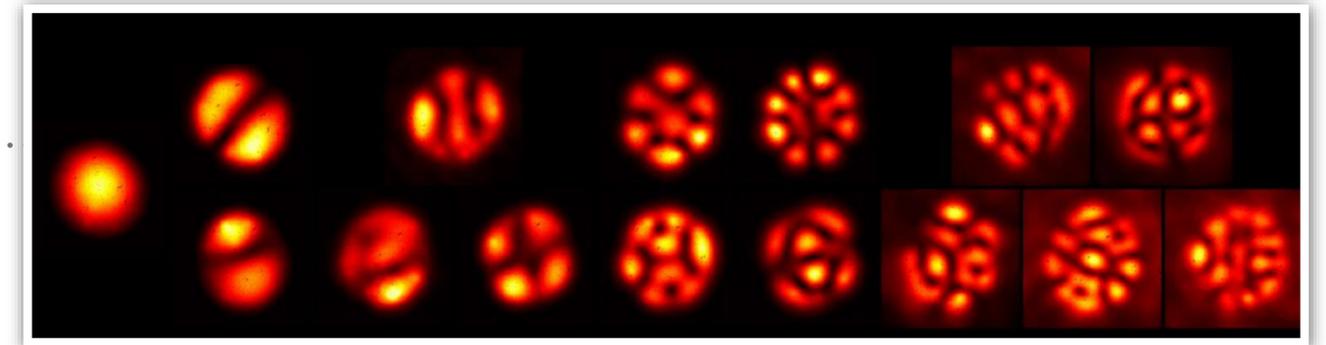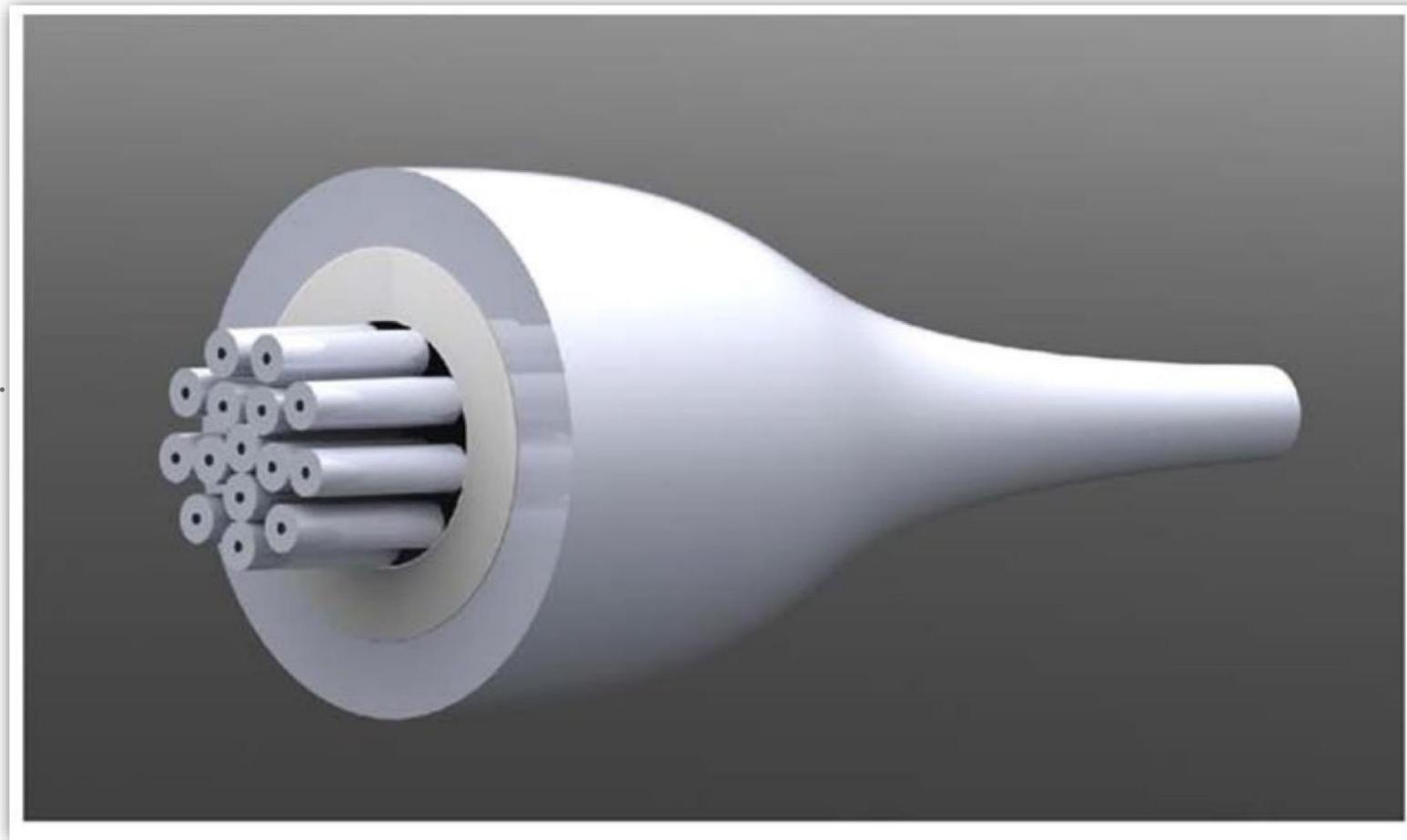# Demonstration of a photonic-lantern focal-plane wavefront sensor using fibre mode conversion and deep learning

Image credit: Velázquez-Benítez+ 2018

Why?

- Focal-plane WFS directly samples complex E field
  - Minimal NCPA
  - Sensitive to 'blind' modes, e.g. petalometry
  - Measure WF and PSF all at once
- Entire WFS in small, stable, monolithic photonic package
  - Compact, fits in standard fibre connector, easy to implement (incl multi-object)
  - Outputs in standard fibres, easily routable to detector
  - Optimal pixel usage - one pixel per mode (per wavelength...)
- Simple to spectrally disperse (standard fibre slit + grating)
  - Phase unwrapping
  - Scintillation
- Optimal SM fibre injection
  - Multi channel, high-R spectroscopy wants SM fibres
  - Normally it's very hard to inject into SMF!
  - Combine FP-WFS and science fibre(s) into single device
- Complete spectro-imaging and wavefront sensing
  - Like an IFU but
    - Modal, rather than pixel, basis
    - Get complex electric fields for each spatial element - provides WFSing, image reconstruction with optimal speckle suppression
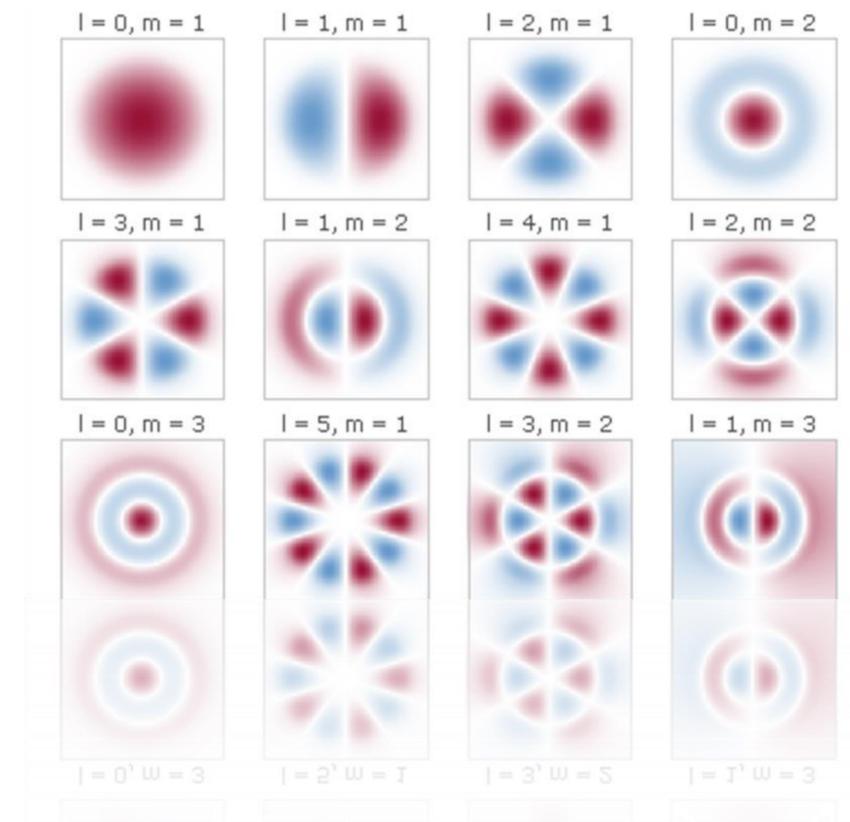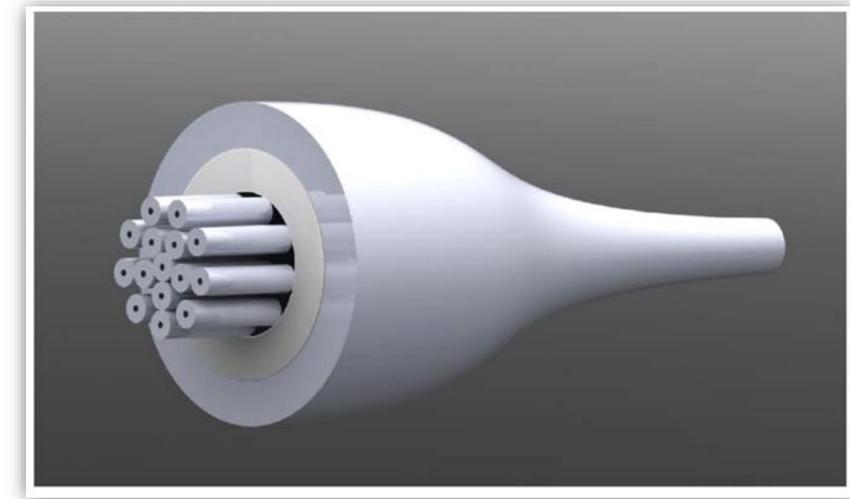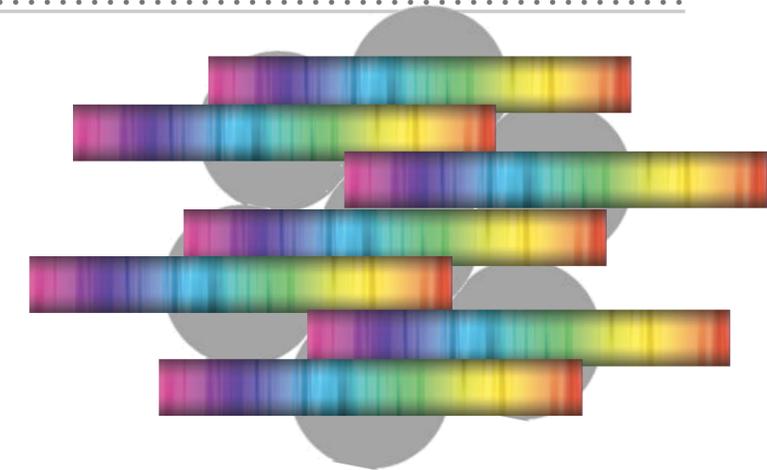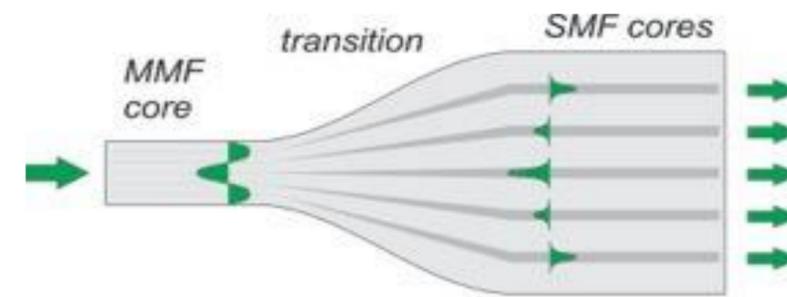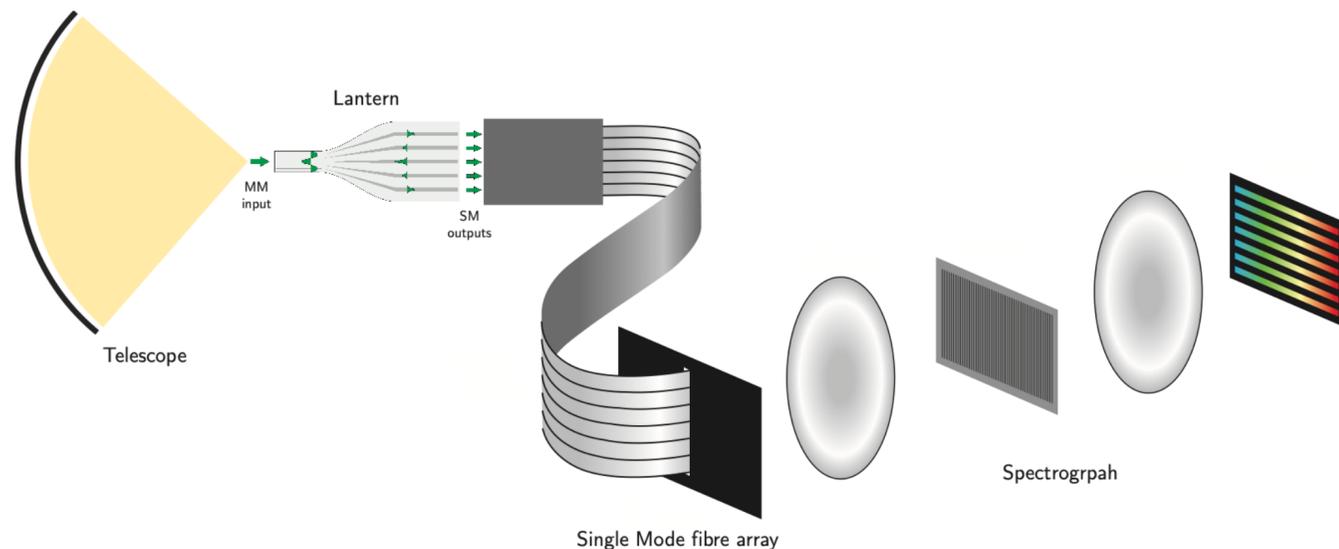
What's a photonic lantern wavefront sensor?

What's a photonic lantern? ~~wavefront sensor?~~

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

"It is a <u>photonic device</u> that converts light from a multimode to a single-mode system and vice versa with low loss"

How do we make them?

Photonics transition to "transform" the MM system into the SM one and vice versa.

A
MM fiber
Low index jackets
Multicore fiber

B
Fiber bundle
MM fiber

C
Waveguide array
Bulk glass cladding
MM waveguide

A) Multicore fibre to MM fibre (37x1)

B) SM fibres to MM fibre (7x1)

C) Ultrafast laser inscription (16x1) – bulk glass
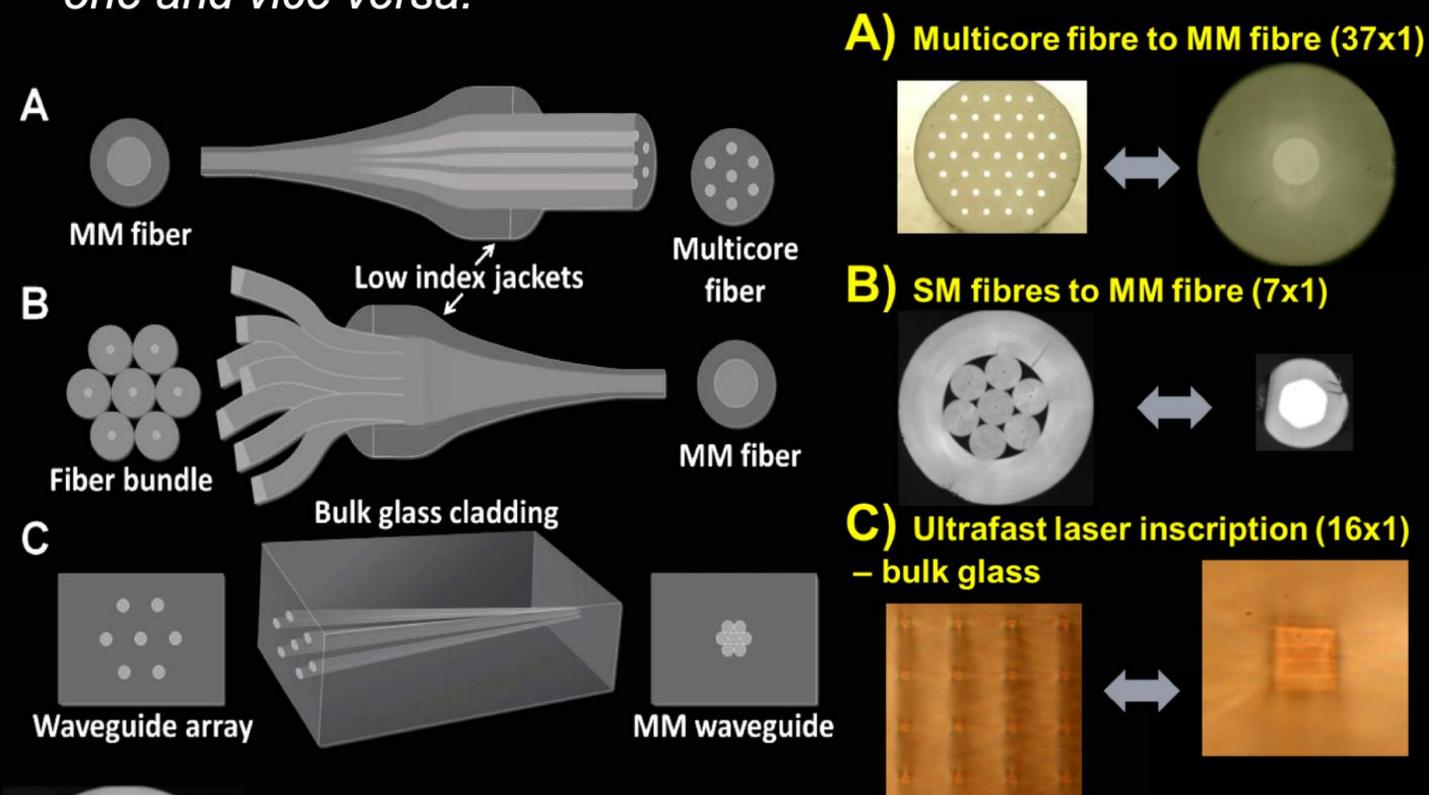
How do they work?
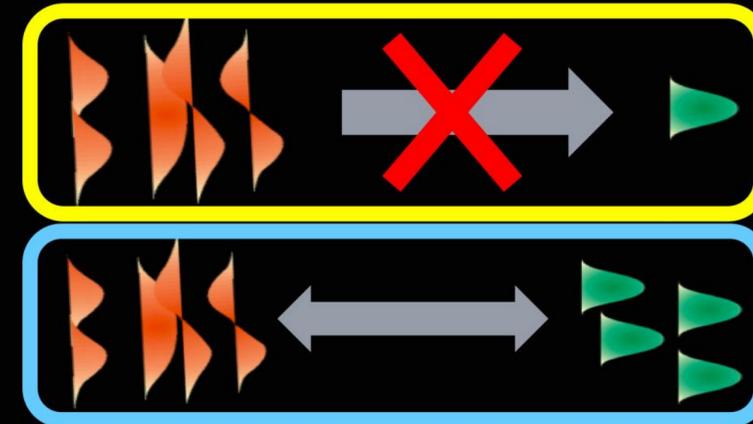
*The second law of thermodynamics (brightness theorem) prohibits the lossless coupling of light from an <u>**arbitrarily excited**</u> MMF into <u>**one**</u> SMF HOWEVER low-loss coupling to another degenerate multimode system with at least as many degrees of freedom is possible.*

$$S = k_B \ln M^*$$

Low-loss ➔ $M_{in} \leq M_{out}$

*M*=unpredictably or incoherently excited modes*

Low-loss when Entropy (S) is not decreased

10 mm
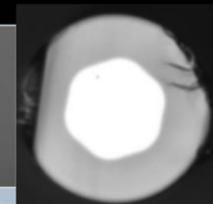
Linear complex transfer matrix - MM to SM

