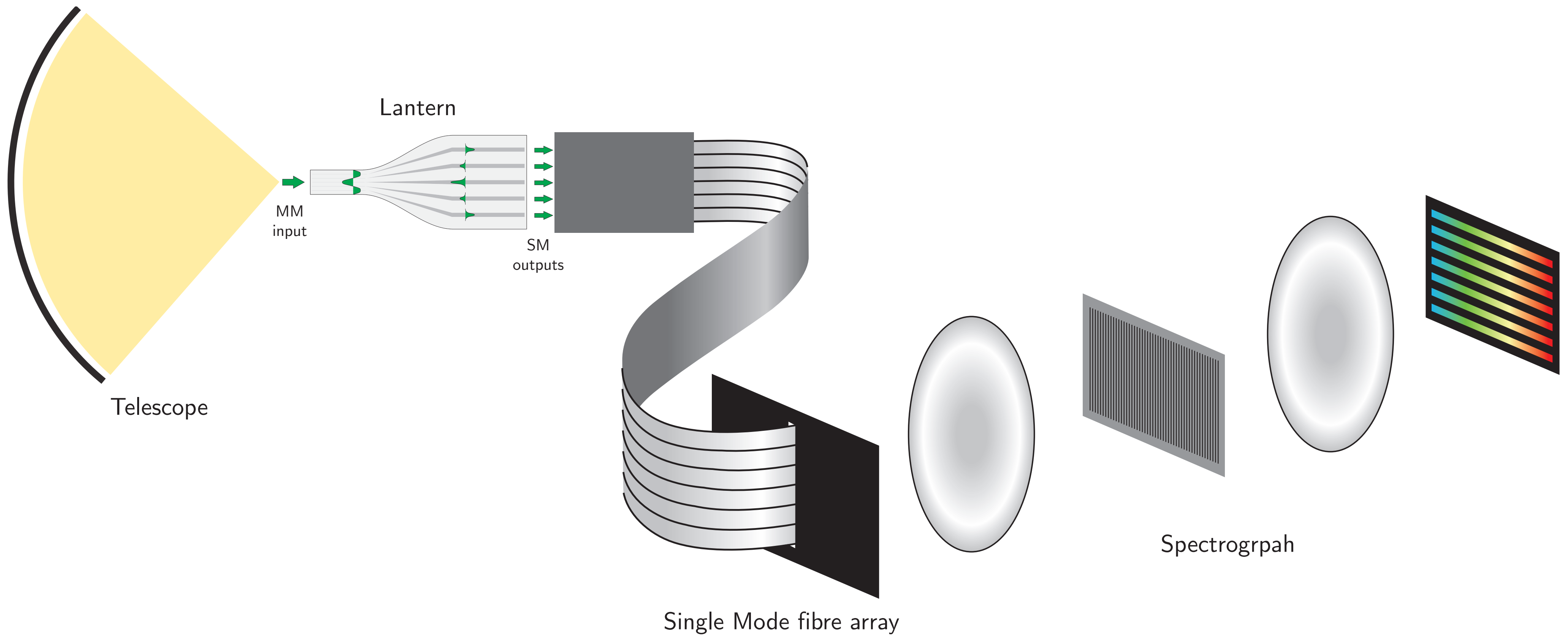
AAO

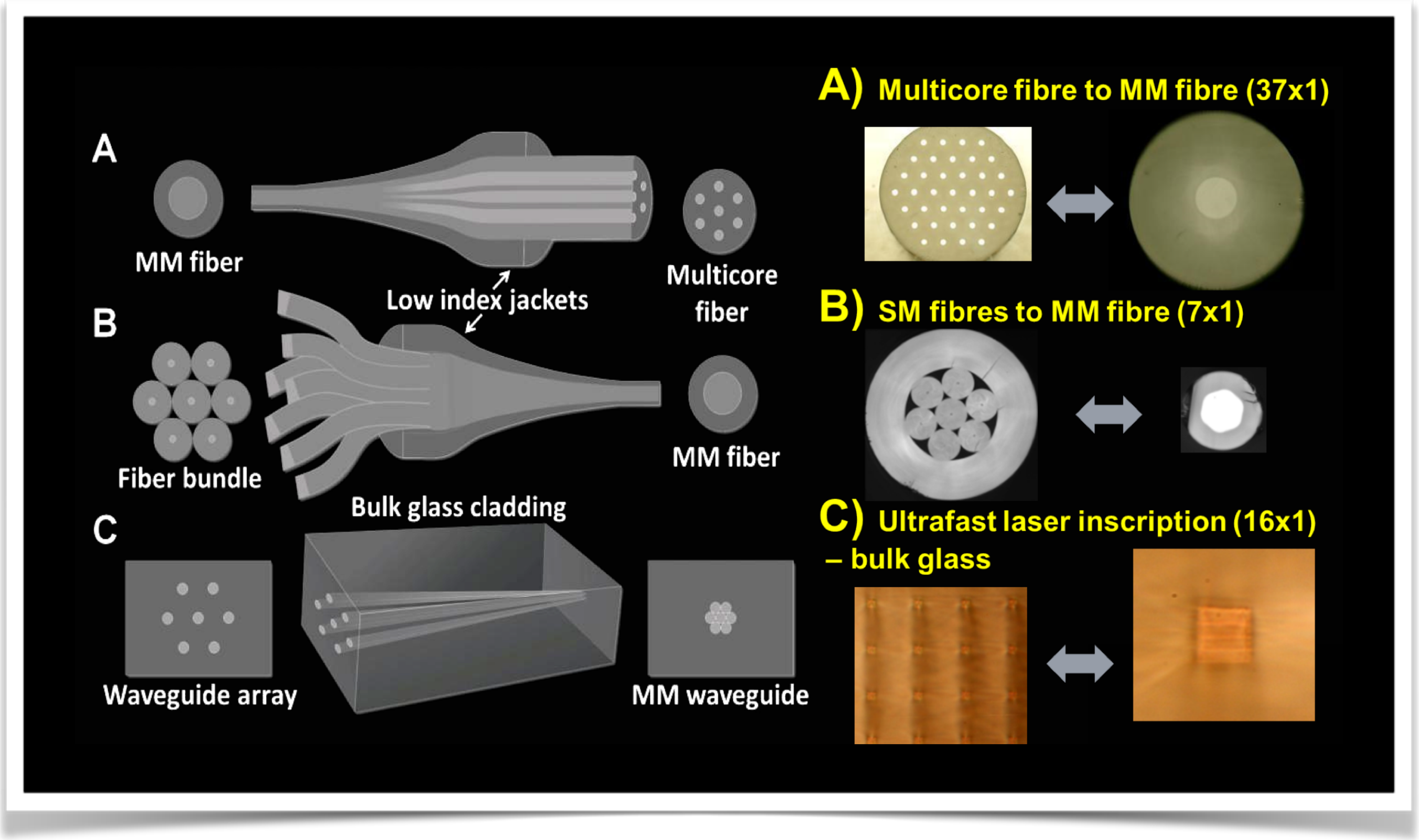
The photonic lantern

- Photonic device that converts light from a multi-mode to single-mode system and vice-versa with low loss
  - e.g. 1 MMF to multiple SMFs
- Direct relationship between input modes excited and output SMF flux (information preserved -> light preserved)
- Proposed use in astronomy to allow single-mode-spectroscopy despite seeing
- Used in telecommunications in SDM