Transfer matrix

- Linear in complex amplitudes only
- Can't really know this in real life, only in simulations (shown here)
- In real life, measure intensities
- Output intensities are a non-linear function of input wavefront
- Here, for WFSing, $n_{outputs} = n_{modes}$ (current status)
  - For full imaging, etc., want $n_{outputs} = 2*n_{modes}$ (under development)
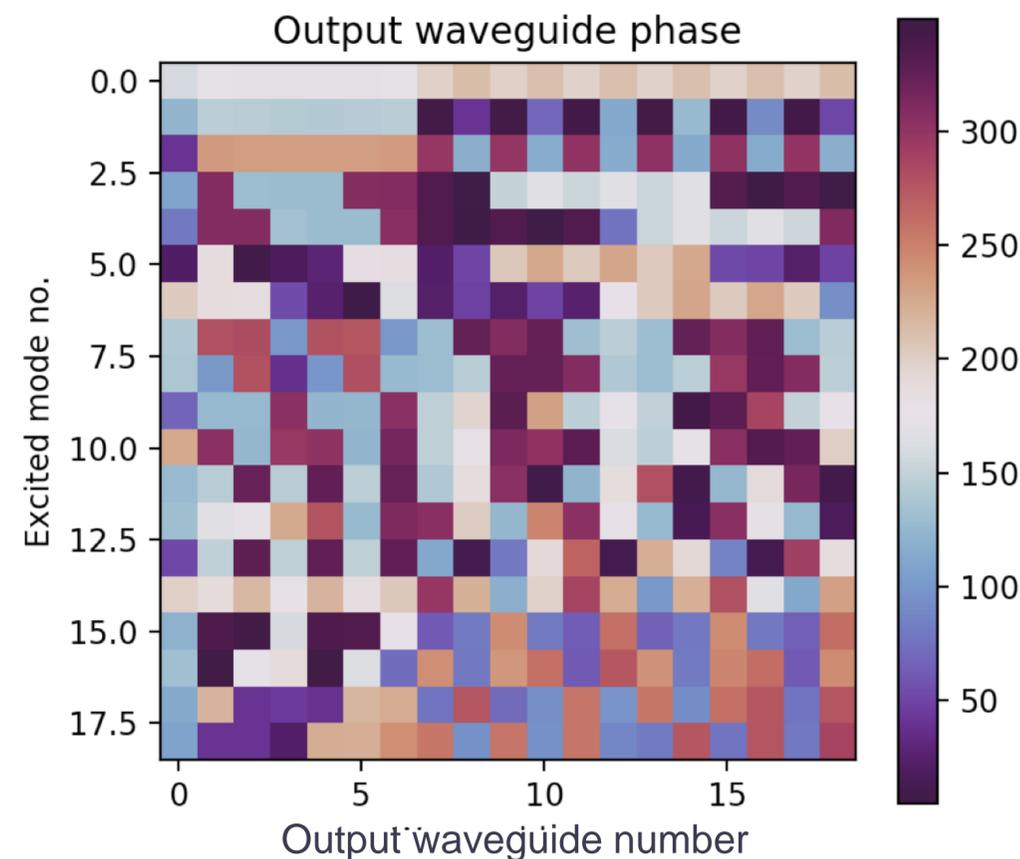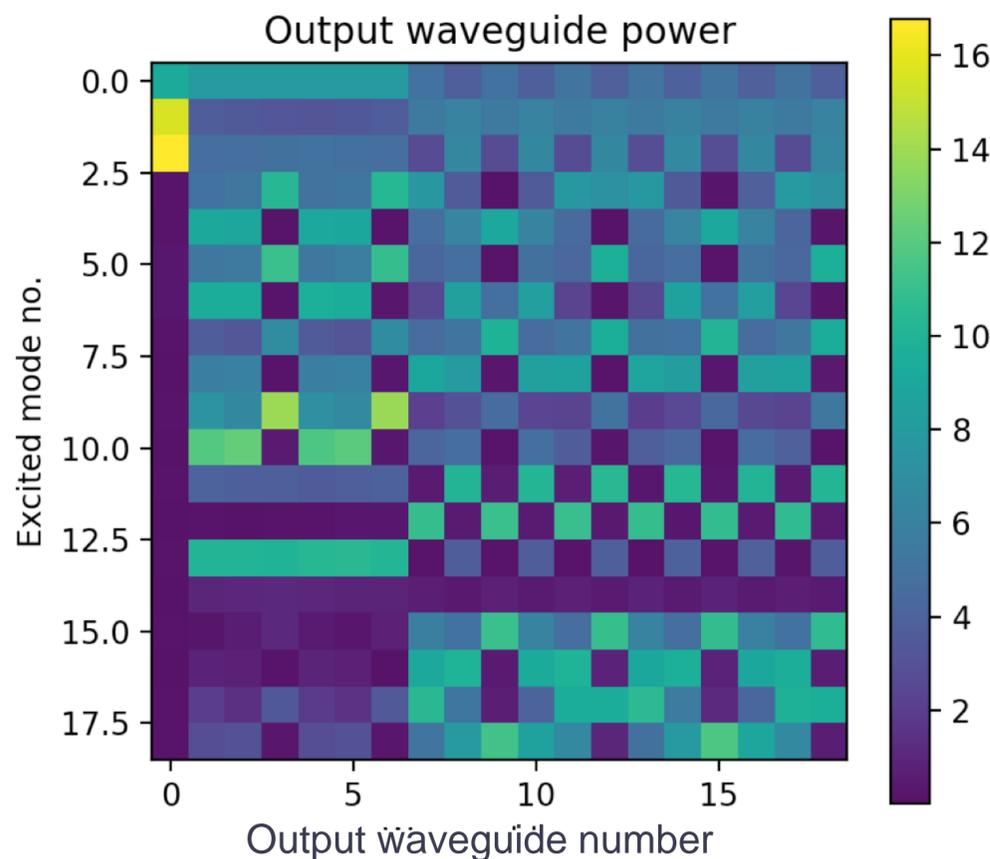
Example prediction -
randomly excited input mode ampls & phase
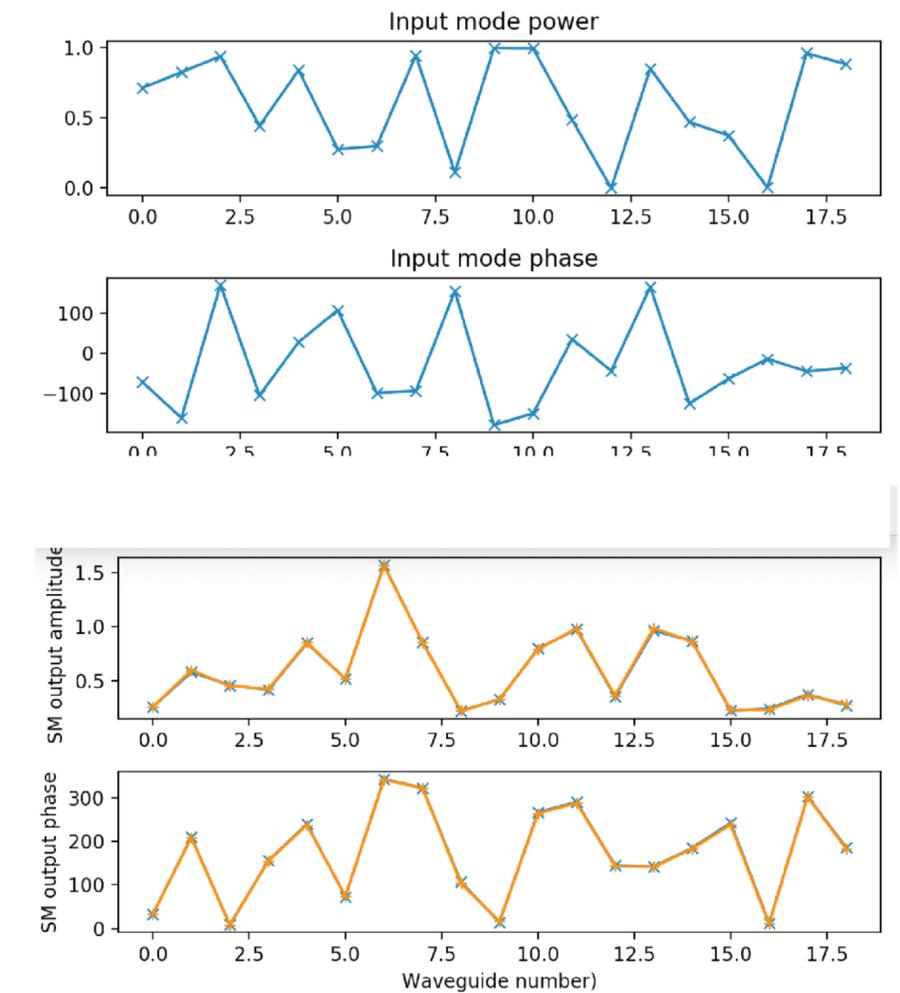
Sample PSF in fibre-mode basis

Image the PSF using fibre modes, not pixels, as basis

- Simple step-index fibre modes ~LP modes (Bessel functions)

- More complex in practice (vector modes, remnant core structure)

- Could potentially customise (GRIN, PCF...)
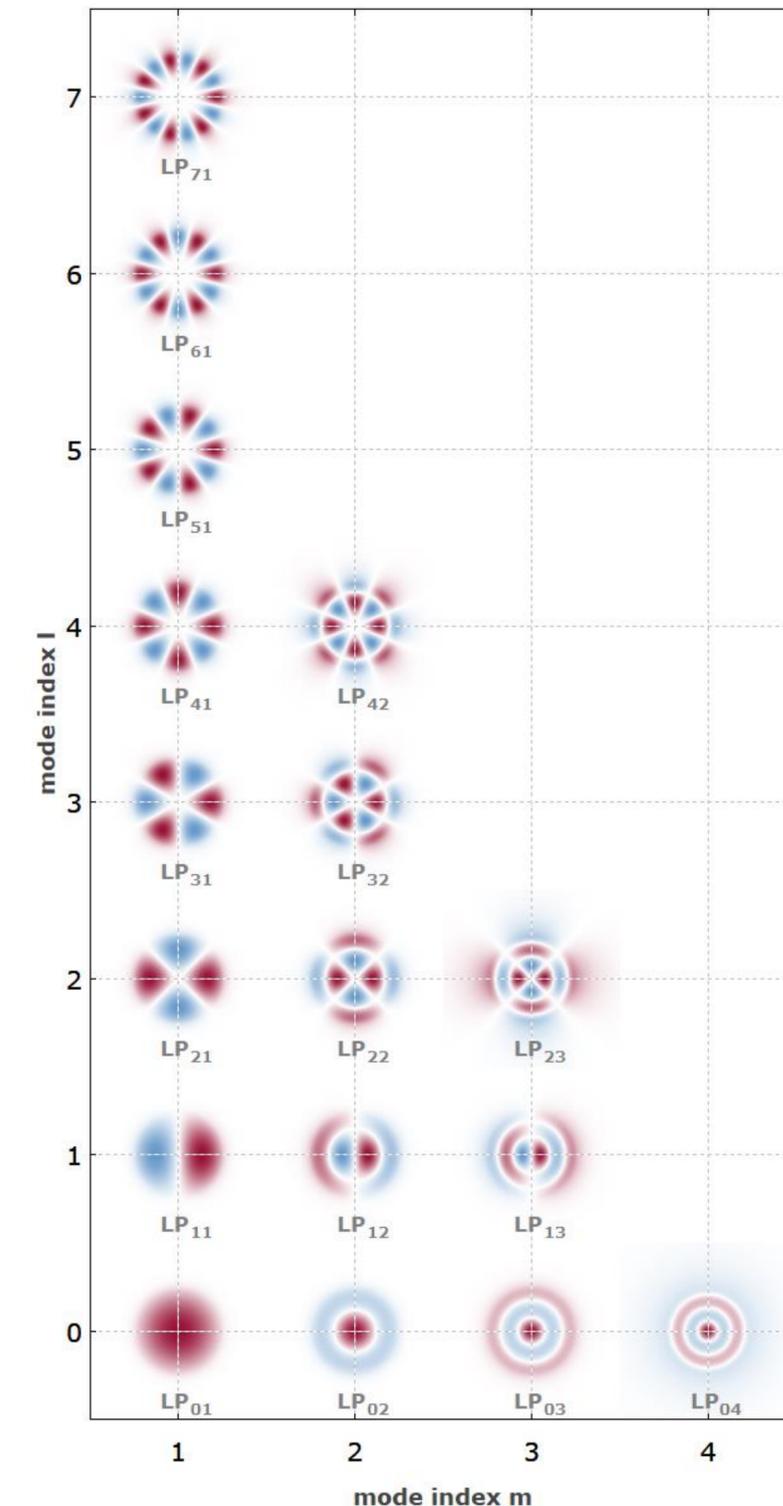
PDF -> modal coefficients is complex overlap integral

- Unlike detector pixels, mapping (complex coupling coeff η) depends on amplitude & phase

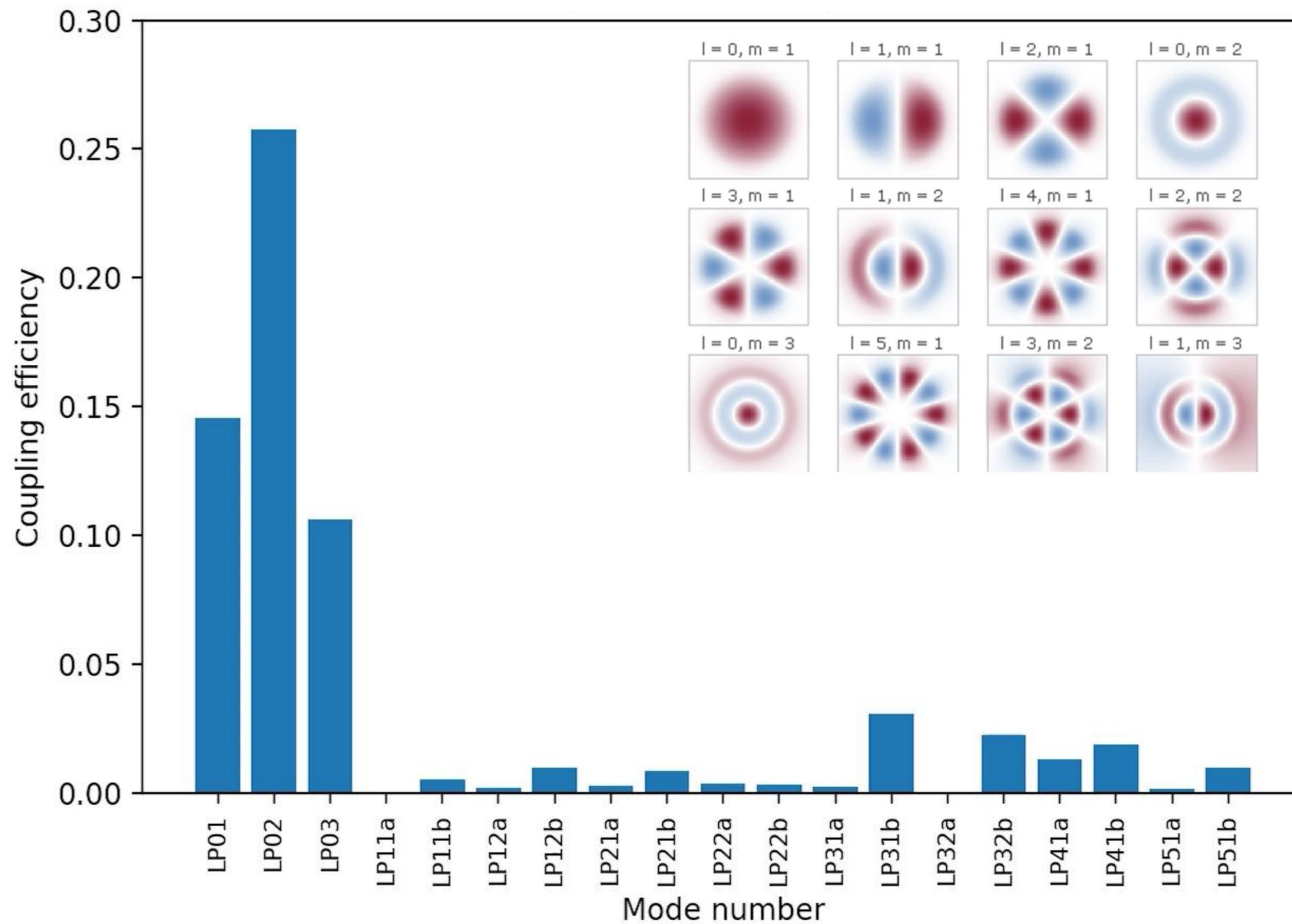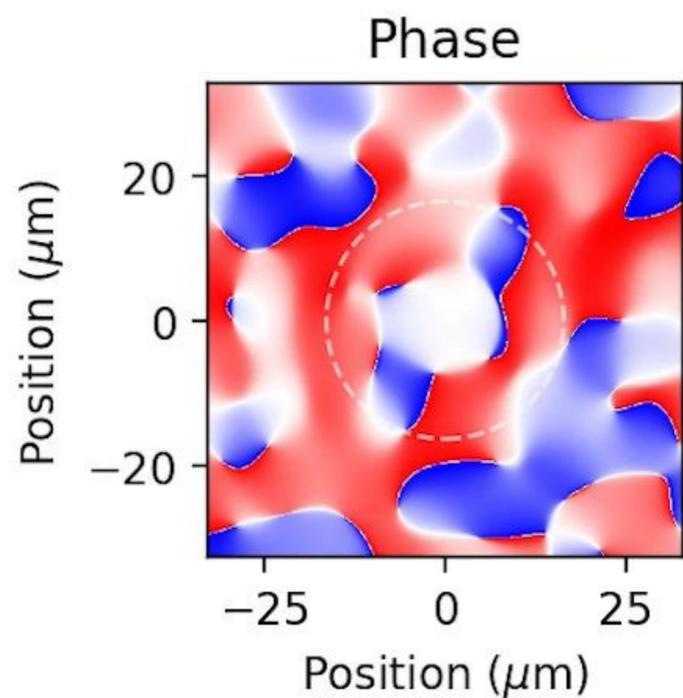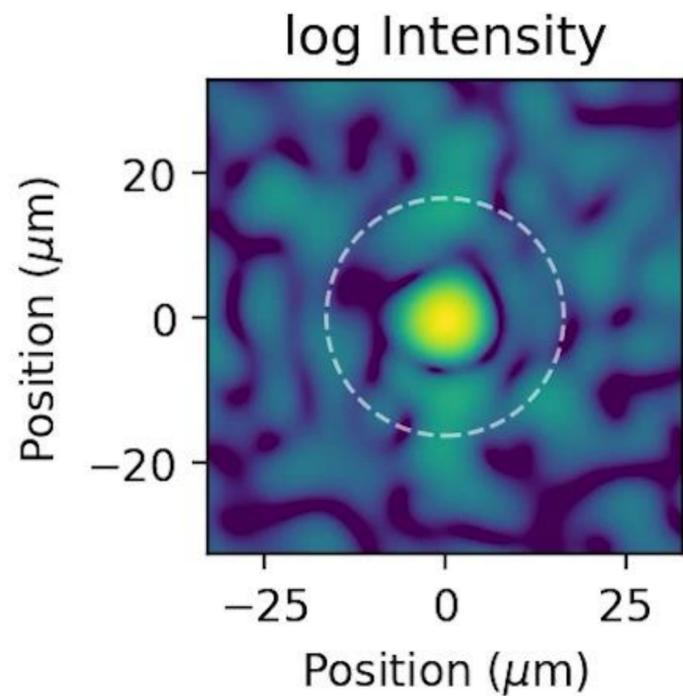$$\eta = \frac{\int E_1 E_2 \, dA}{\sqrt{\int |E_1|^2 dA \int |E_2|^2 dA}}$$