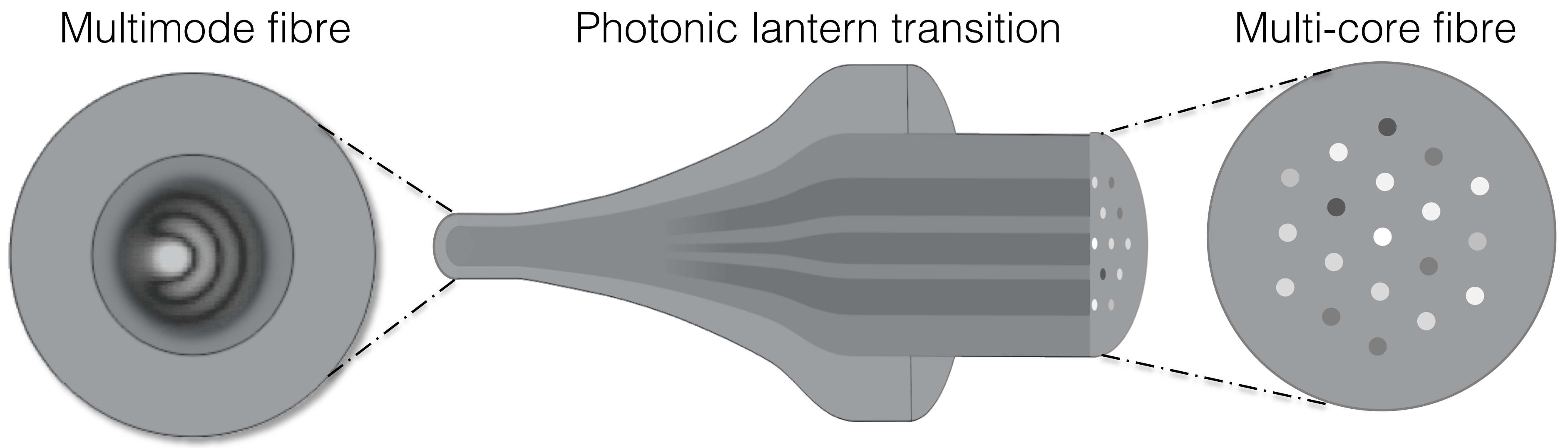
Photonic lantern as wavefront sensor

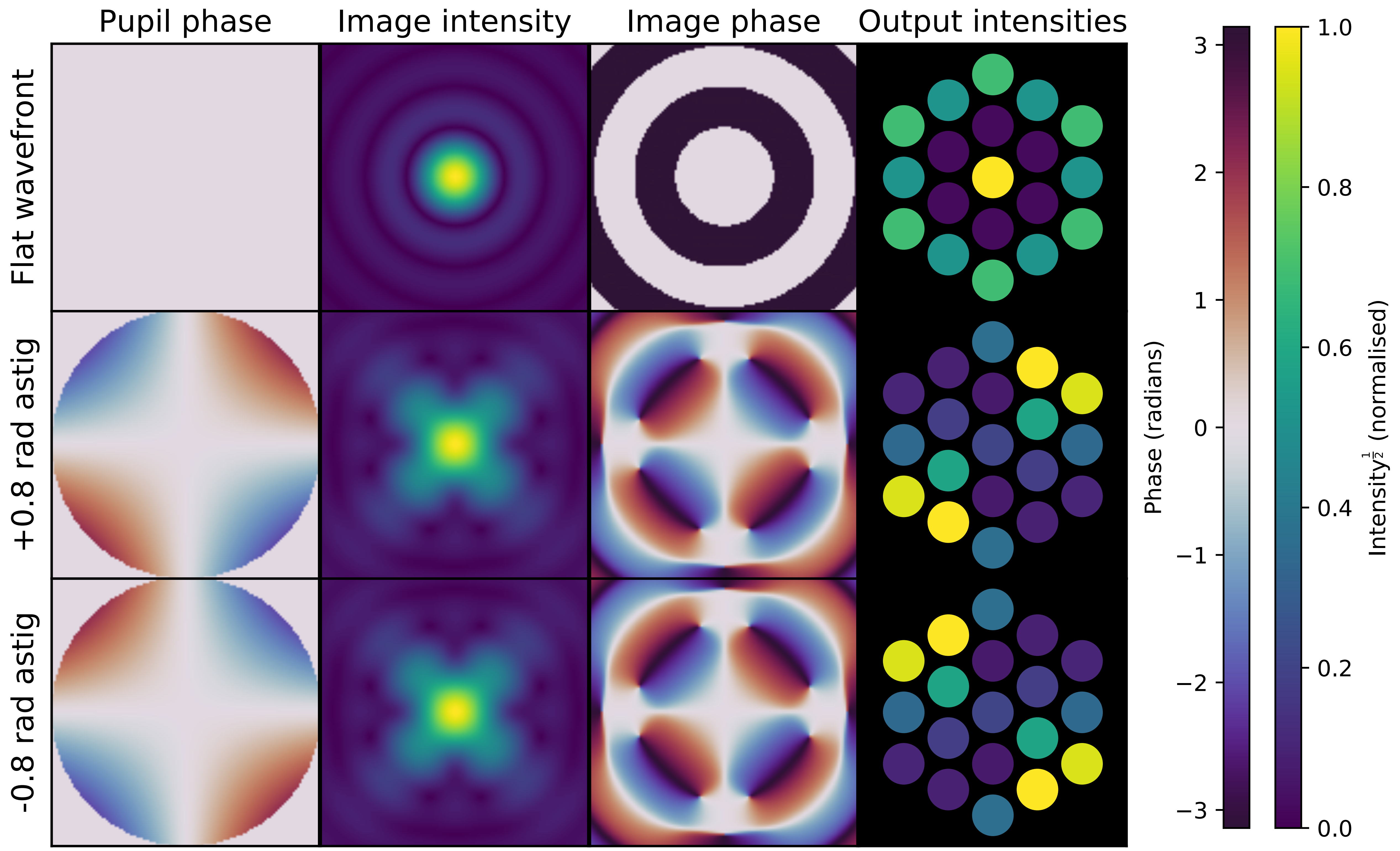
Use fluxes at SM outputs to infer wavefront…

- Modes excited at MM input are a function of complex amplitude of light -> SM outputs are also
- If transfer function is known, can work backwards and predict wavefront
  - Note TF is function of both PL itself and injection into MM region
- Cannot precisely specify transfer function at design / manufacture

Key advantages:

- True focal plane wavefront sensor with instantaneous measurement, without linear approximations
- Optimally feed light to spectrograph with truly zero non-common-path
  - MCF directly on spectrograph in Tiger configuration
- Wavelength information for wavefront sensing! Long sought after, e.g. for atmospheric scintillation
- Scales to multiple astronomical objects in field (MOAO)