- Where E_1 is complex PSF, E_2 is complex fibre mode field

Modes are orthogonal

- LP modes, etc., span image space

- Can construct arbitrary complex image from linear complex combination of modes

PSF mapping to mode intensity

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)
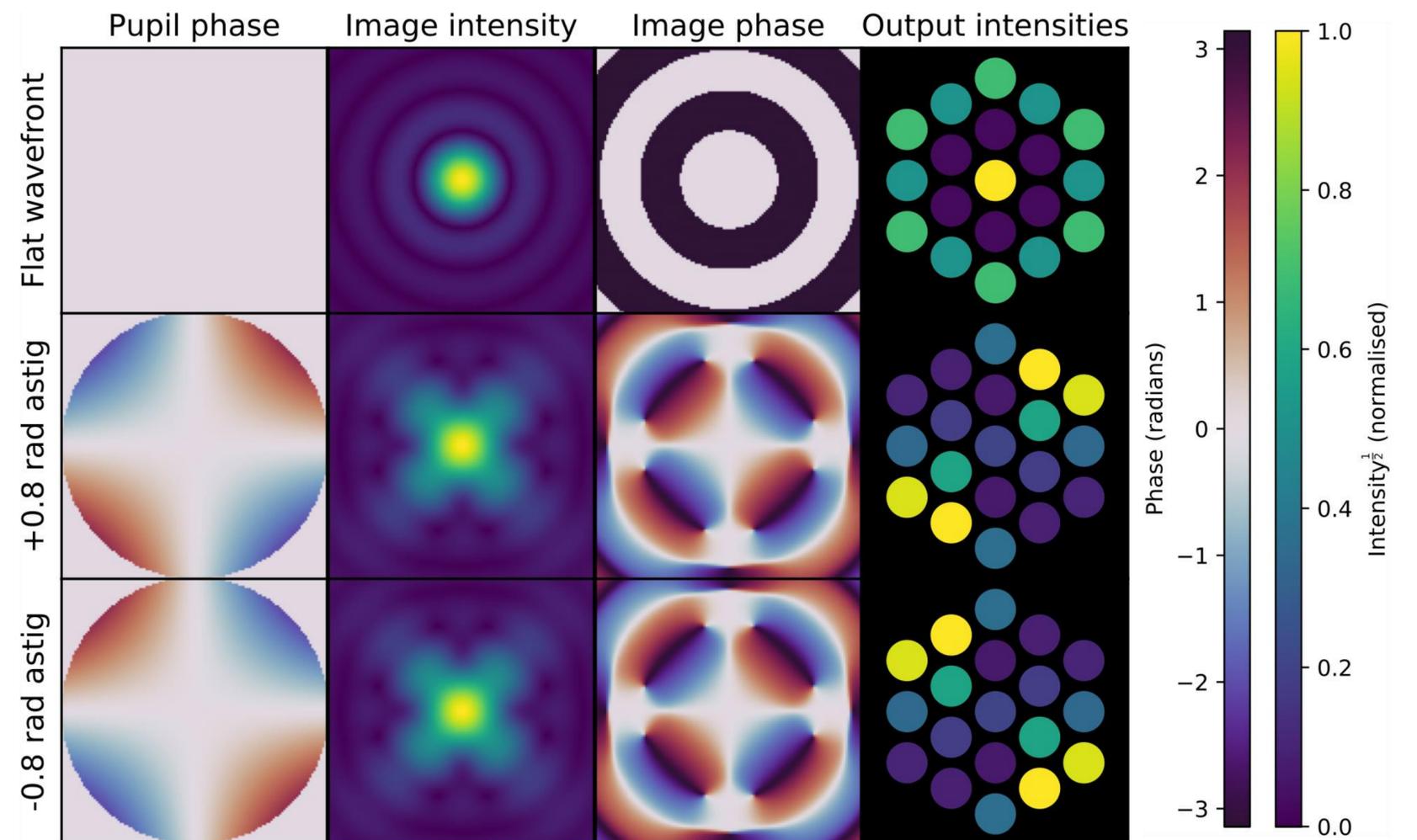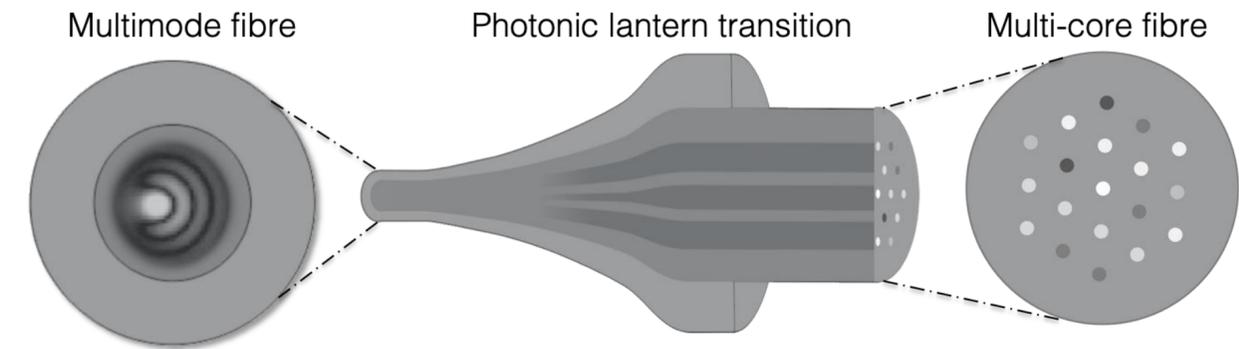
Photonic lantern as wavefront sensor

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
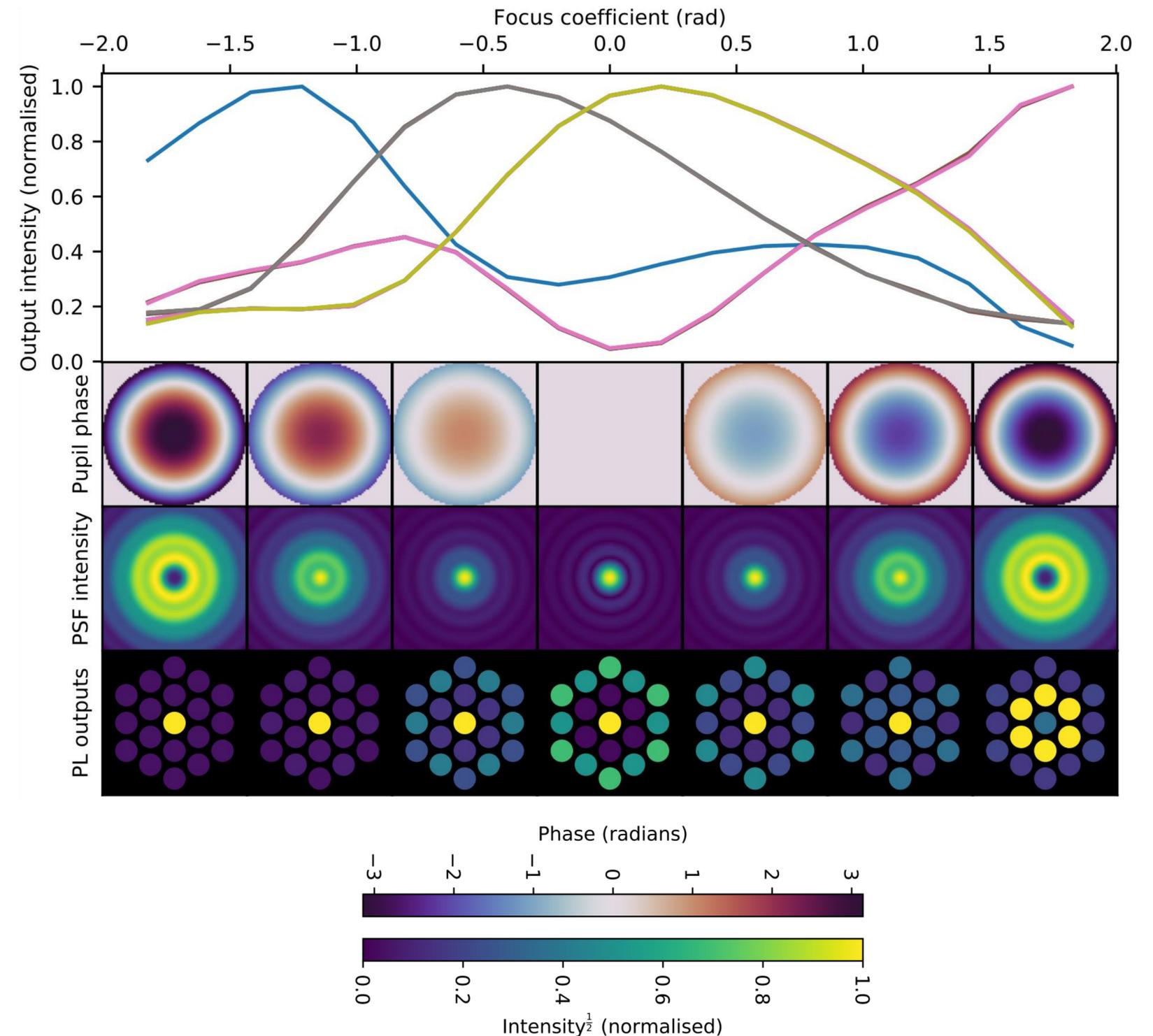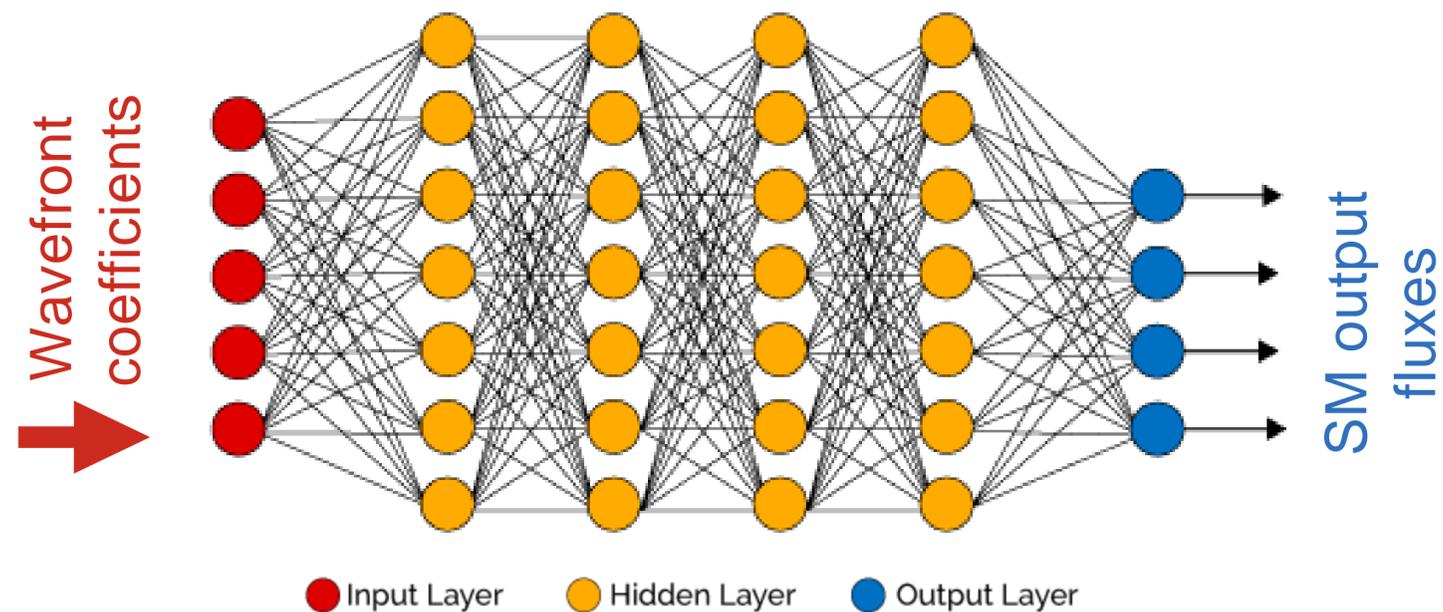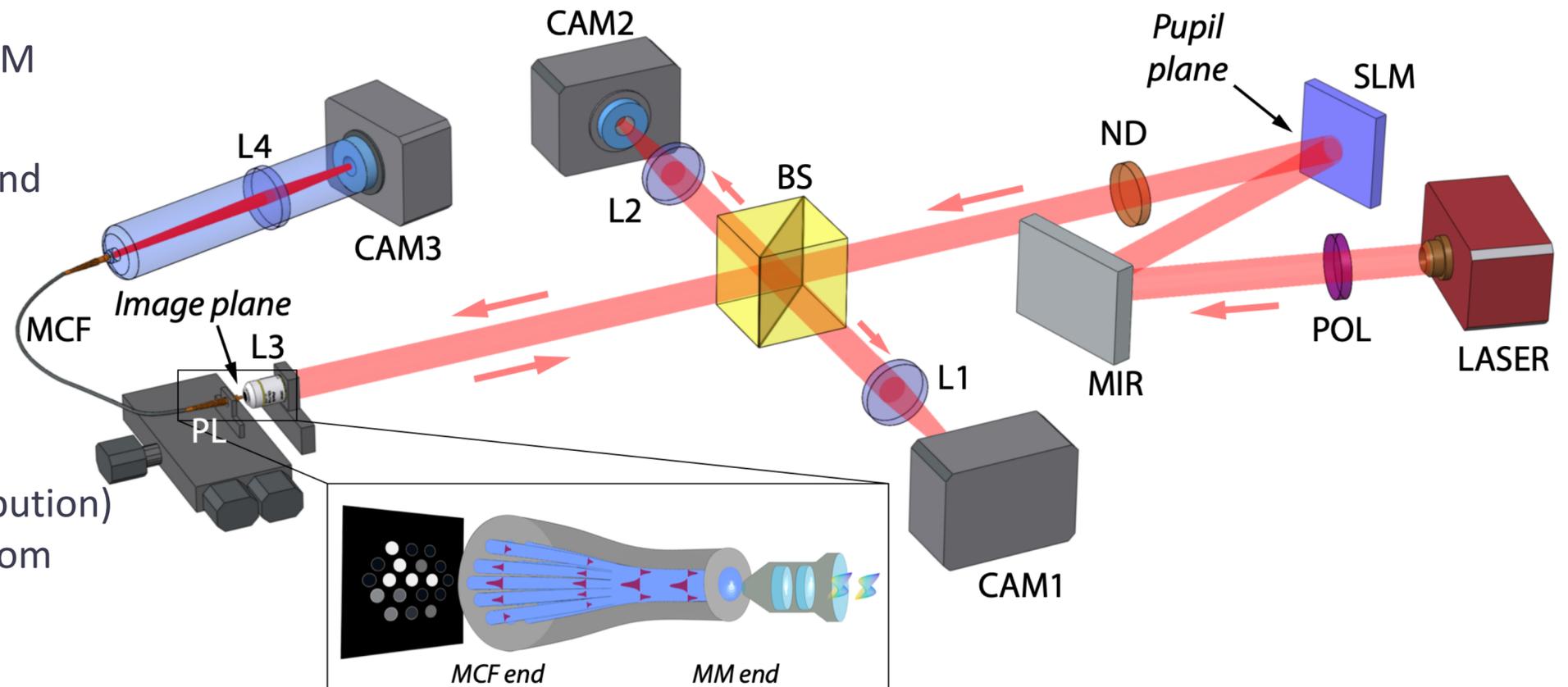
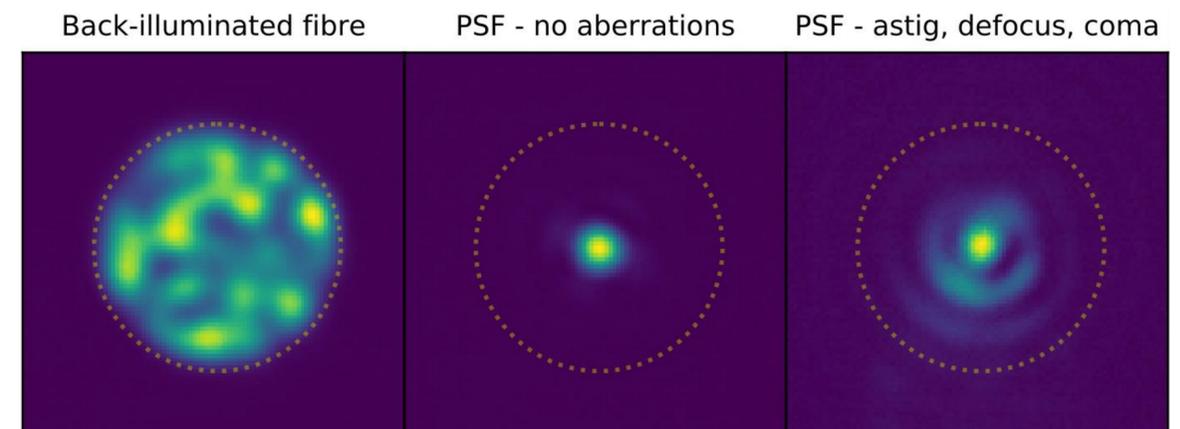# Lab Results

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
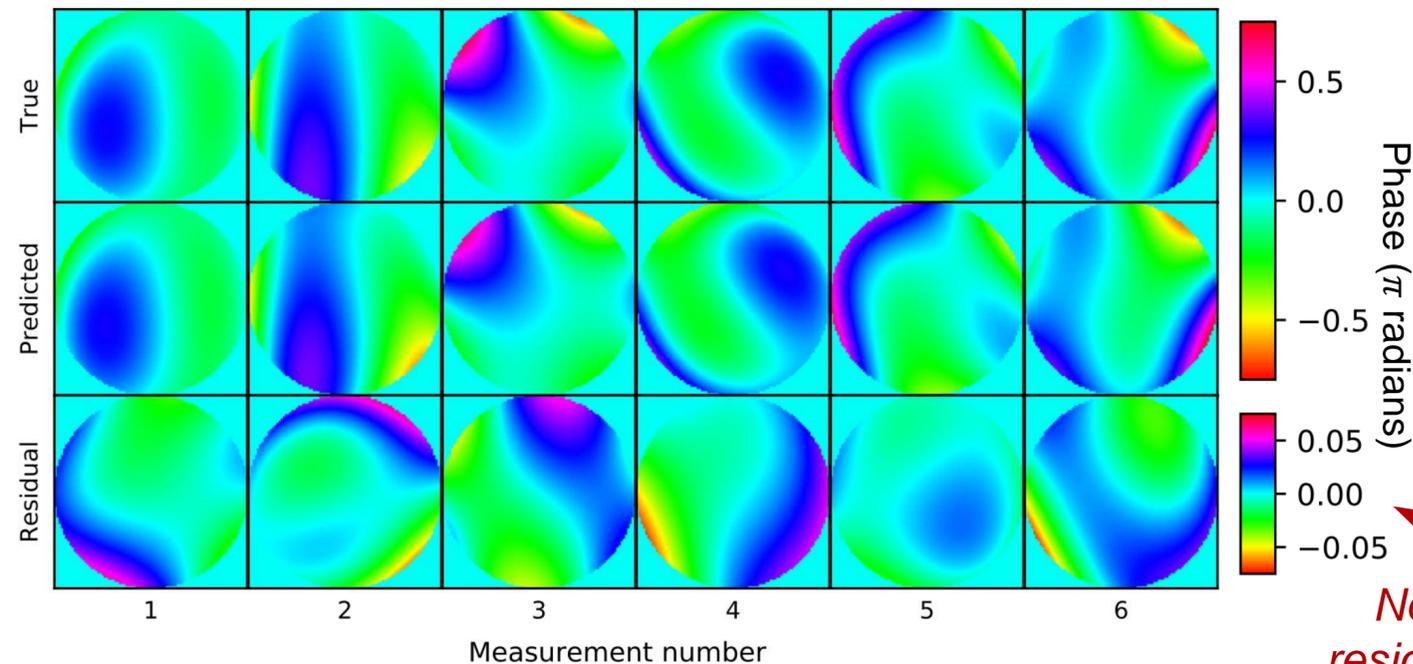
- 685 nm (1.2nm bw)

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%.