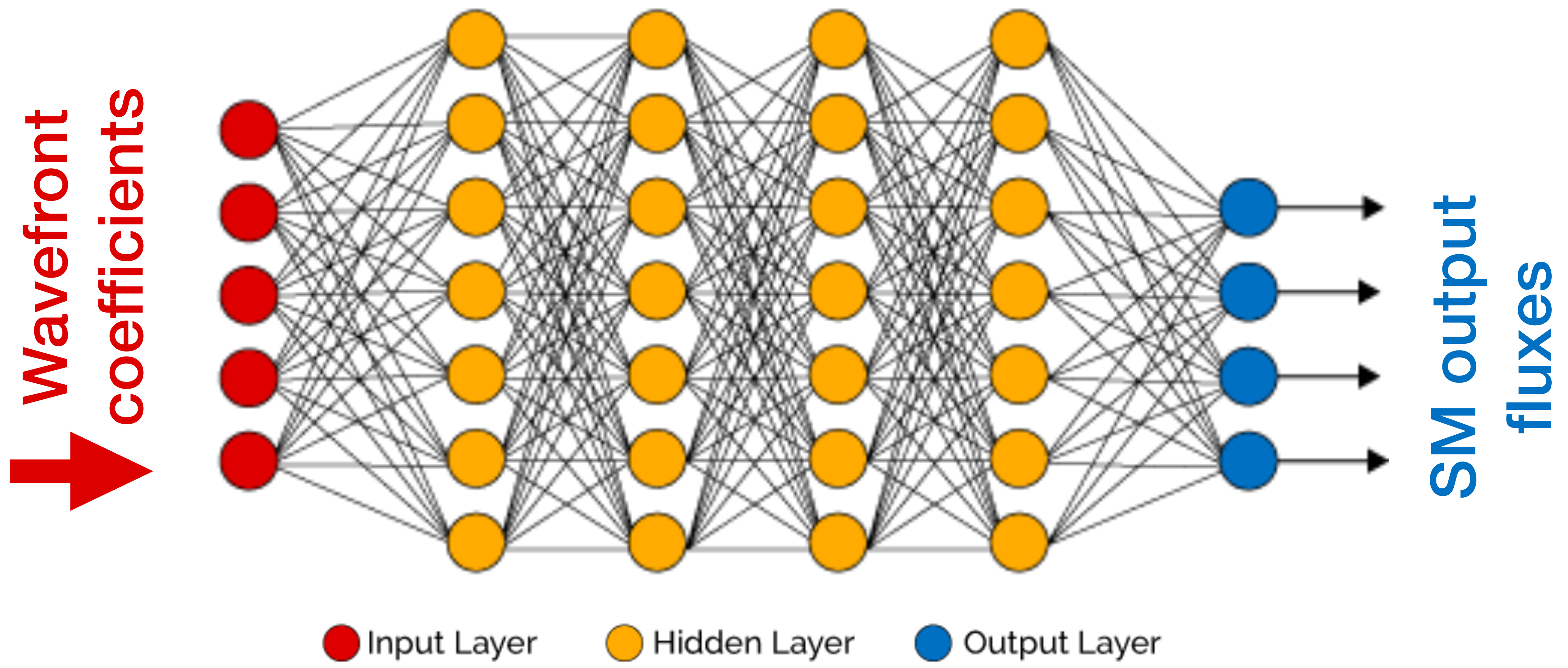


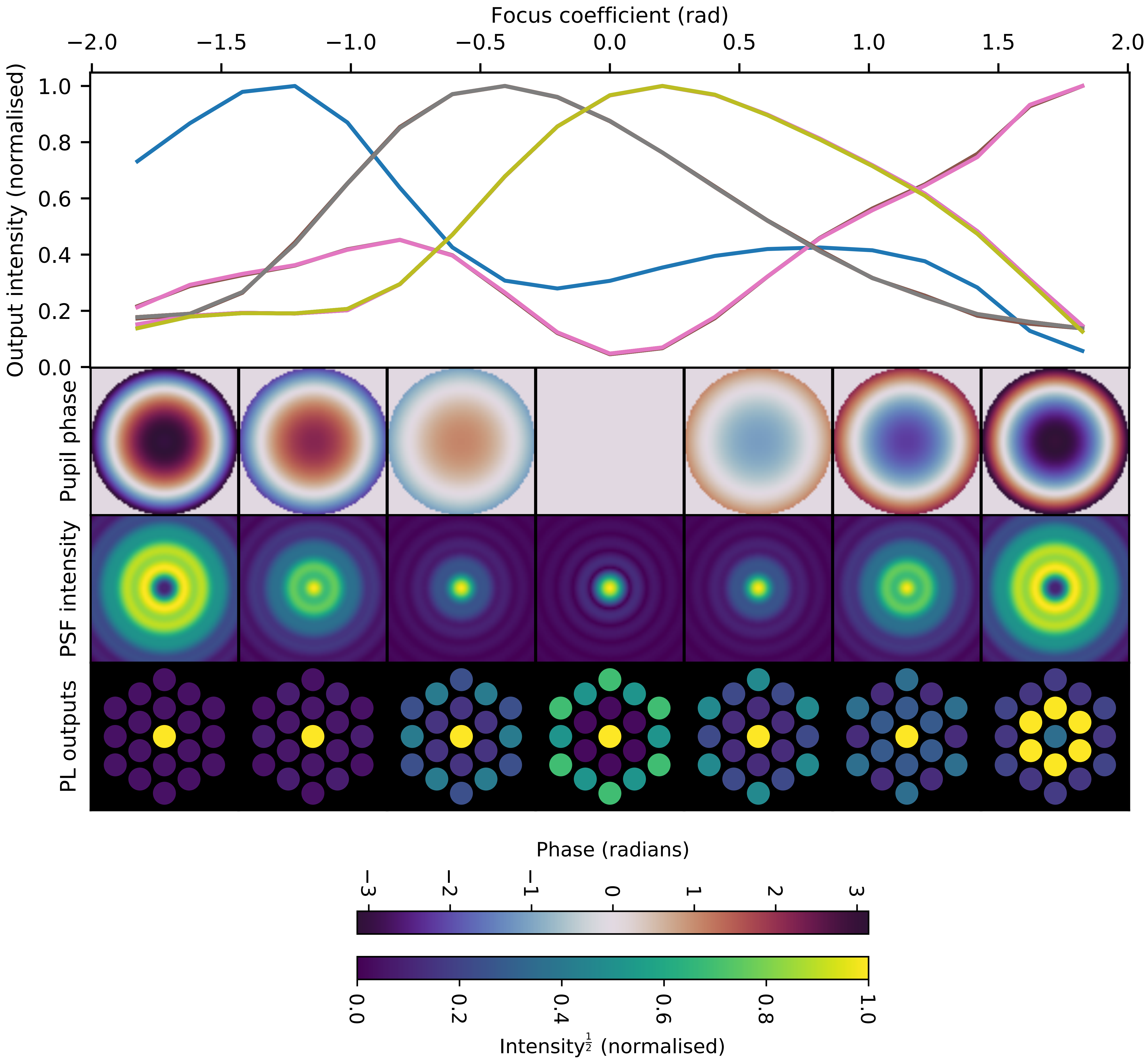


Photonic lantern as wavefront sensor

The transfer function

- Output fluxes are a ***non-linear*** function of input wavefront (so not a matrix)
- Since can't specify this transfer function during design, so need to ***learn*** it after implementation
- Use a ***deep neural network*** to learn the transfer function, and then predict unknown wavefronts from output fluxes