CAM2

CAM3

L4

L2

BS

MCF

Image plane

L3

PL

L1

MIR

MCF end   MM end

CAM1

ND

Pupil plane

SLM

POL

LASER

Back-illuminated fibre   PSF - no aberrations   PSF - astig, defocus, coma

Laboratory results

Reconstruct input wavefront with *RMS error of 5 x 10⁻³π radians* (for π radian input WFs)

Activation	Neurons in first layer	Neurons in final layer	Number of hidden layers	RMS error ×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**

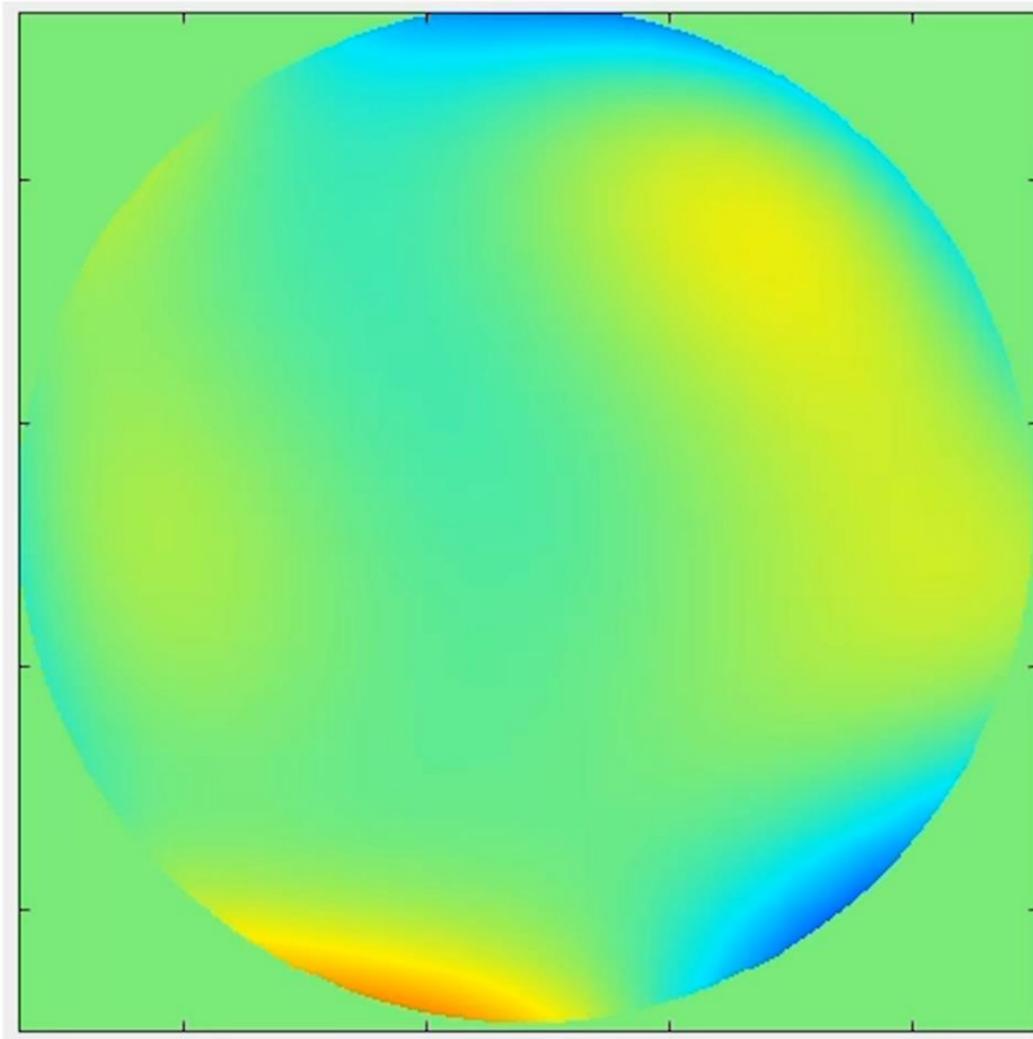

Note - color scale on residuals 10 times smaller
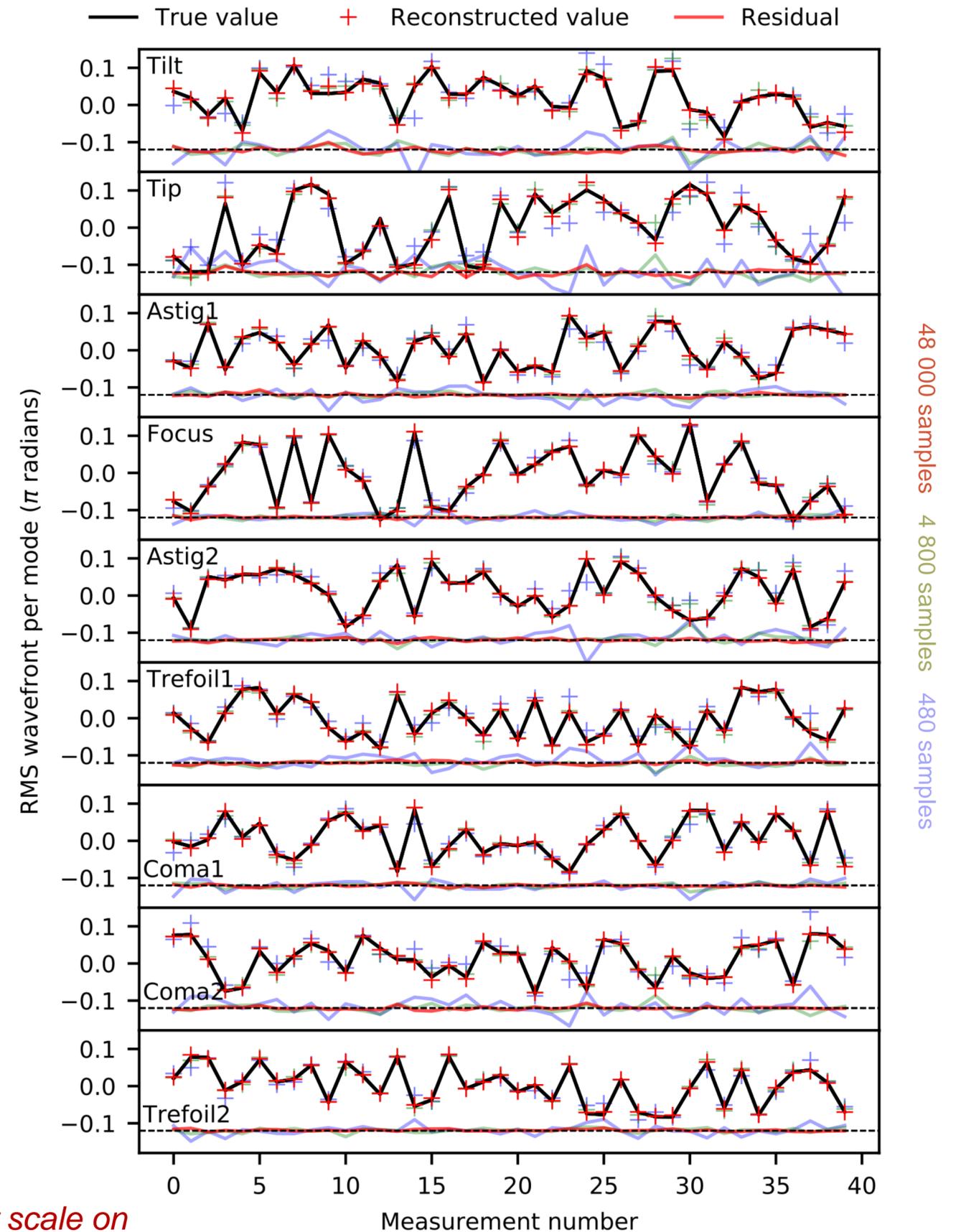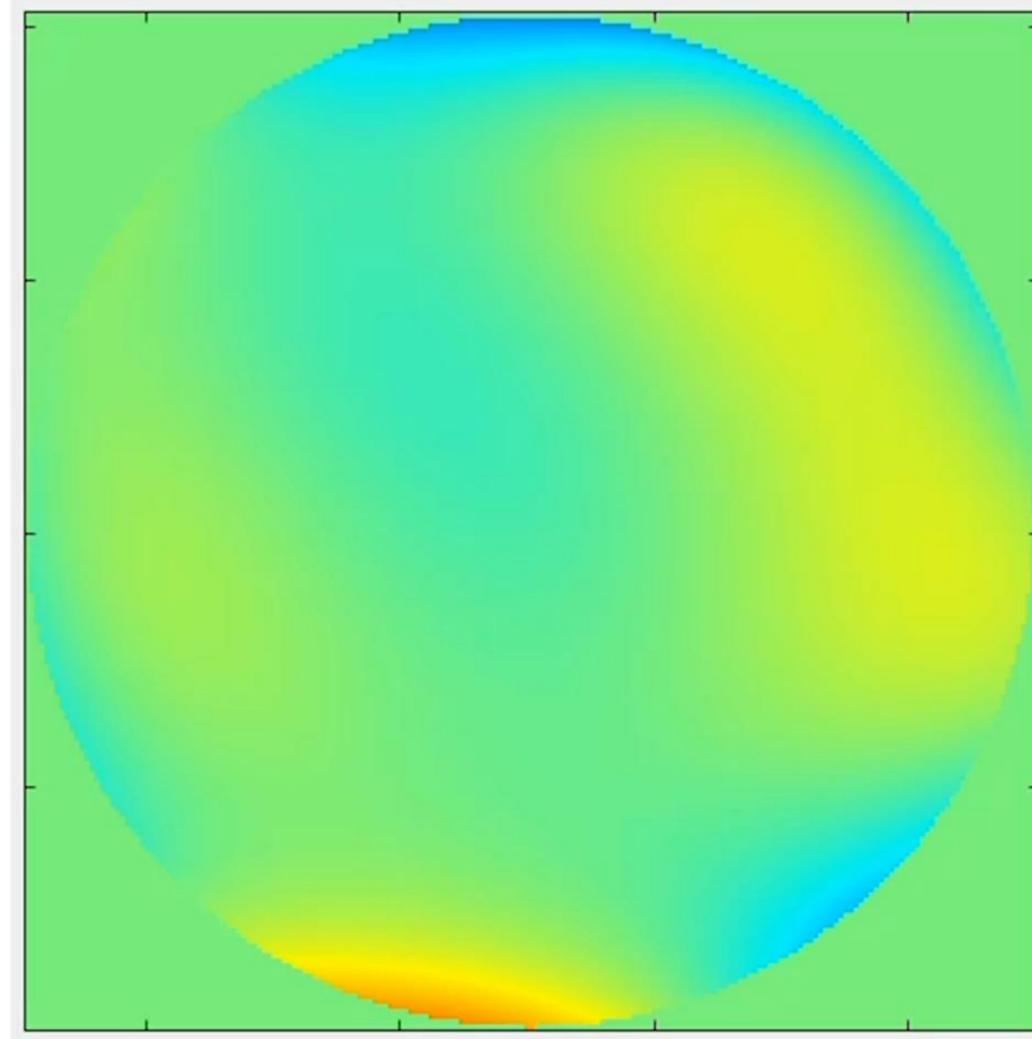
Laboratory results

Reconstruct wavefront composed of 19 Zernike terms

Wavefront RMS ~3 rad

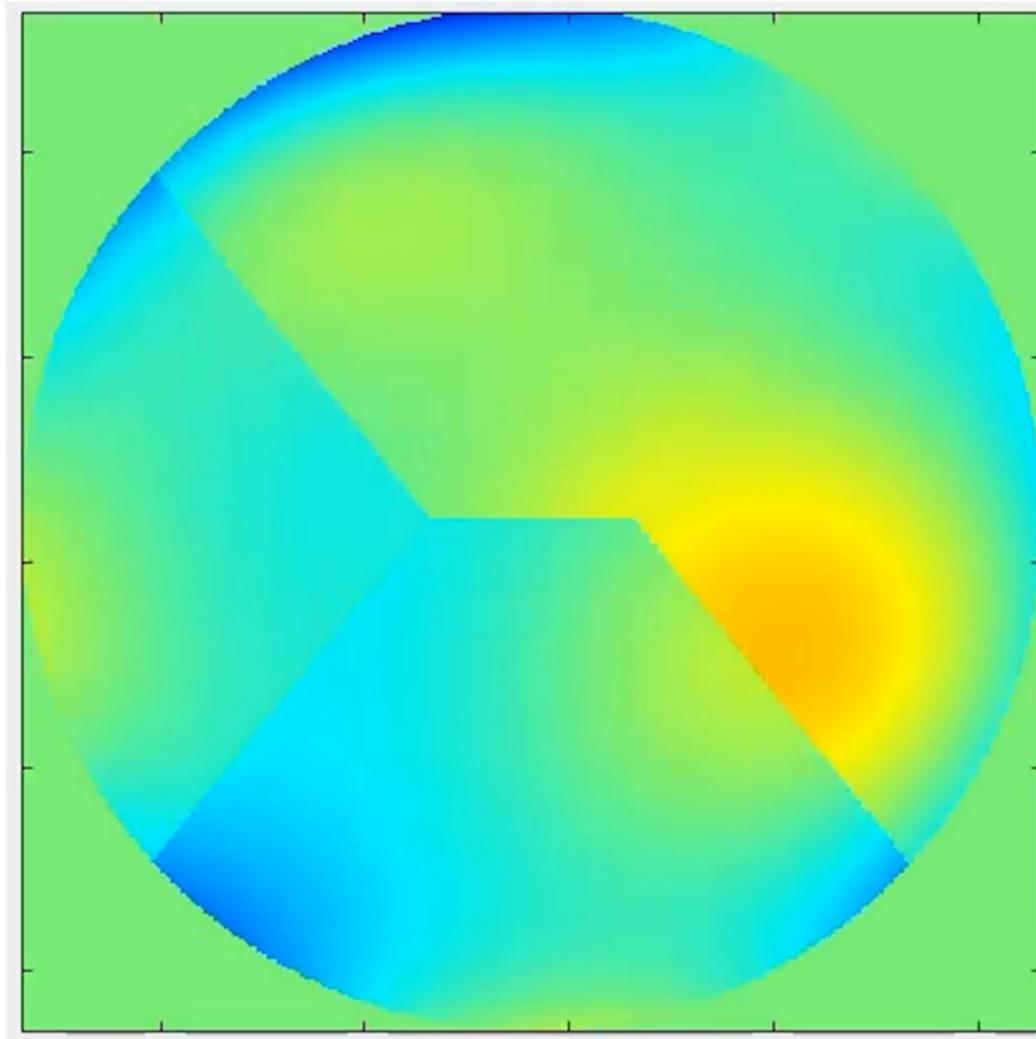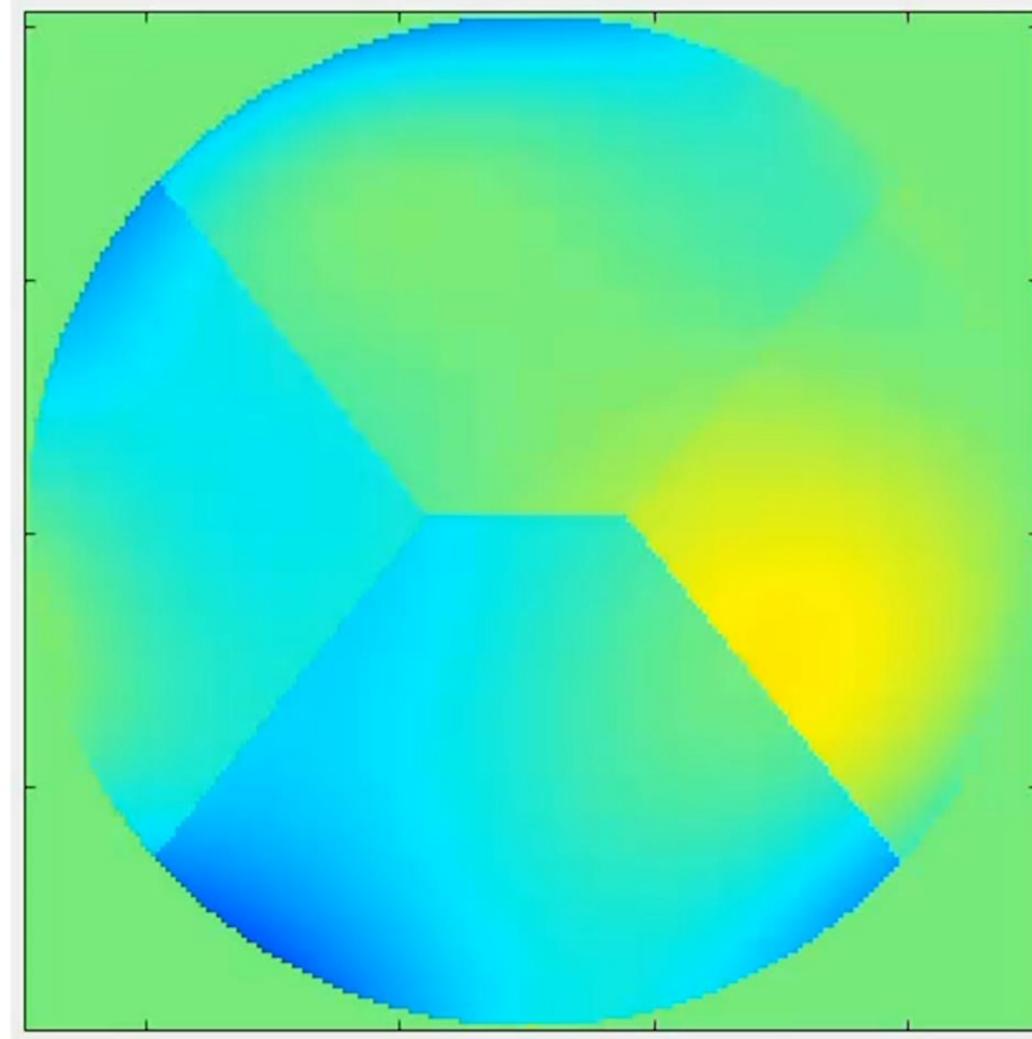**True WF applied to SLM**   **Predicted WF from photonic lantern**

Laboratory results

Reconstruct wavefront composed of 19 Zernike terms + low wind effect (11 coefficients)

Wavefront RMS ~3 rad
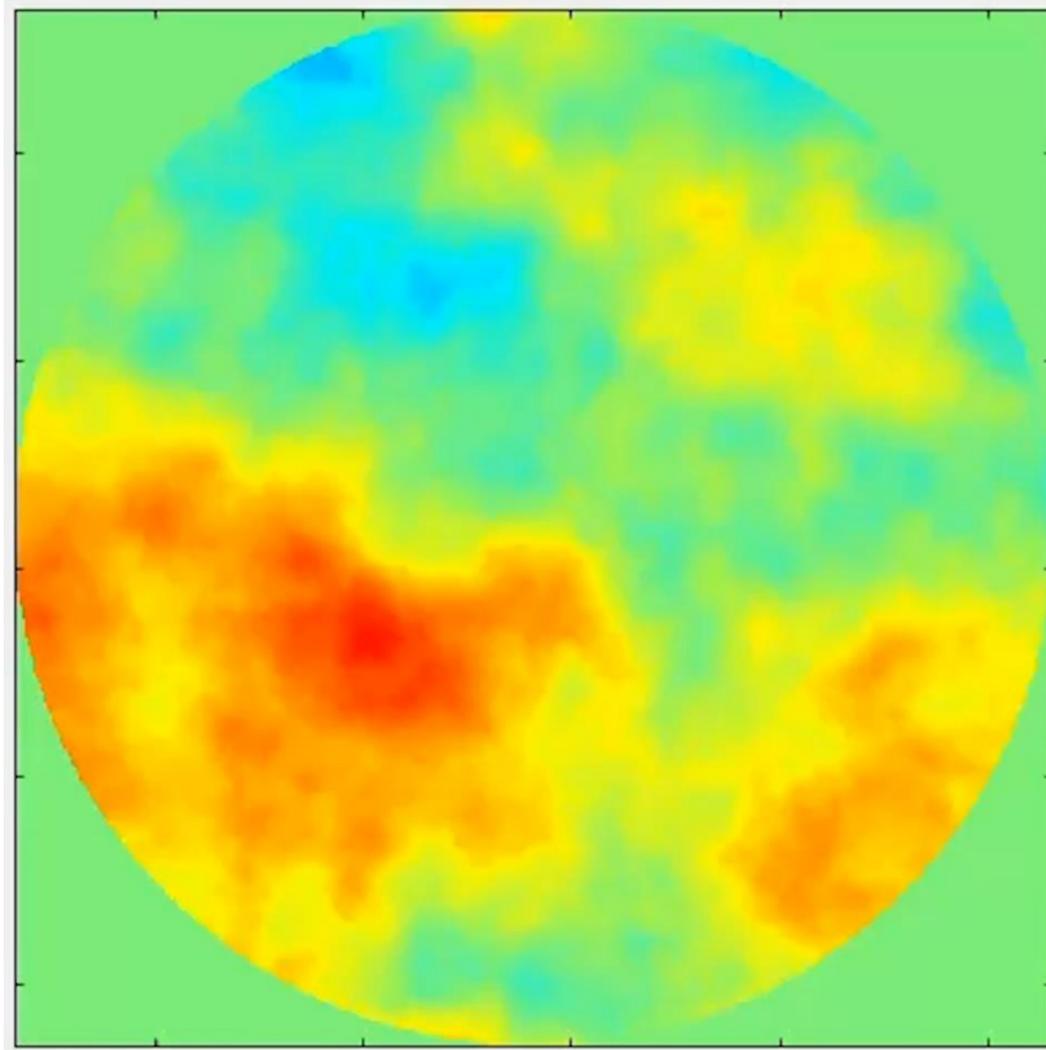

True WF applied to SLM

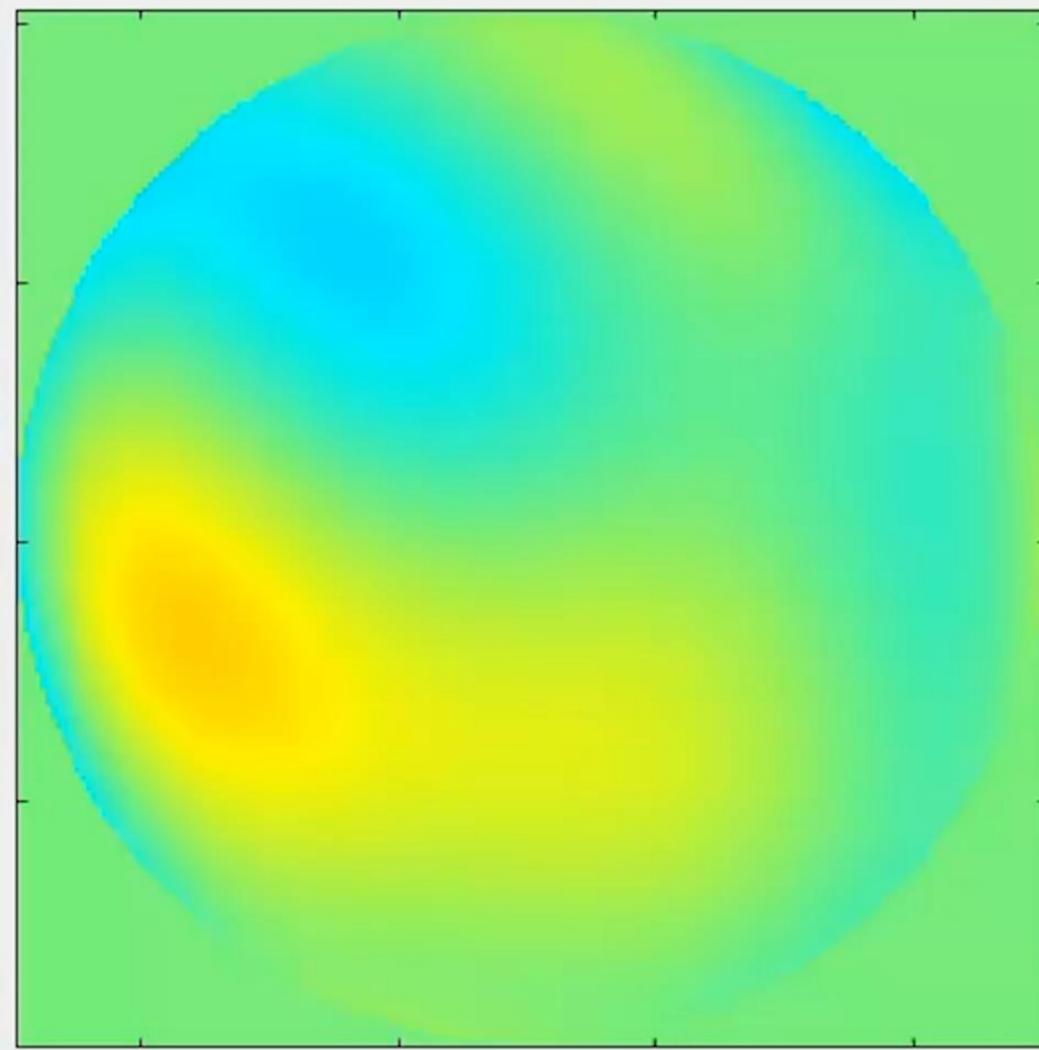Predicted WF from photonic lantern

Laboratory results

Reconstruct Kolmogorov phase screen, using NN predicting first 19 Zernike terms

Wavefront RMS ~3 rad

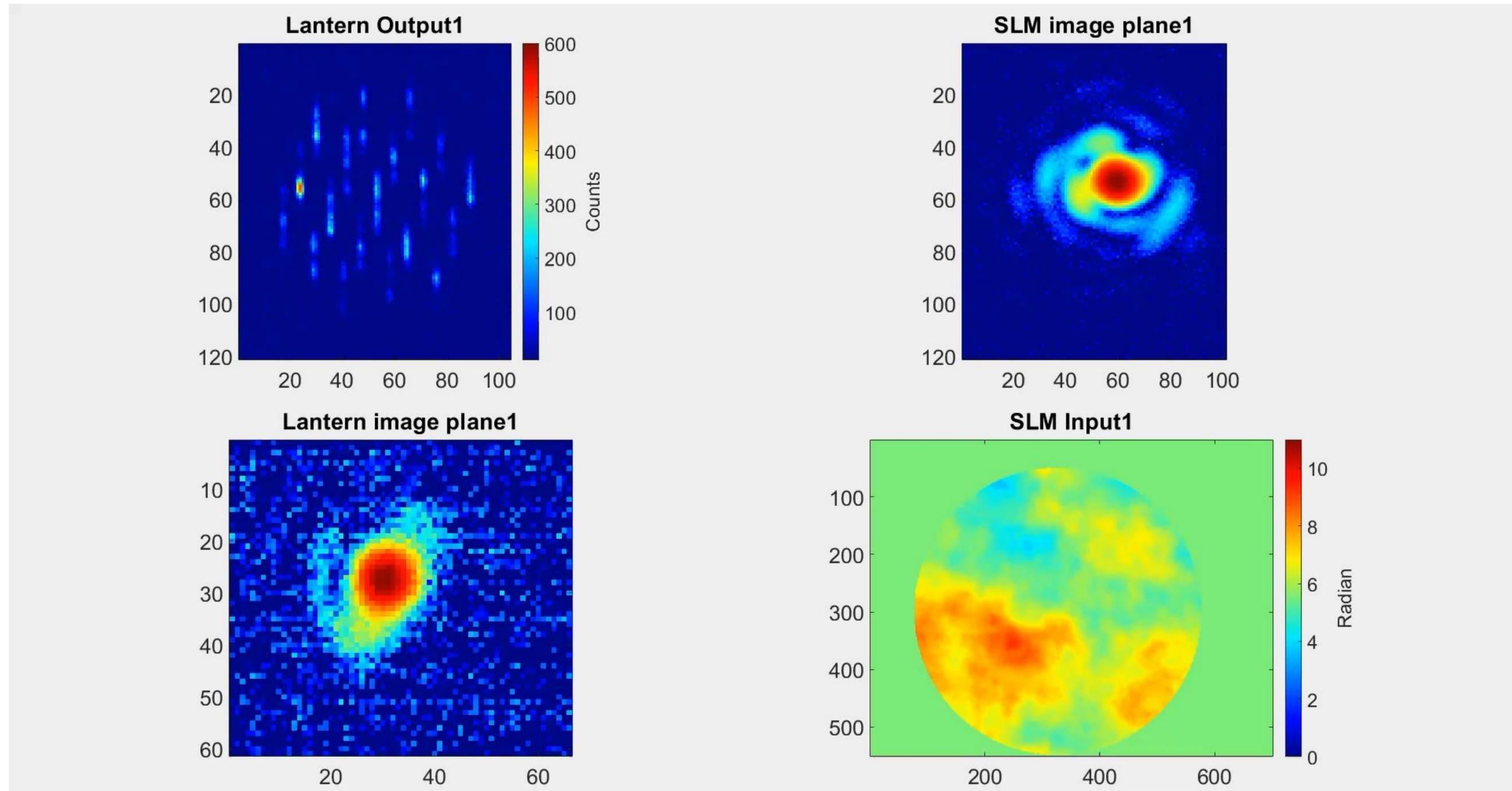True WF applied to SLM   Predicted WF from photonic lantern
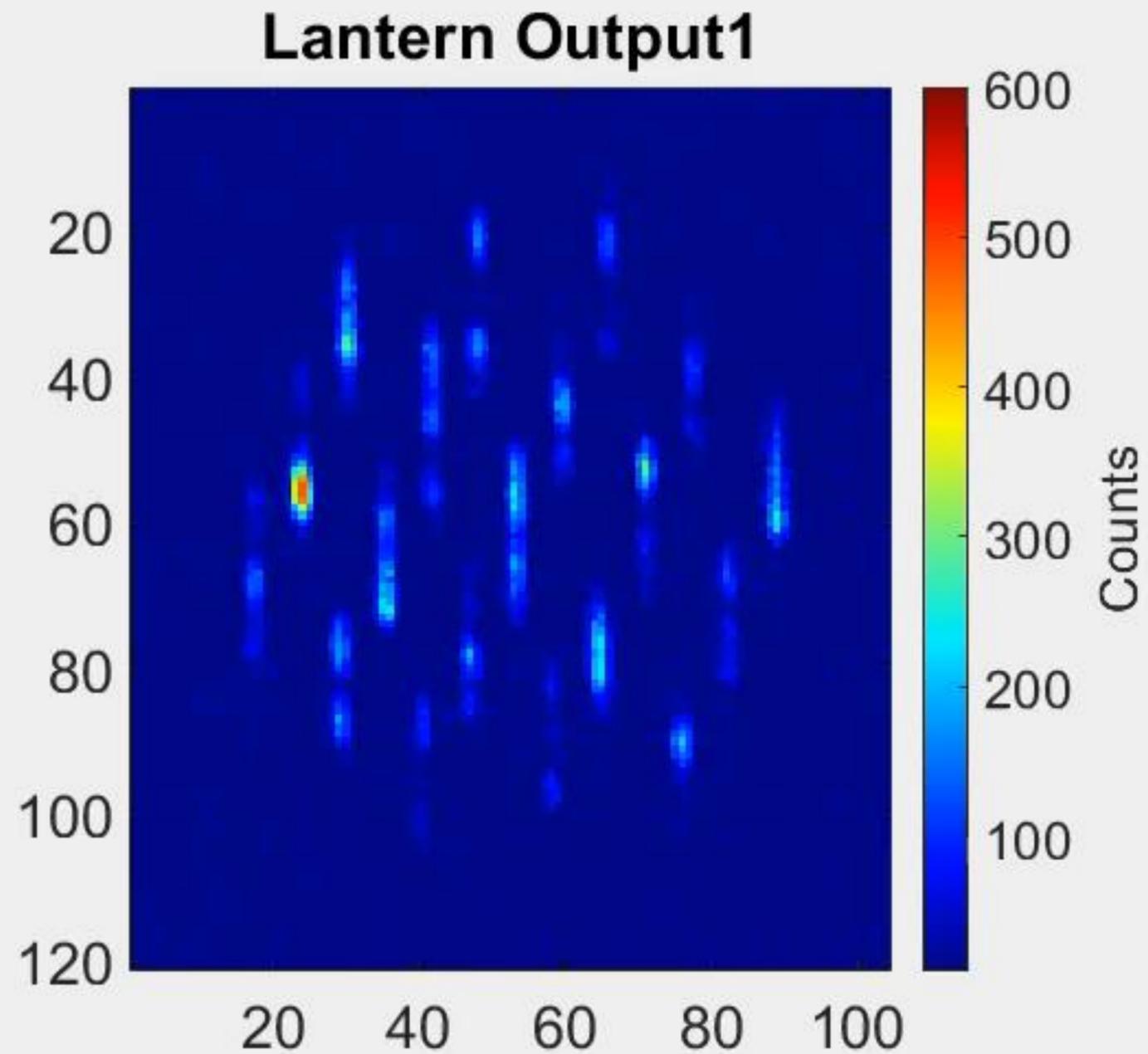
Laboratory results

Raw multi-wavelength data (analysis in progress)

Laboratory results

Raw multi-wavelength data (analysis in progress)

SCExAO Implementation

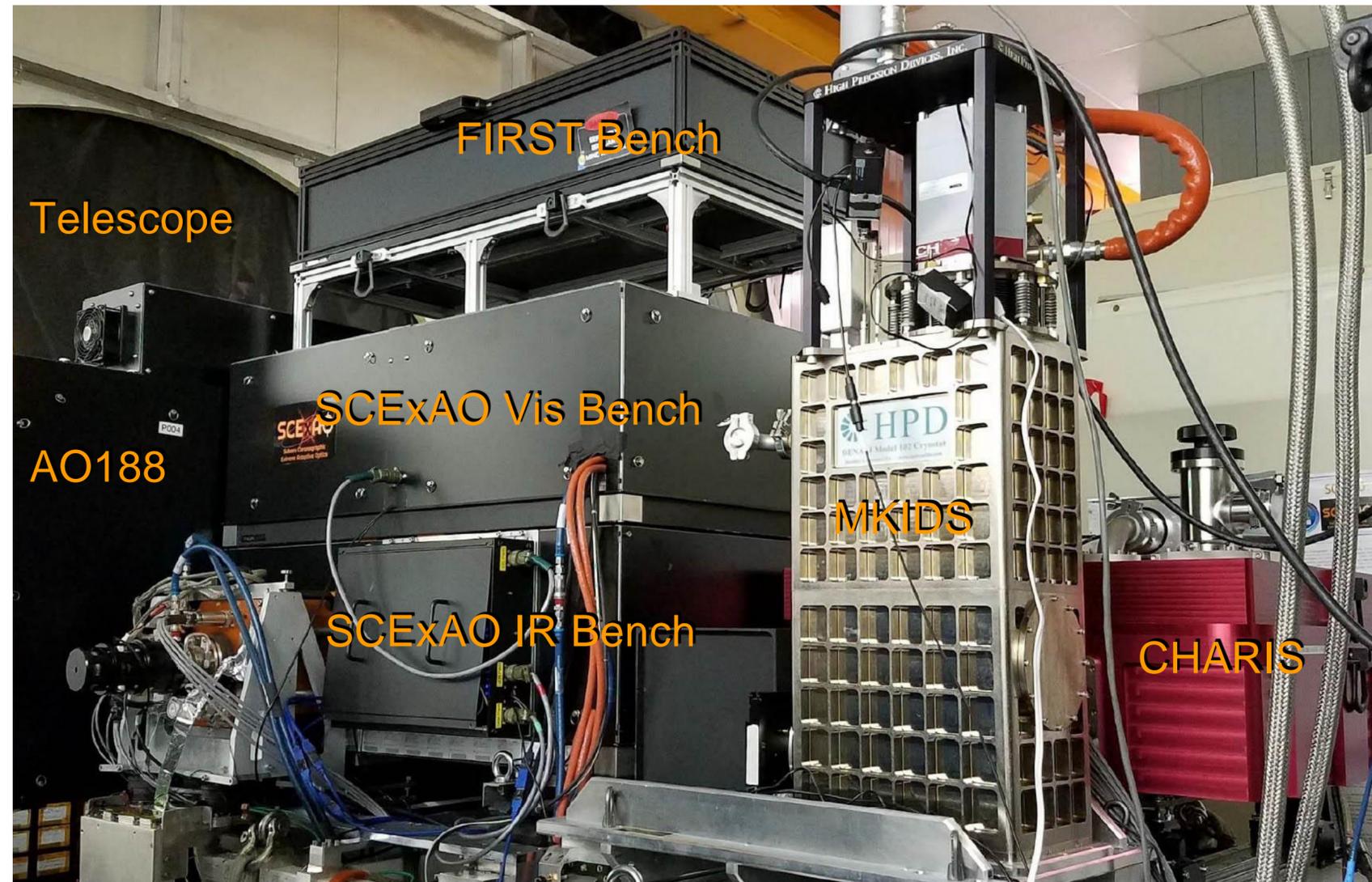# PL @ SCExAO

Currently 19 core PL, simple to swap to future high-mode-count PLs

- Currently monochromatic (1550nm) on C-red 2; Spectrographic (Y though H) with C-Red 1 end 2022
- Daytime tests - apply known wavefronts to SCExAO DM, evaluate PL-WFS reconstruction accuracy
- On-sky tests - compare reconstructed PSF, and reconstructed WF to PWFS*
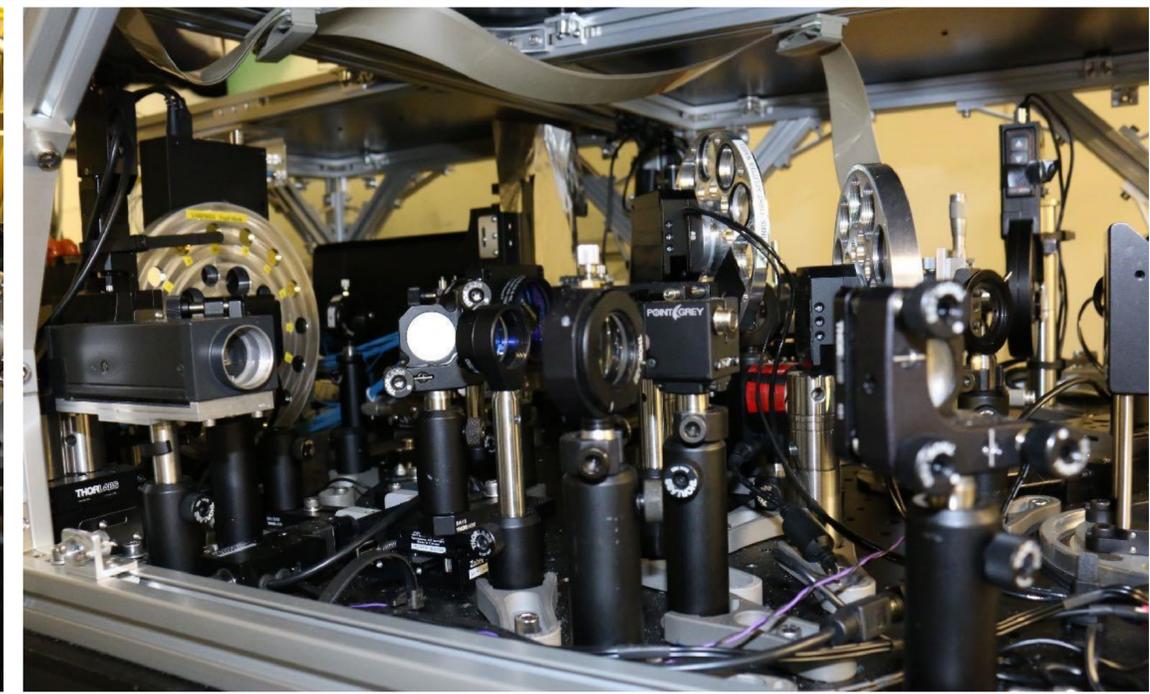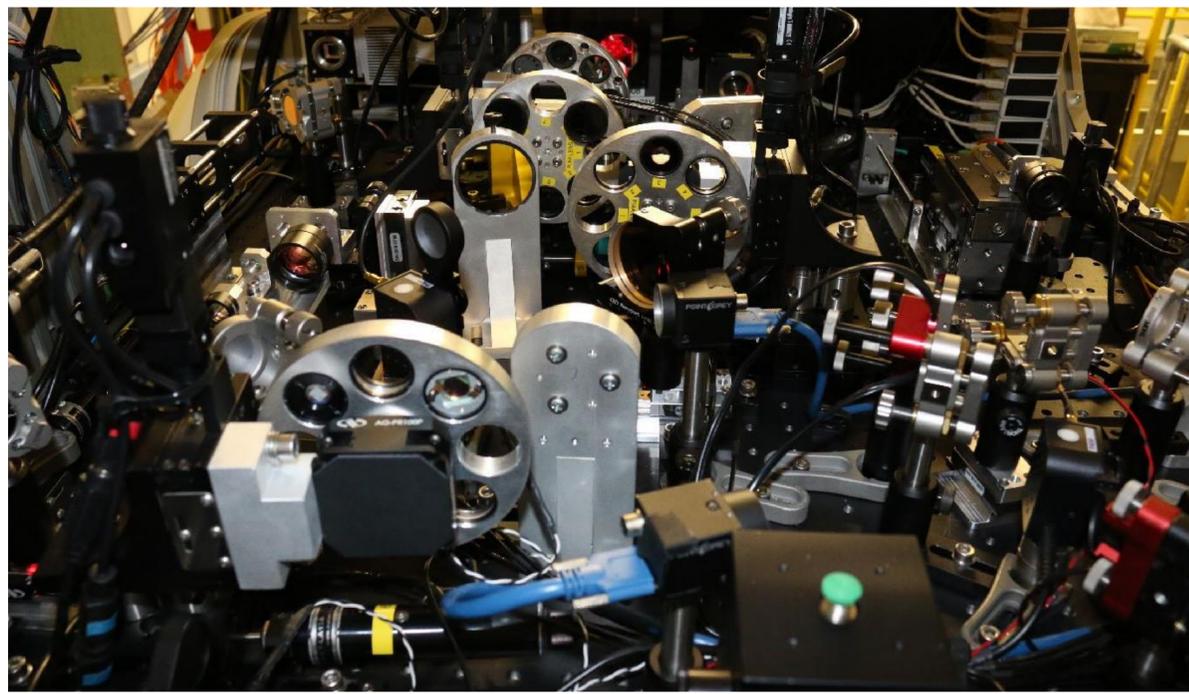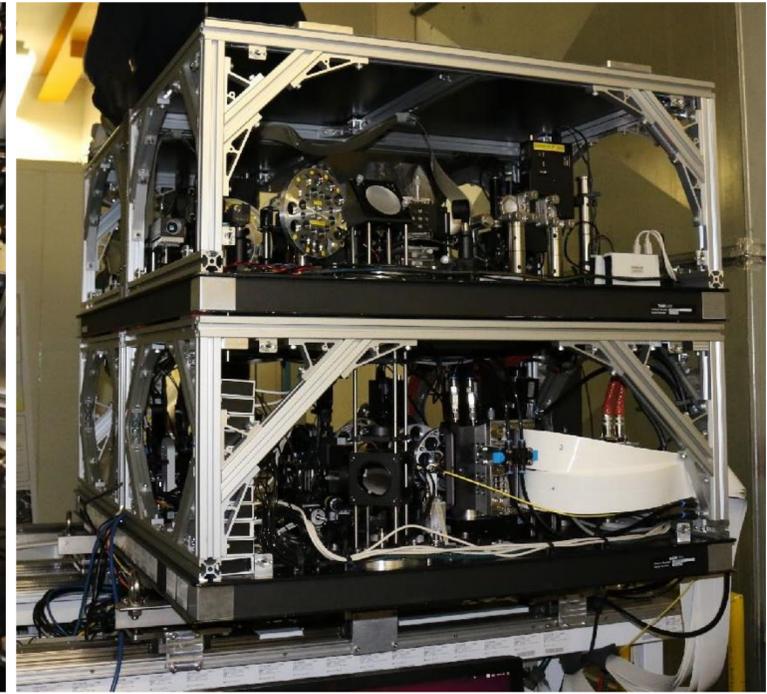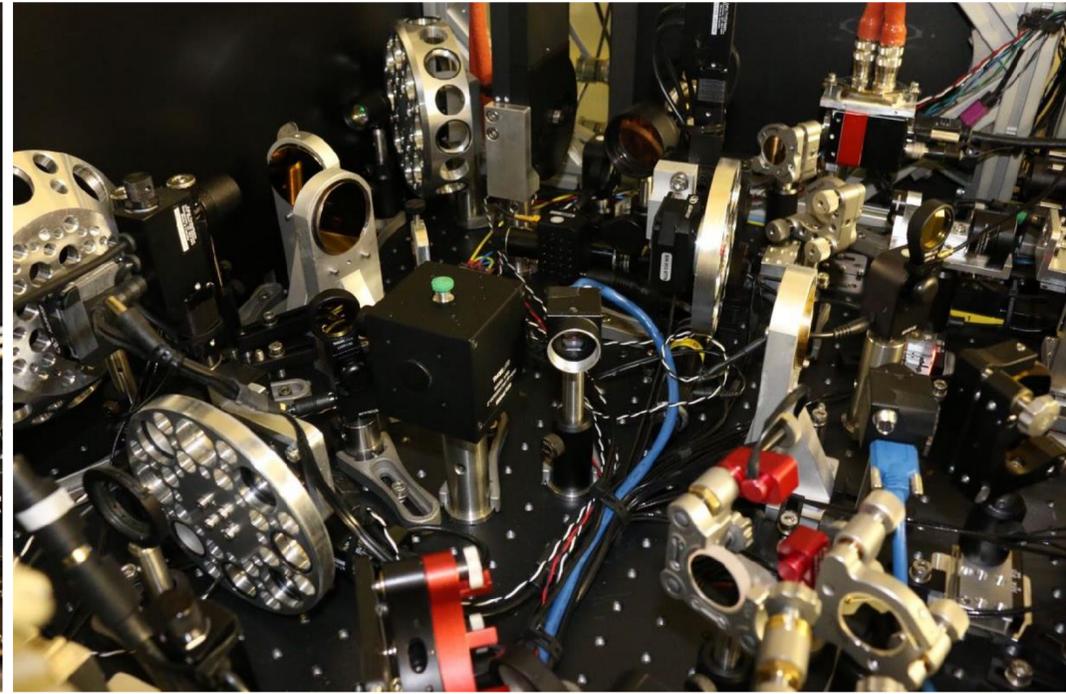- Todo - close the loop!