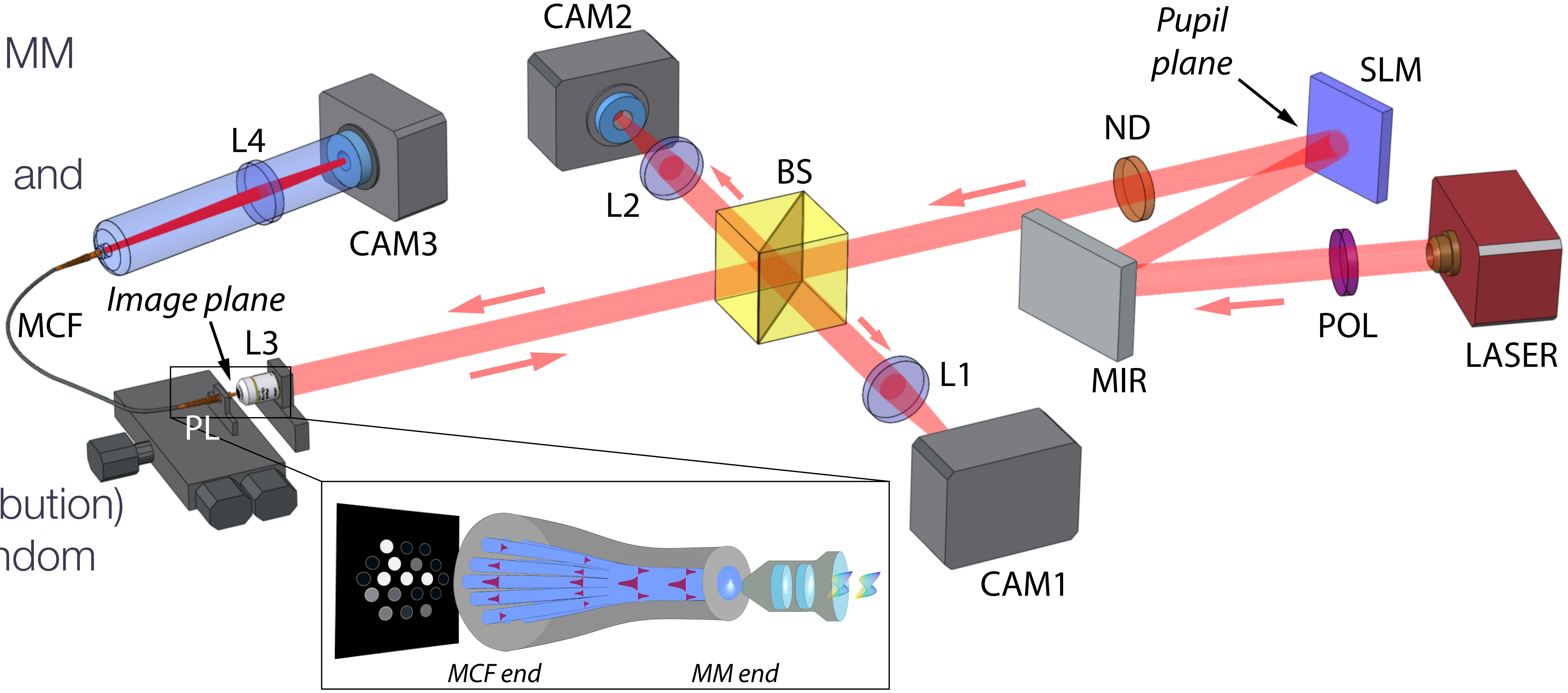
Laboratory demonstration

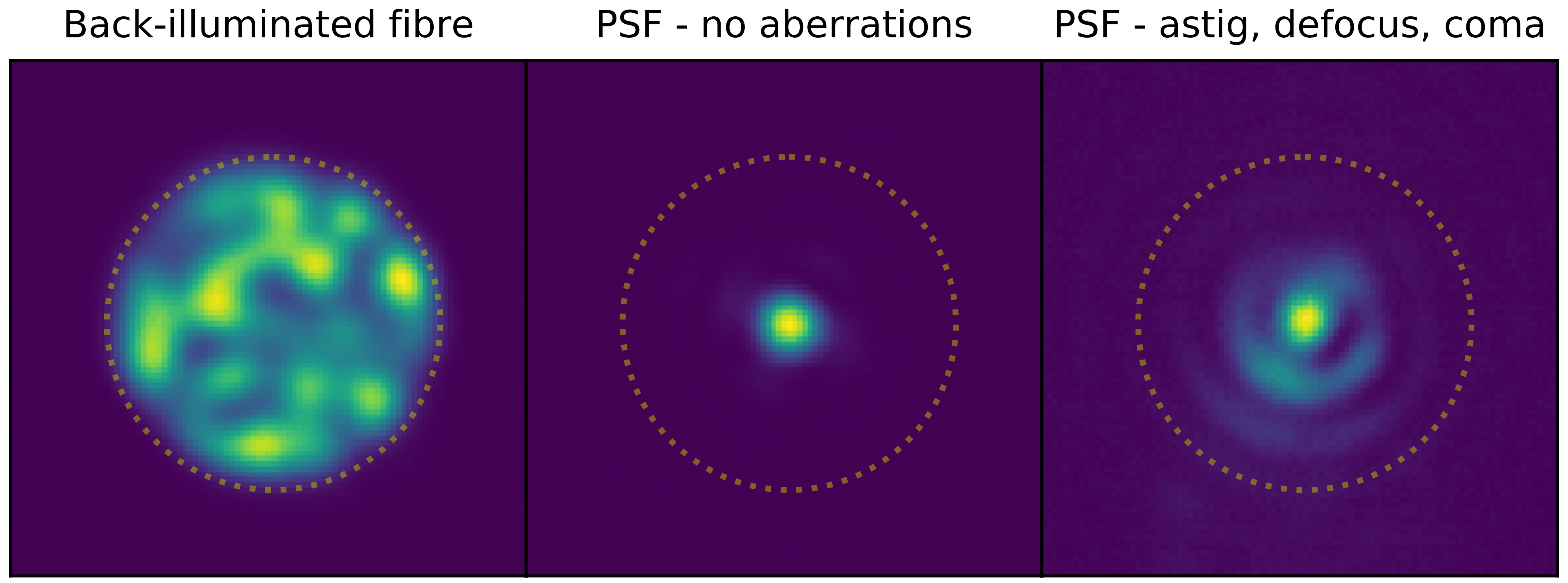
Laboratory setup

- Apply arbitrary wavefronts via SLM, inject PSF into MM region of 19 mode PL
- Also includes back-reflection imaging for alignment and characterisation
- 685 nm (1.2nm bw)

Training and measurement

- Generate wavefront by drawing (from uniform distribution) random Zernike coefficients for first 10 modes - random combinations probe nonlinearity.
  - Each wavefront on average was π radians P-V
- Apply to SLM and measure PL output fluxes for each
- Acquired ~60 000 measurements (much more than needed). ~30 s on modern AO system
- Kept 20% secret for testing performance, trained on other 80%.