System Overview
Hardware

CALIBRATION SOURCE

1523 nm HeNe
Halogen lamp
Super continuum source
Collimators
650 nm
1550 nm
Rotating mirror
IR ND filters
VIS ND filters
Spectral filters
Endlessly SMF
To SCExAO

FIRST RECOMBINATION BENCH

Single-mode fibers
Pick-off mirror
Cylindrical lenses
Micro-lens array
Alignment camera
Right angle mirror
Prism
Science camera
From SCExAO
Anamorphic telescope

RHEA SPECTROGRAPH

From SCExAO
Echelle grating
Bundle of 3x3 SMF
Prism
OAP
RHEA camera

VISIBLE BENCH

RHEA pickoff mirror
Pupil viewing camera
VAMPIRES
WFS beamsplitter
VAMPIRES/FIRST splitter
BRTL2
Aperture masks
50/50
Polarization beamsplitter
Periscope
Field stop
FLC
Filters
Imaging optics
VAMPIRES Camera 1
QWP
Single-mode fiber bundle
Hα/Continuum differential filter wheel
Segmented mirror
Polarizing beam cube
Telescope
Micro-lens array
To FIRST recombination bench
VAMPIRES Camera 2
RHEA focusing lens
FIRST INJECTION
Piezo tip/tilt mirror
Roof prism
Pyramid optic
Pyramid WFS camera
Filters
Alignment camera
RHEA
Alignment camera
Single-mode IFU
To RHEA spectrograph
Calibration fiber
Micro lenses

PHOTONIC SPECTROGRAPH

From photometric setup
SMF
Arrayed waveguide grating
Prism
NIR camera

PHOTOMETRIC SETUP

90% port
To spectrograph
SMF
10% port
From SCExAO
Collimators
filters
Photodetector
MMF
90:10 beam cube

IR BENCH

SMF
OAP6
To GLINT
Inverse PIAA lenses
Periscope
MMF
Rails
Fiber injection
CHARIS pickoff
Field stop
Beam to CHARIS
QWPs
Visible light (<950 nm)
Integrating sphere
Lyot mask plane
Steering mirror
F/14 beam from AO188
OAP1
Wollaston
PIAA lenses
Focal plane camera
Alignment camera
Focal mask plane
From calibration source
Dichroic
Focusing lens
Deformable mirror
Polarizer
Pupil mask
Pupil mask wheel
5-axis translation stage
MEC pickoff
Beam to MEC
Internal NIR camera
From SAPHIRA
Pupil lens
To IRD
SMF
Imaging optics
Filters
FLC
Pupil lens
Low order wavefront sensor camera
Wollaston

CHARIS

Lo-res and Hi-res prisms
HAWAII-2RG
Filter
Microlens array
Beam from SCExAO
Pupil viewer

MEC

From SCExAO
Steering mirror
MKIDS in cryostat

REACH SWITCHYARD

Injectors
Injectors
To SCExAO's photometric setup
90:10 beam cubes
To IRD
Collimators
Translation stage
From SCExAO's injection

GLINT BENCH

Segmented deformable mirror
beamsplitter
filter
Pupil camera
beamsplitter
Recombination chip on 5-axis stage
Focal plane camera
x16 outputs
Pupil mask w/ 4 holes + Periscope

GLINT SPECTROGRAPH

V-groove on 3-axis stage
Prism
GLINT camera
16x single mode inputs
From Injection

Segmented mirror Polarizing beam cube Micro-lens array *To FIRST recombination bench* VAMP Camera

FIRST INJECTION

RHEA focusing lens

Piezo tip/tilt mirror

Roof prism
Pyramid optic

Pyramid WFS camera

Filters

Alignment camera

Alignment camera

RHEA

Single-mode IFU

To RHEA spectrograph

Calibration fiber

Micro lenses

VISIBLE

Periscope

SMF

OAP6

To photometer

To GLINT

Inverse PIAA lenses

QWPs

MMF

CHARIS

Rails

Fiber injection

F/14 beam from AO188

Integrating sphere

OAP1

Lyot mask plane

Field stop

PIAA lenses

Focal plane camera

Alignment camera

Steering mirror

Visible light (<950 nm)

From calibration source

Focal mask plane

Deformable mirror

Polarizer Pupil mask
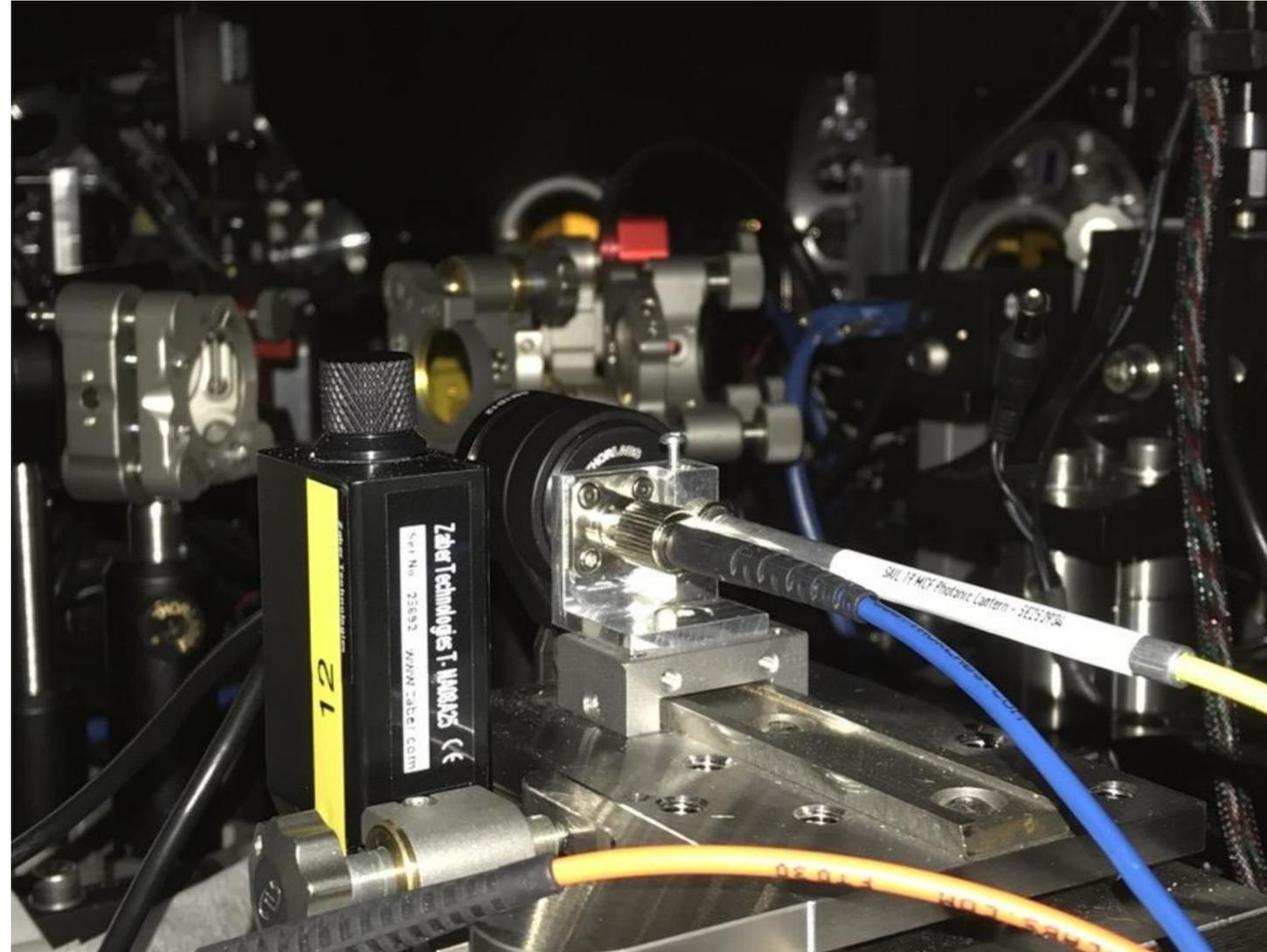
Dichroic

Pupil mask wheel

5-axis

Focusing lens

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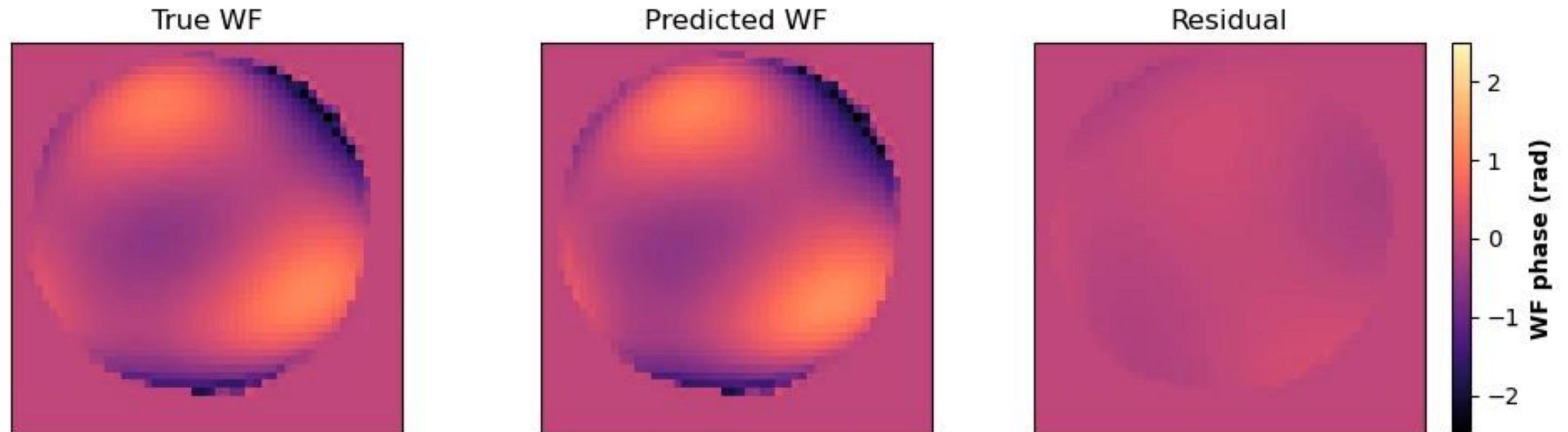- Todo - close the loop!

SCExAO daytime tests

Low-order Zernike basis

- Here - first 10 Zernike modes, average of 1.3 radians RMS (~5 rad P-V) wavefront error applied

- Randomly drawn 40,000 training images (~ 1 minute)

- RMS reconstruction error 0.07 radians

SCExAO daytime tests

Low-wind-effect modes

- Each pupil quadrant parametrised with tip, tilt, piston

- Average applied WF error 1.7 radians RMS

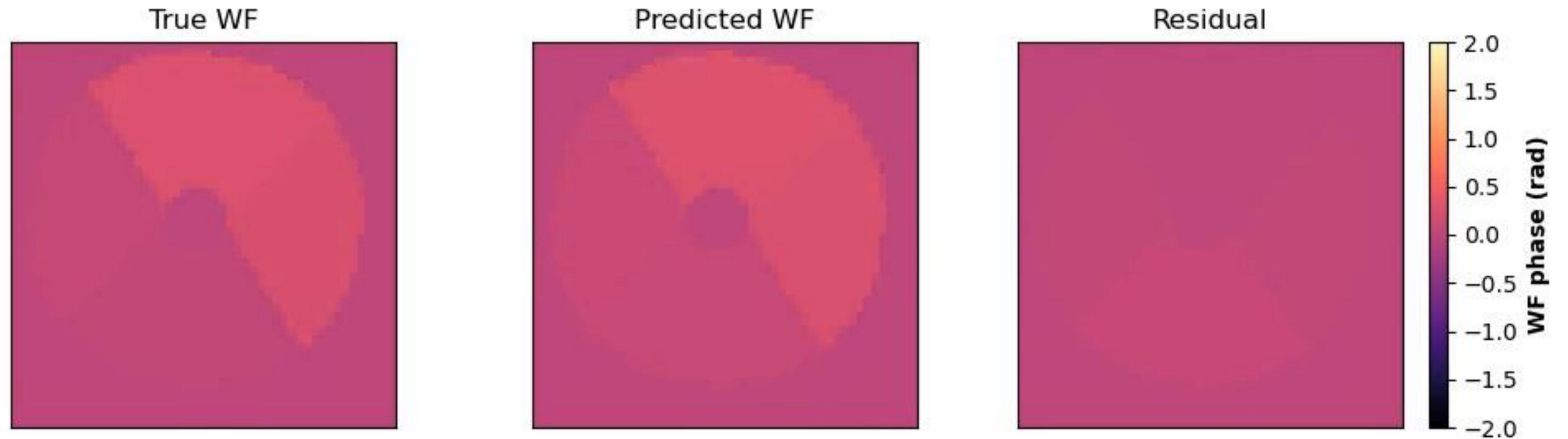- RMS reconstruction error 0.1 radians
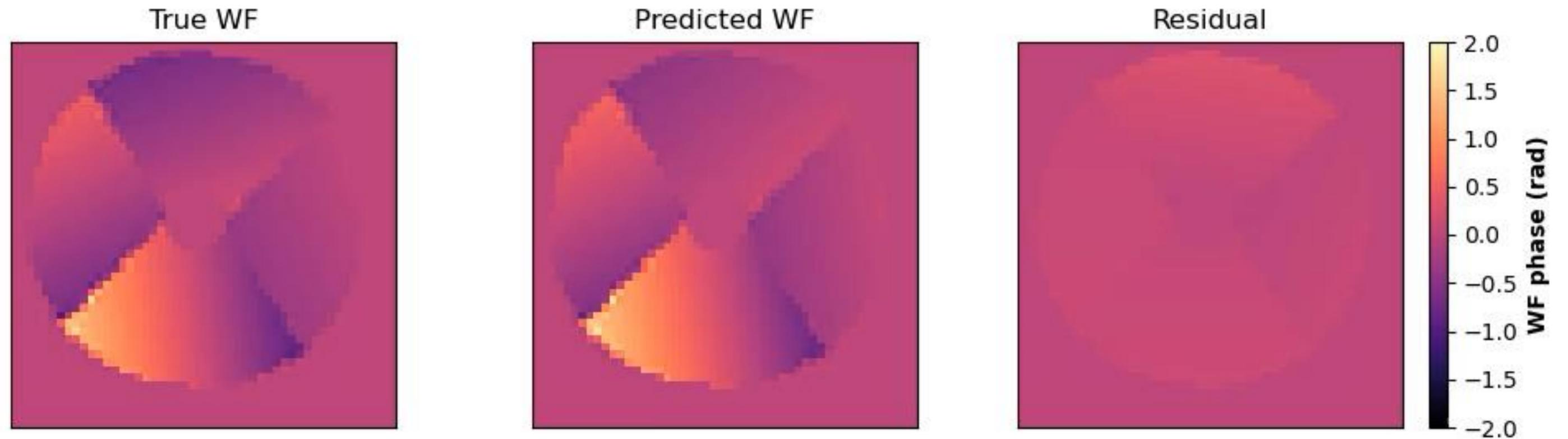
SCExAO daytime tests