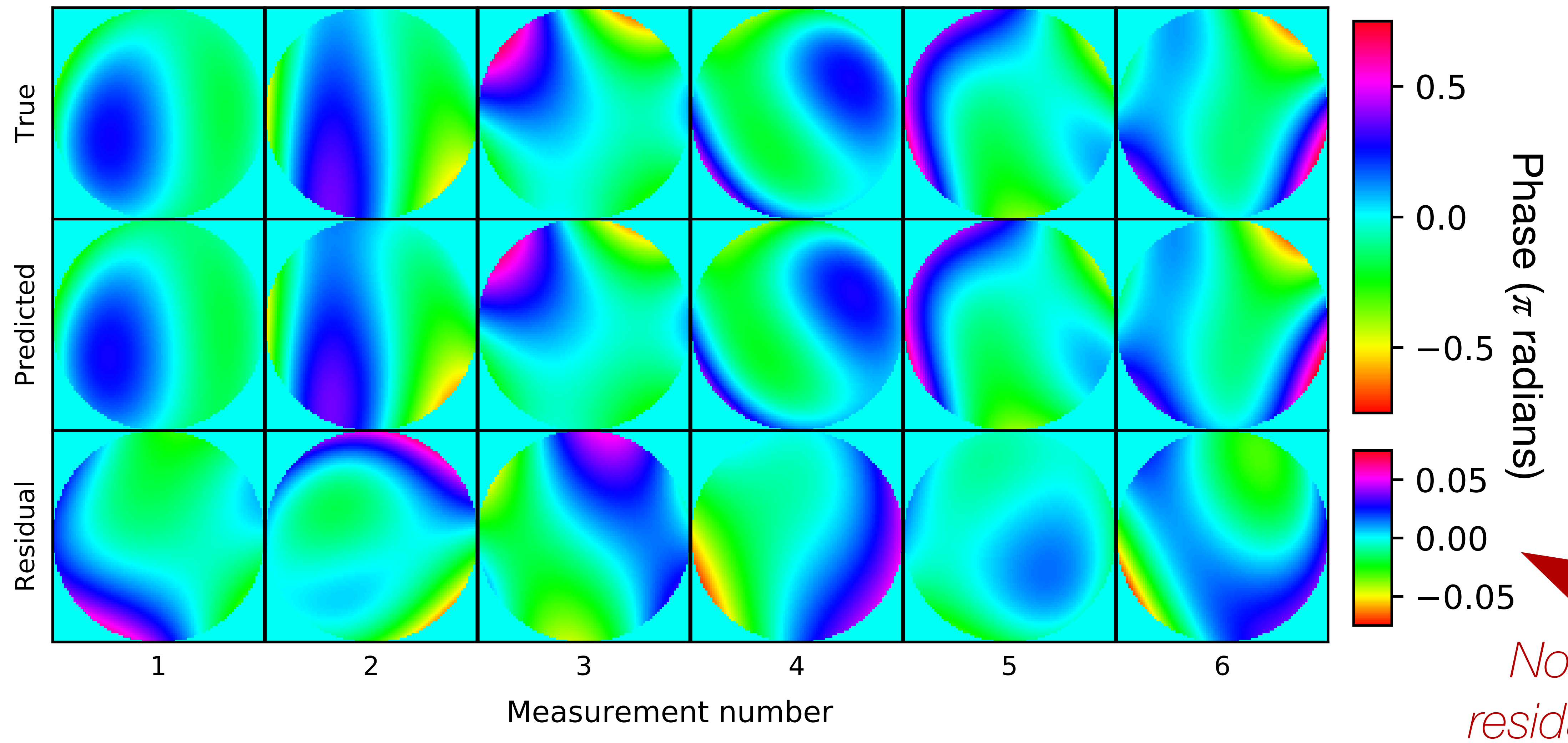




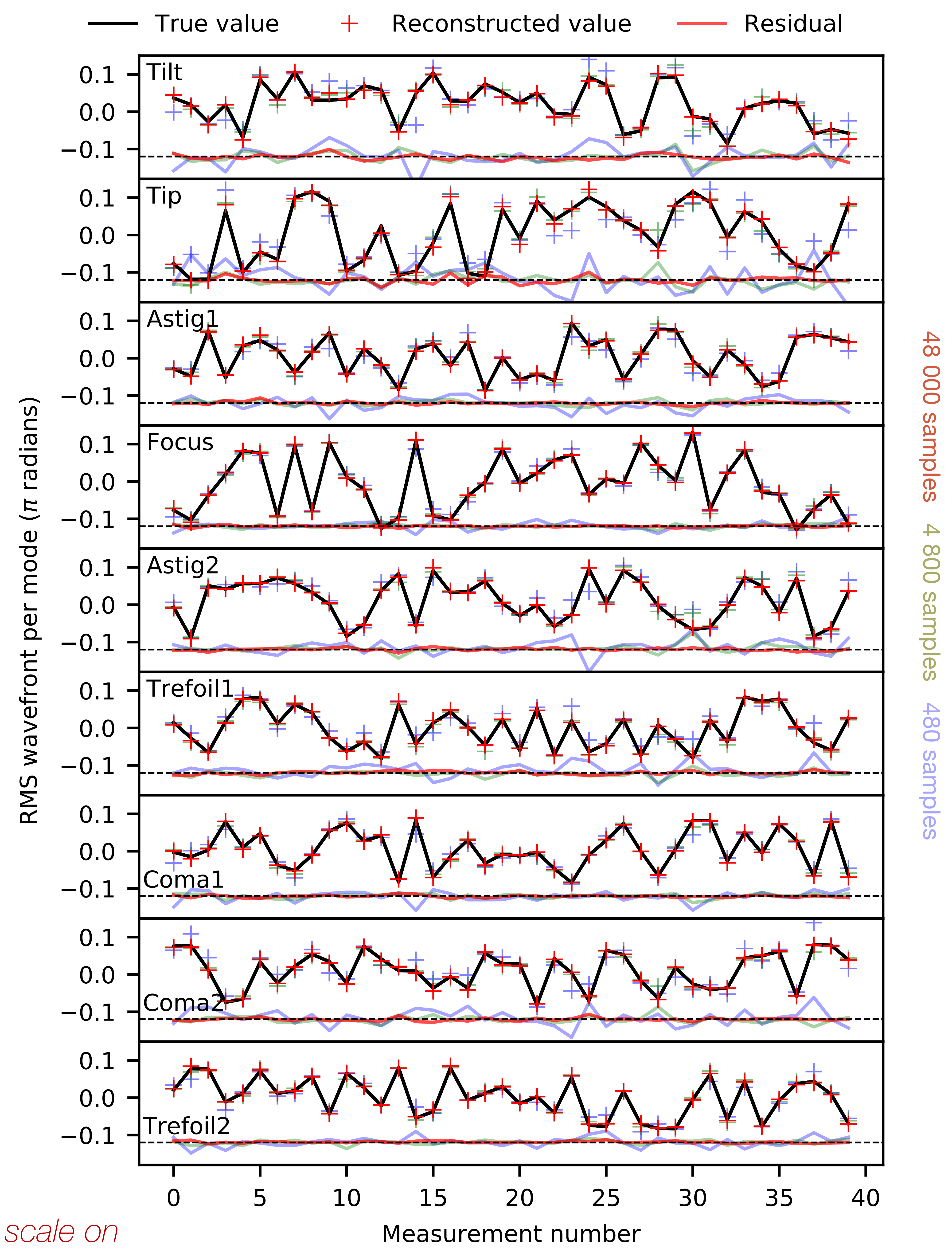
Laboratory results

Reconstruct input wavefront with ***RMS error of 5 x $10^{-3}\pi$ radians*** (for π radian input WFs)

Activation	Neurons in first layer	Neurons in final layer	Number of hidden layers	RMS error $\times 10^{-3}$ π radians
Non-linear (ReLU)	2000	100	2	**5.1**
	2000	2000	2	**5.1**
	2000	100	1	**5.9**
	200	30	6	**6.4**
	2000	-	0	**7.6**
	100	100	3	**7.6**
	100	-	0	**17**
Linear	-	-	-	**30**



Note - color scale on residuals 10 times smaller

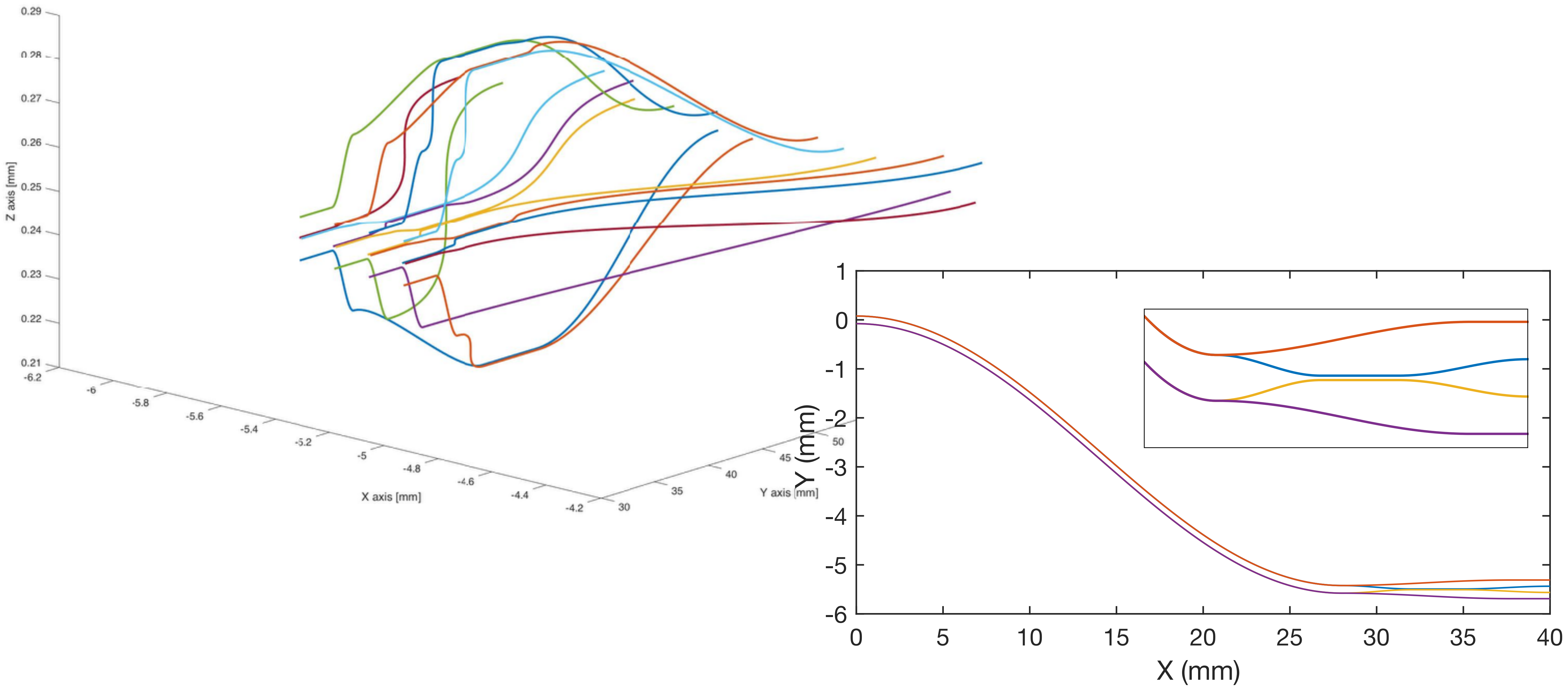


GLINT: Photonic nulling chip…

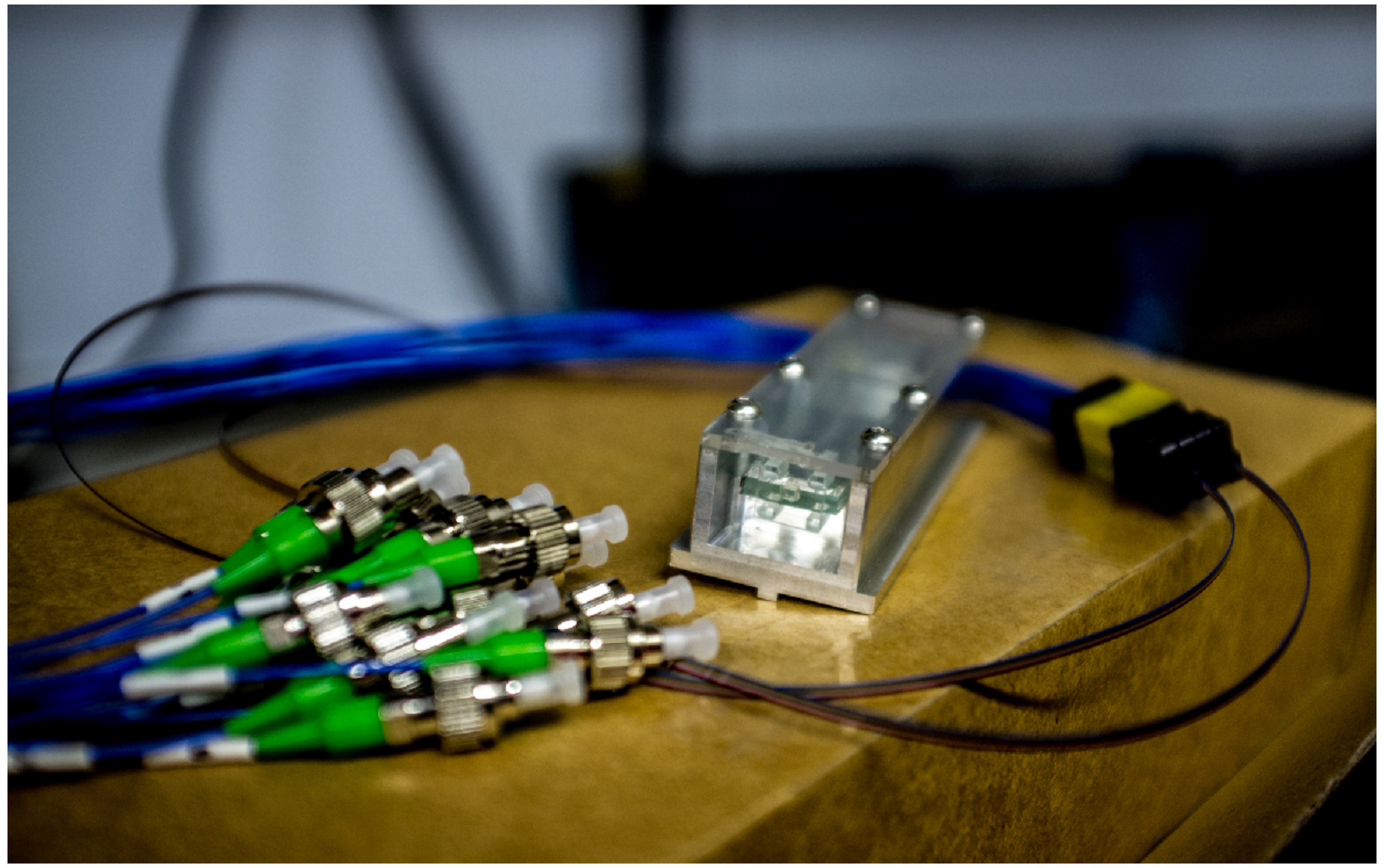
Uses a 3D photonic chip (ULI) to destructively interfere starlight, revealing signal of high contrast structure