Petalling-only modes

- Each pupil quadrant parametrised by piston term
- Average applied WF error 2 radians RMS
- RMS reconstruction error 0.09 radians
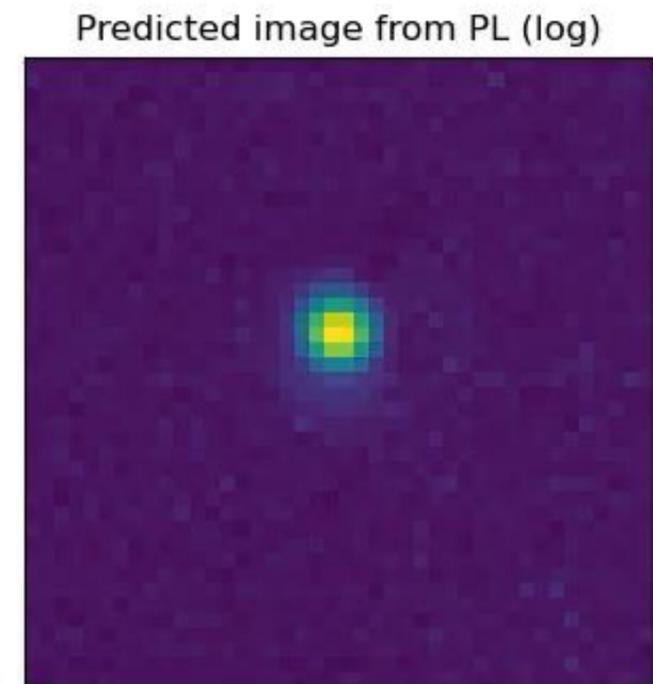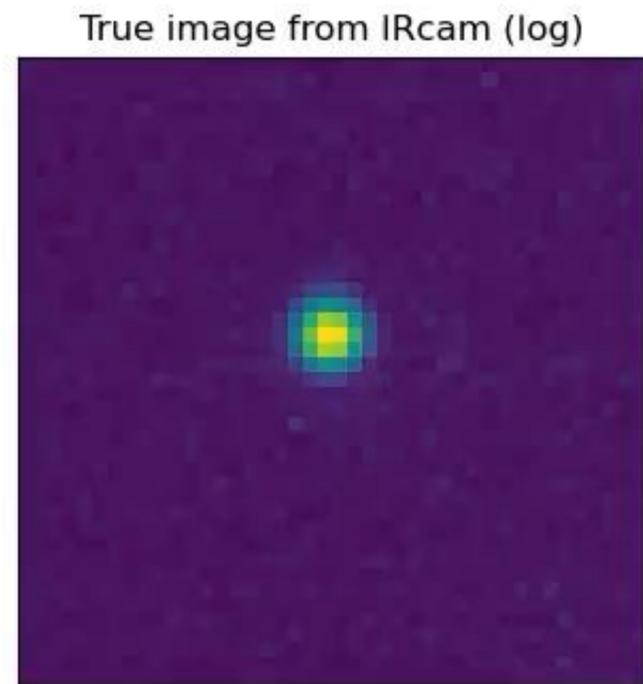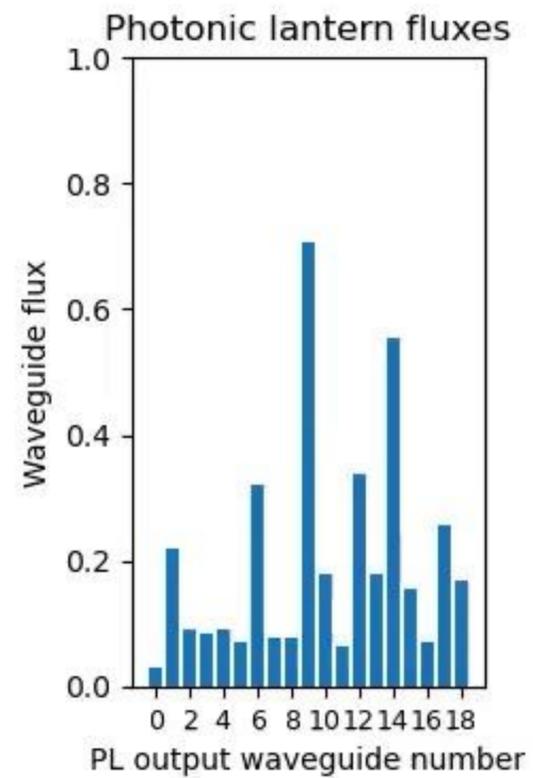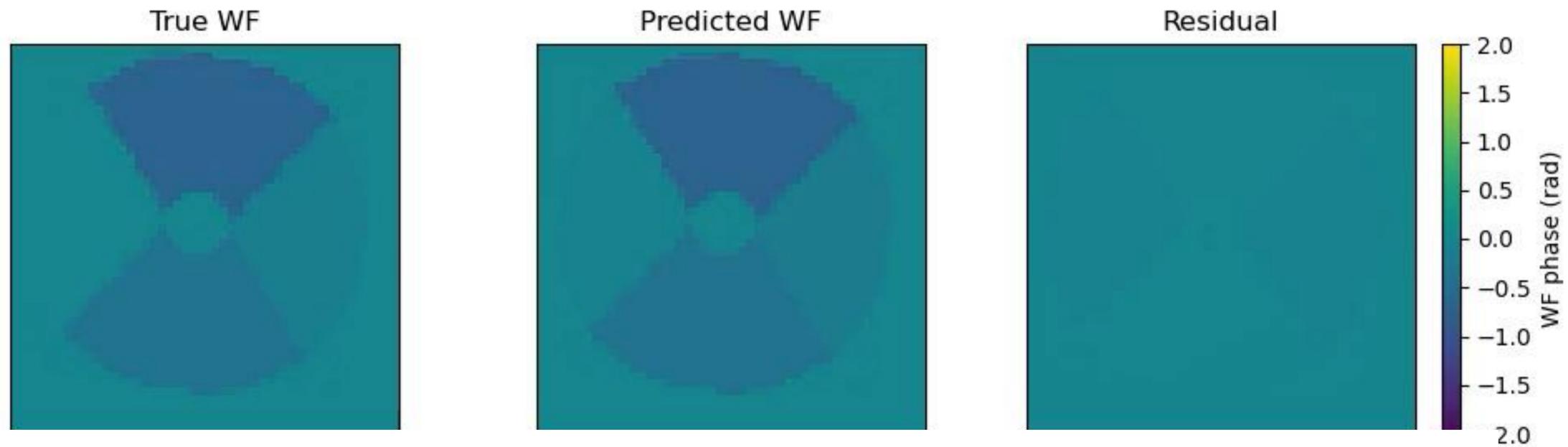
SCExAO daytime tests
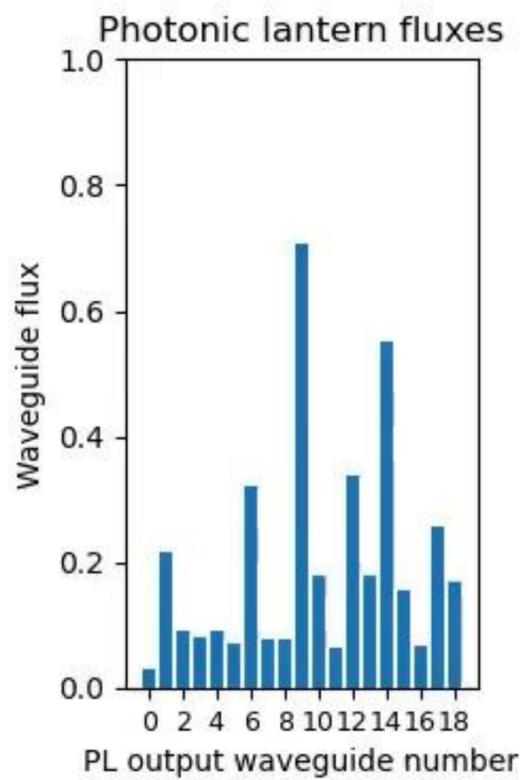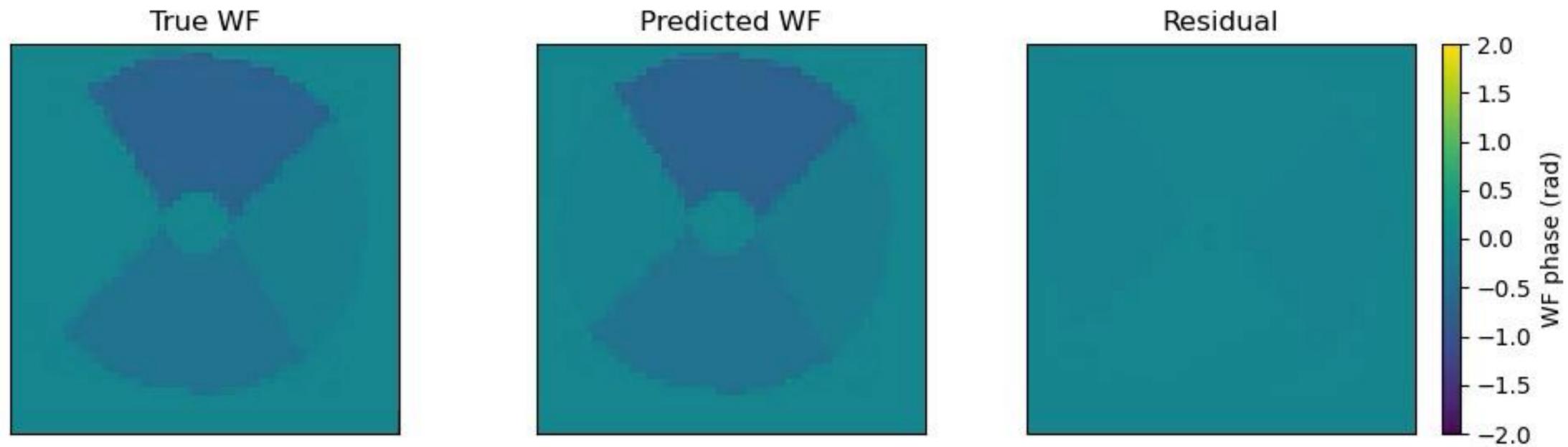
Petalling-only modes

- Each pupil quadrant parametrised by piston term

- Average applied WF error 2 radians RMS

- RMS reconstruction error 0.09 radians
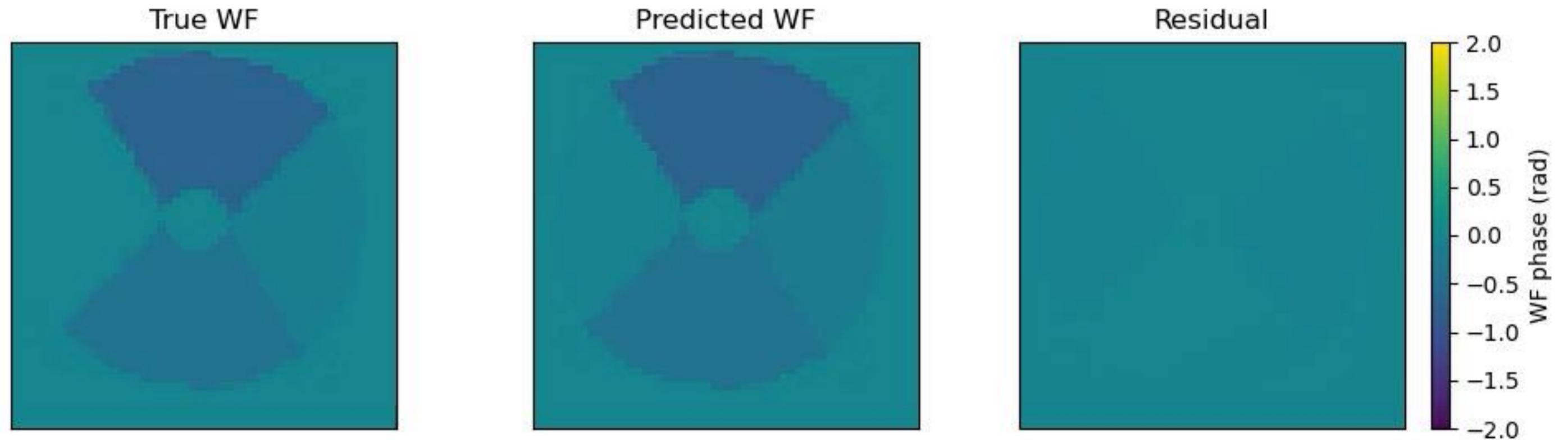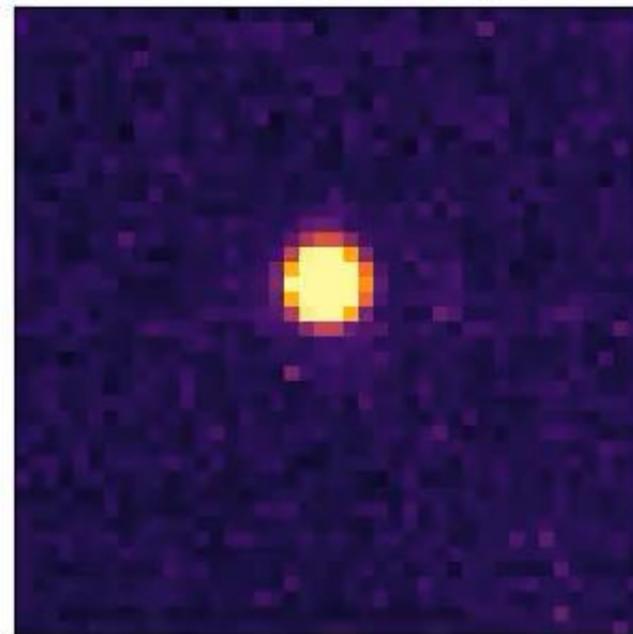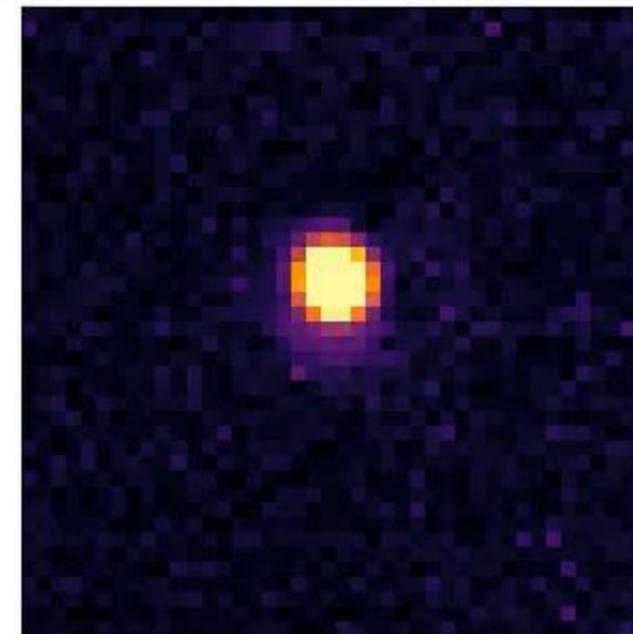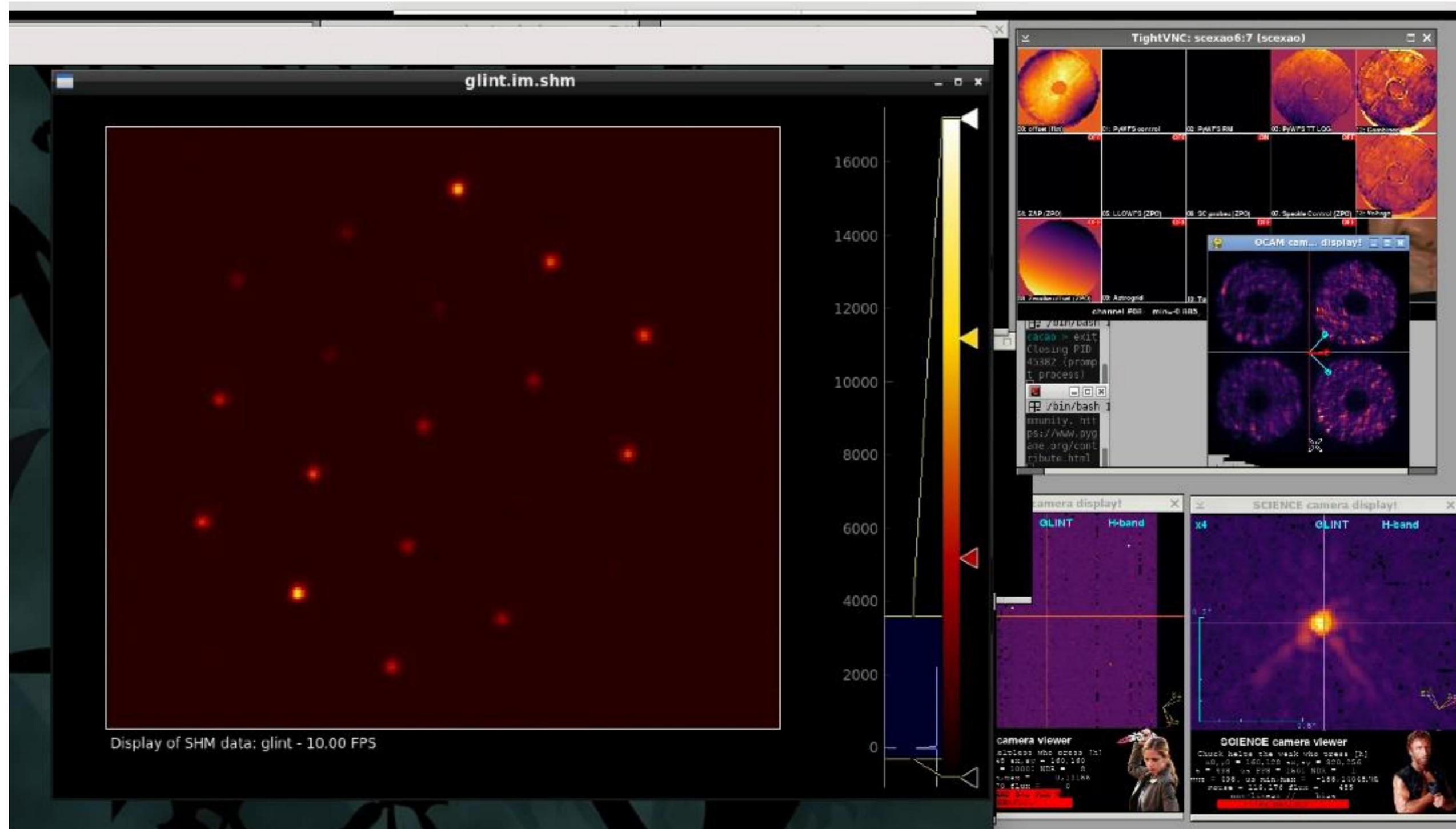
SCExAO daytime tests

# SCExAO daytime tests

On Sky Results

First light of (non-mode selective) time-resolved PL (@ Subaru)

On sky observations at SCExAO

Here - WF truth data used is first 19 modes from PWFS, as per usual linear basis used in SCExAO

- Prediction is in DM actuator space

- Linear PWFS modes mean won't see LWE, etc. Next step to use optimal modal representation for comparison.

Photonic lantern fluxes   **'True' wavefront (PyWFS)**   **Predicted WF from PL**

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**Photonic lantern fluxes**   **'True' wavefront (PyWFS)**   **Predicted WF from PL**
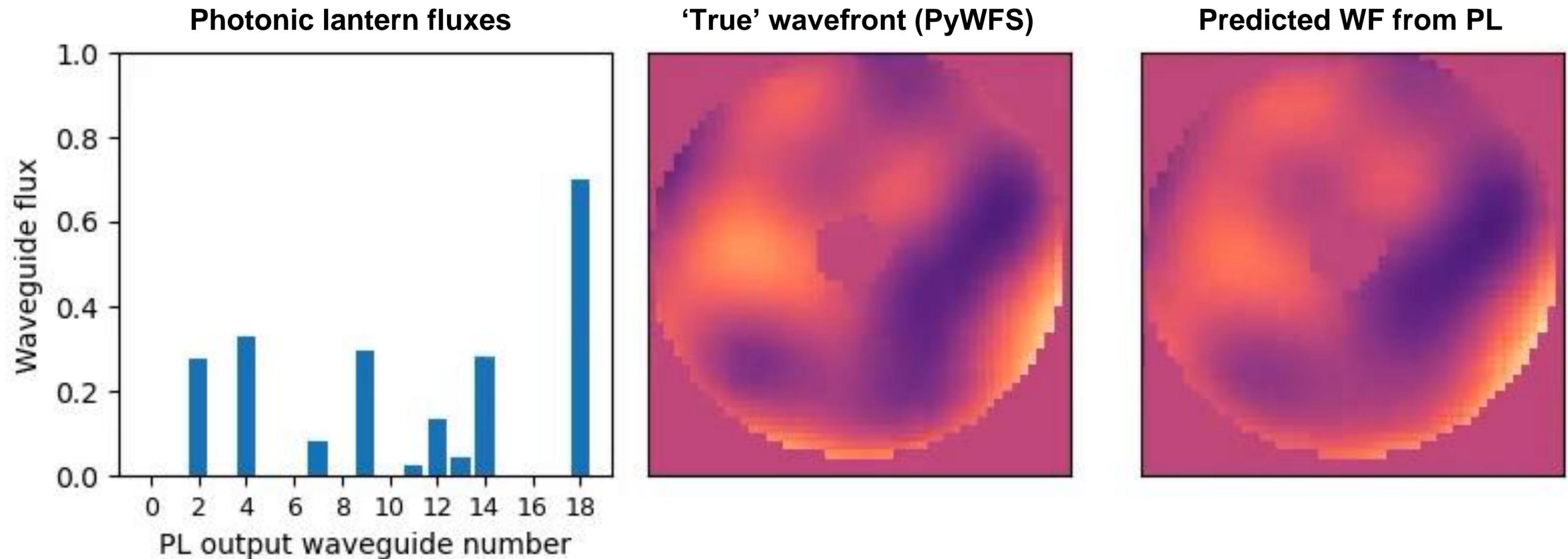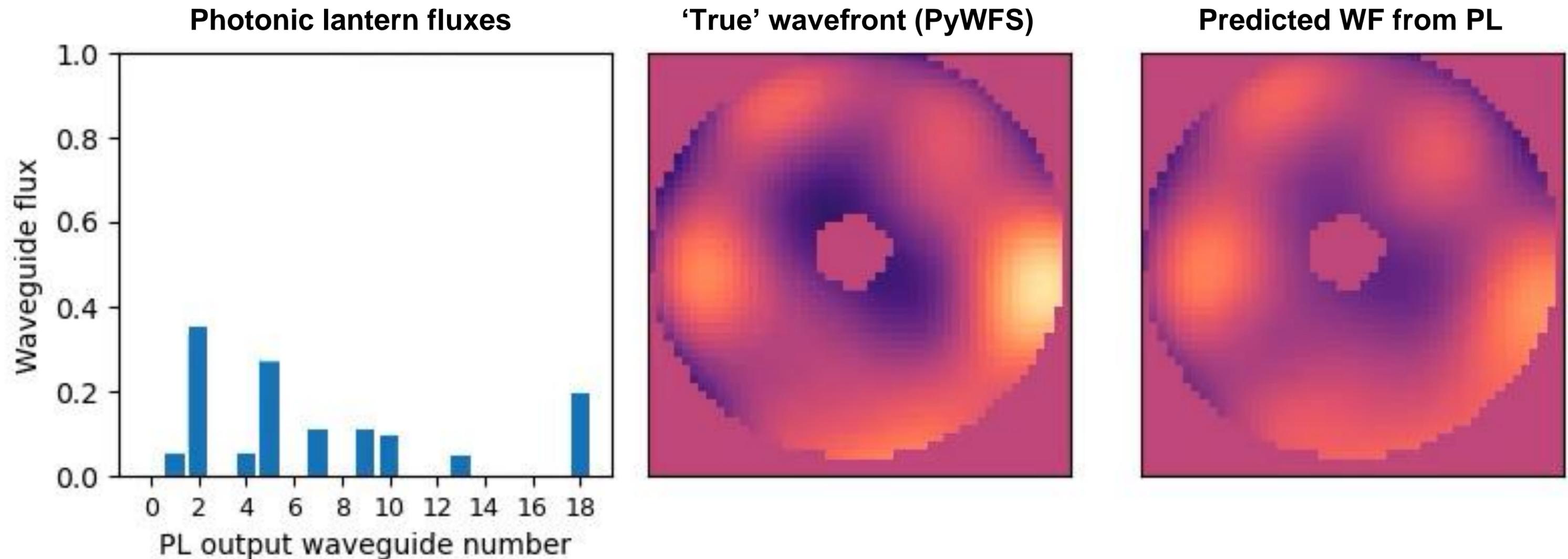
Beyond WFSing