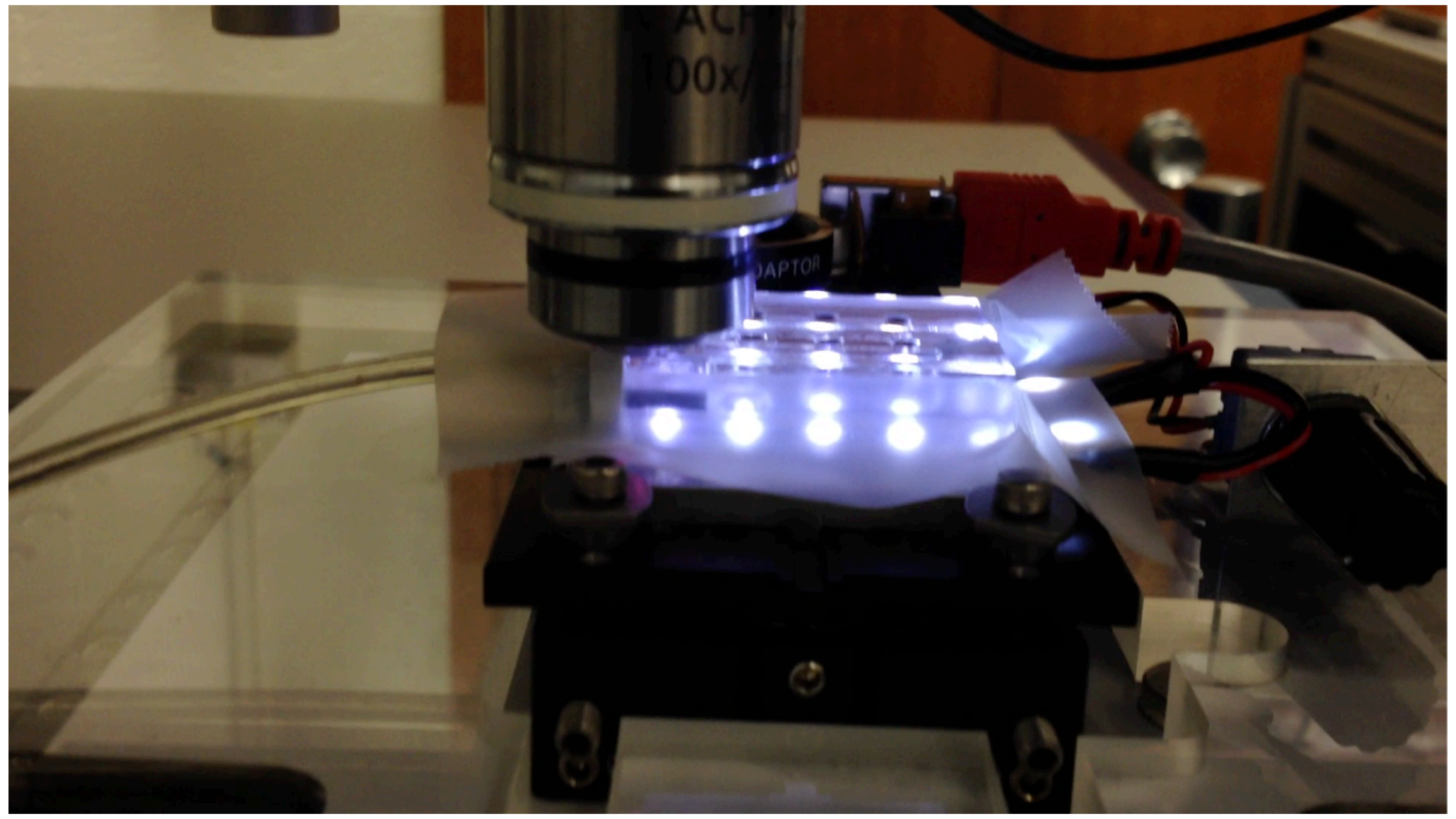
- Telescope pupil imaged onto chip
- Remapping + interference via evanescent couplers in chip
- 10s of outputs, encoding time domain signal as pupil rotates

Photonic equivalent of a coronagraph…
…image features as close as 0.5 λ/D



The waveguide structure of GLINT, including splitters and directional couplers



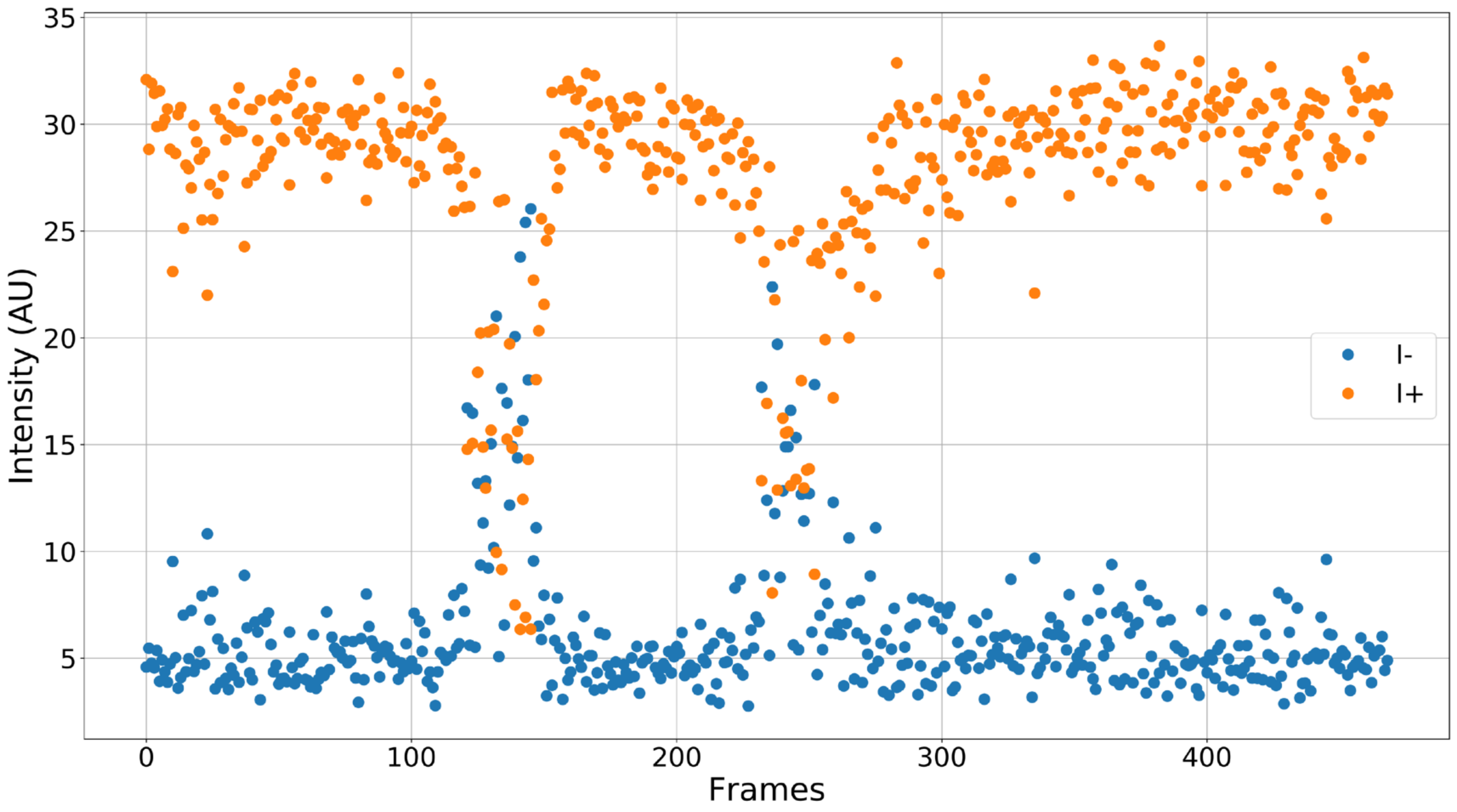


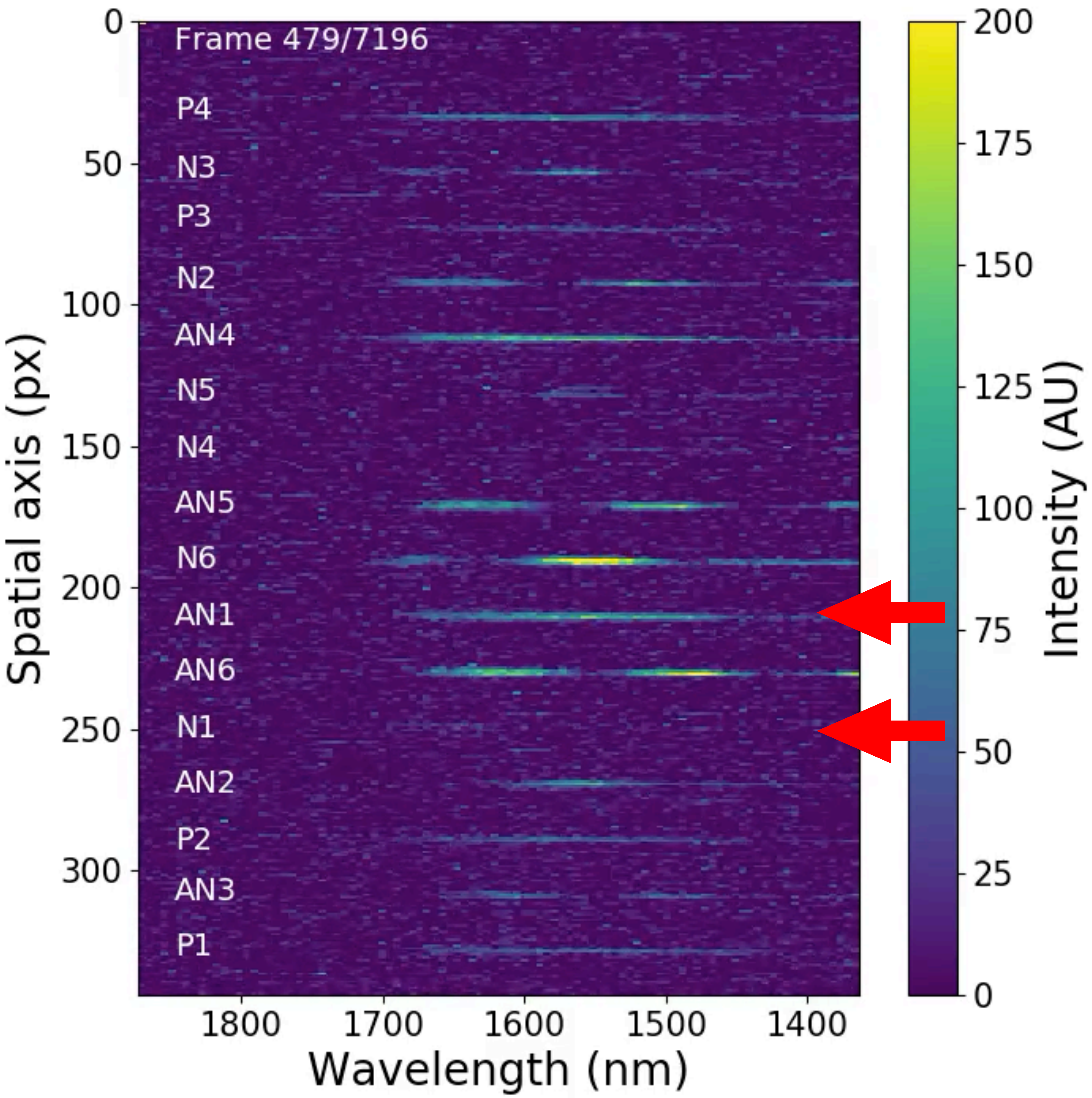
ULI fabrication process at Macquarie University - waveguides inscribed within glass chip via femtosecond laser

…as wavefront sensor!

An interferometric wavefront sensor

- Both for its own fringe-tracking, but also as low-order WFS for entire ExAO system
- Different parts of the pupil directly interfered with each other -> robust to phase shear e.g. across spiders
- Directly measures low wind effect
- Spectrally dispersed allows phase unwrapping
- Next: tricouplers (120 deg phase offset) - get direction.





Conclusion

Want to know more?

Photonic lantern WFS: Norris, et al. 2020, Nature Communications (In press) / arxiv
Photonic nulling: Norris, et al. 2020, MNRAS

- **Adaptive optics limited by current wavefront sensors**
  - Non common to science image & blind to some modes
  - Image itself degenerate (not phase information)
- **Photonic lantern wavefront-sensor:**
  - Senses complex amplitude at image plane
  - Infers input wavefront injected into MM waveguide by measuring SM output fluxes from PL
  - Learns transfer function via neural network
  - Laboratory tests show high efficacy with RMS wavefront error of 5 x $10^{-3}\pi$ radians (for π radian input WFs)
- **PL-WFS allows**
  - Zero NCP aberrations,
  - Ideal for fibre-fed spectroscopy and multi-object AO, communications
  - Wavelength-dispersed WFSing,
  - Sensitivity to blind modes
- **Photonic chip WFS**
  - A free 'side effect' of photonic nulling interferometer
  - Directly interfere different pupil regions -> no ambiguity from phase shear
  - Directly measures low wind effect, etc.
  - Spectrally deispersed allows phase unwrapping