On sky PSF reconstructio

Reconstruct IR PSF using PL

- On-sky IR camera data acquired as well as PL on SCExAO

- Note PIAA used, so Airy rings suppressed

- NN learns non-linear 'modes' repenting aberrations

- Important 'modes' include tip/tilt with corresponding diffraction features due to misalignment with PIAA

Photonic lantern fluxes
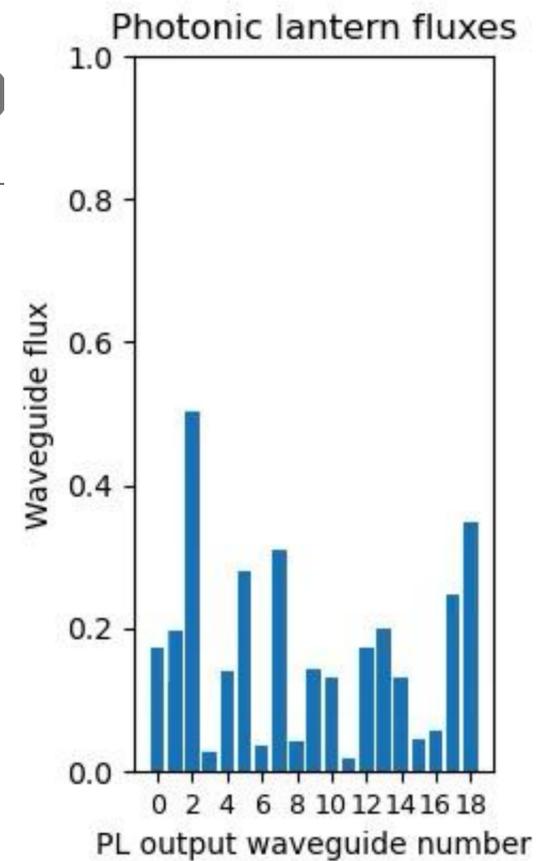
True image from IRcam (log)

Predicted image from PL (log)

True image from IRcam (log, clipped)
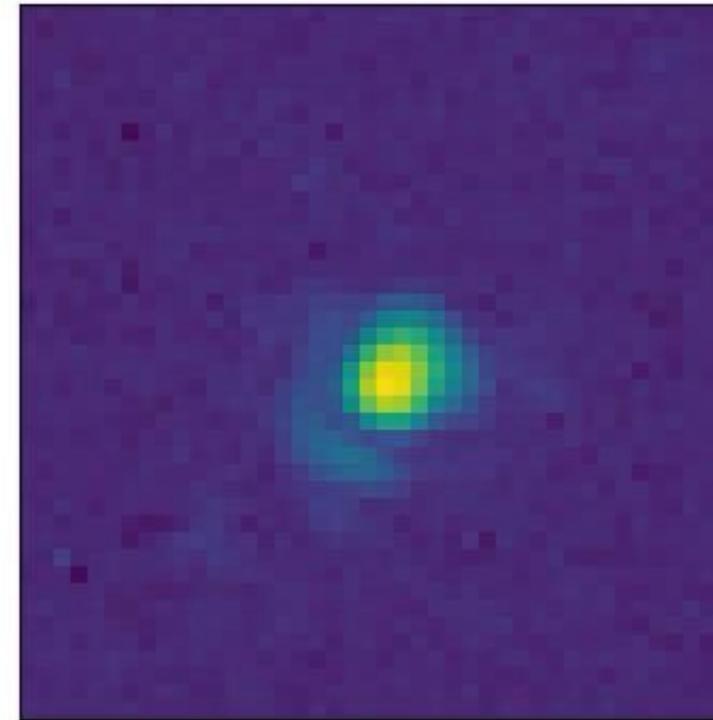
Predicted image from PL (log, clipped)

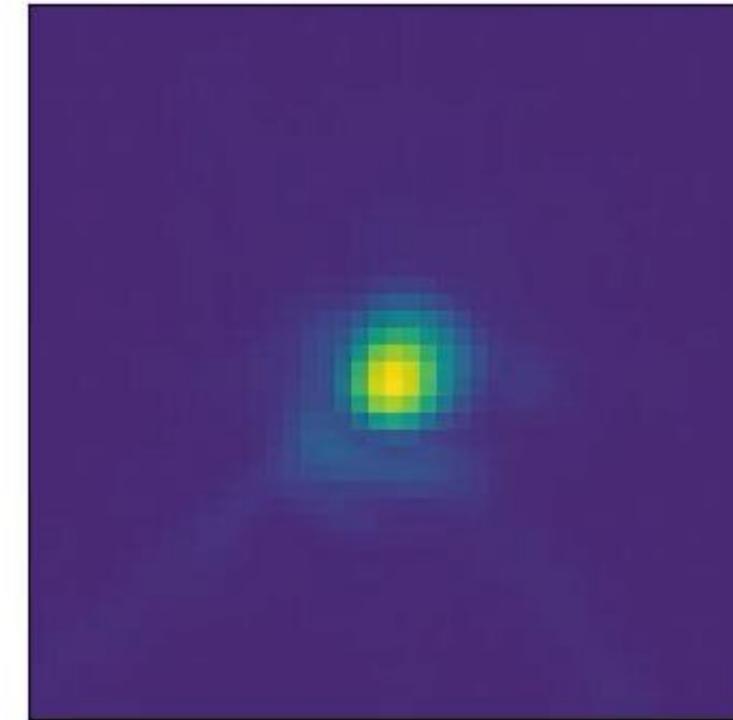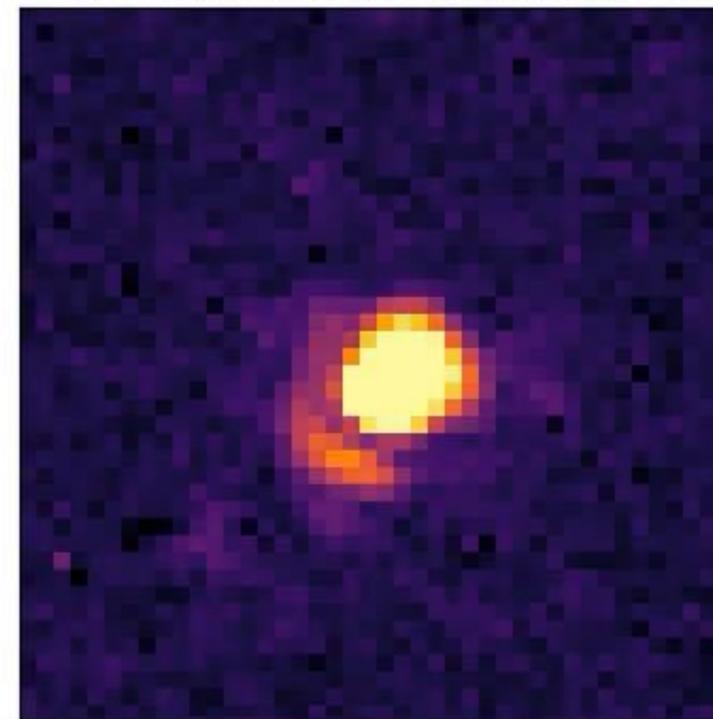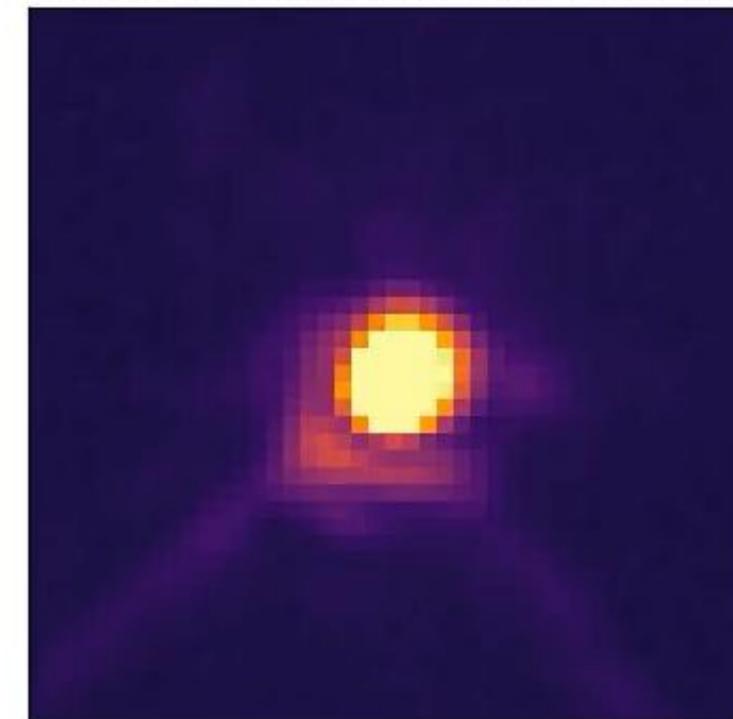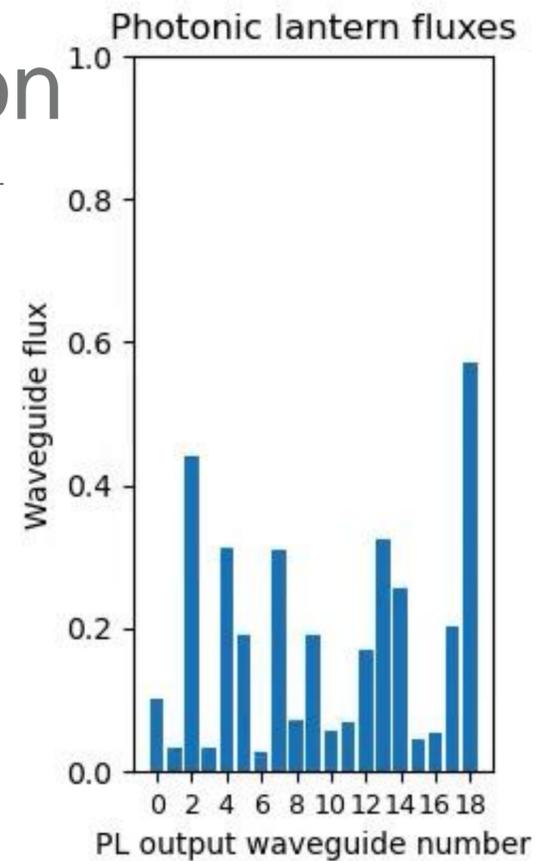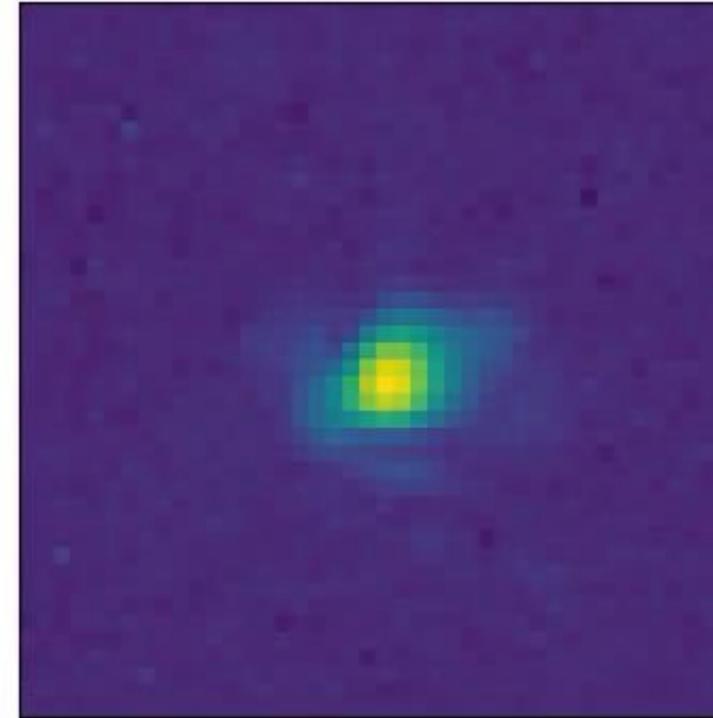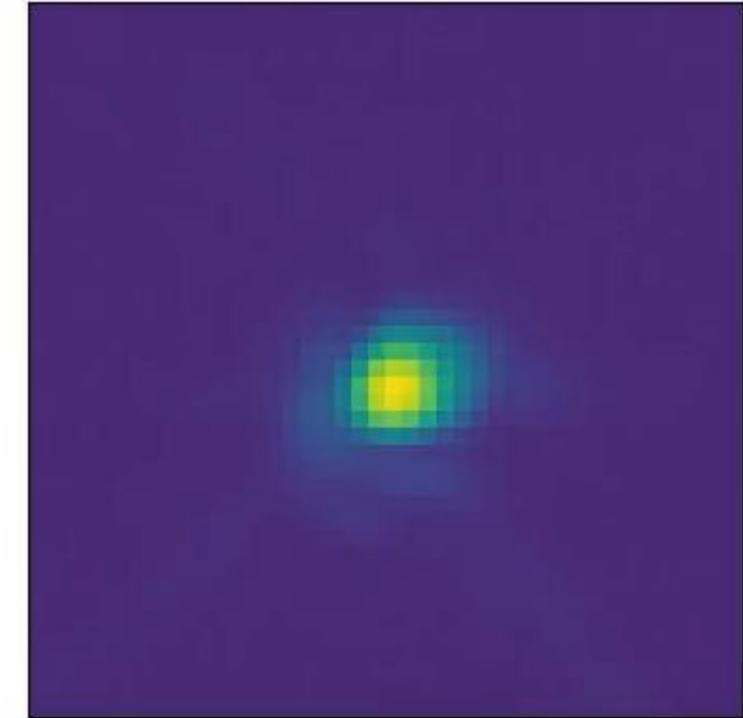# On sky PSF reconstruction

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Exploring the model's latent space

What "modes" does the model use to represent the PL system?

- "Modes" in quotes since it's non-linear function, not linear combination of 19 modes

- But it's informative to move around the (19-d) input space to see how PL / model describes system with 19 DOF

- Here - pick a PL measurement instance and perturb the PL output intensities

Photonic lantern fluxes

Predicted image from PL (log)

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OPTIMAL SM INJECTION

Optimal SMF injection with integrated WFSing

Implementation

- Introduce anisotropy in preform such that transition to certain mode (LP01 or LP02) has geometric component (not fn of wavelength)
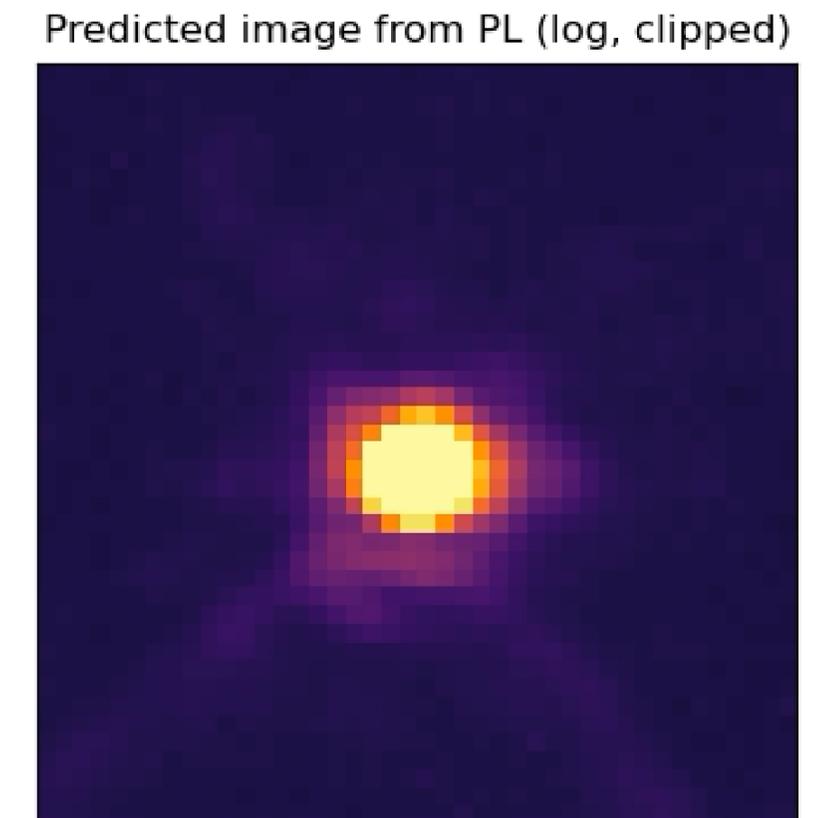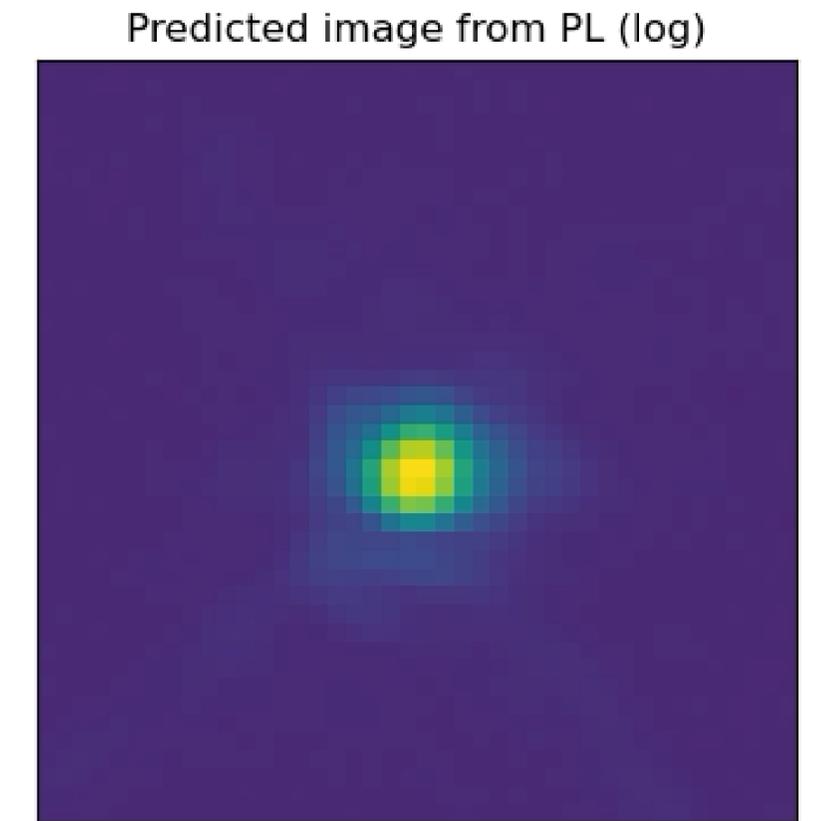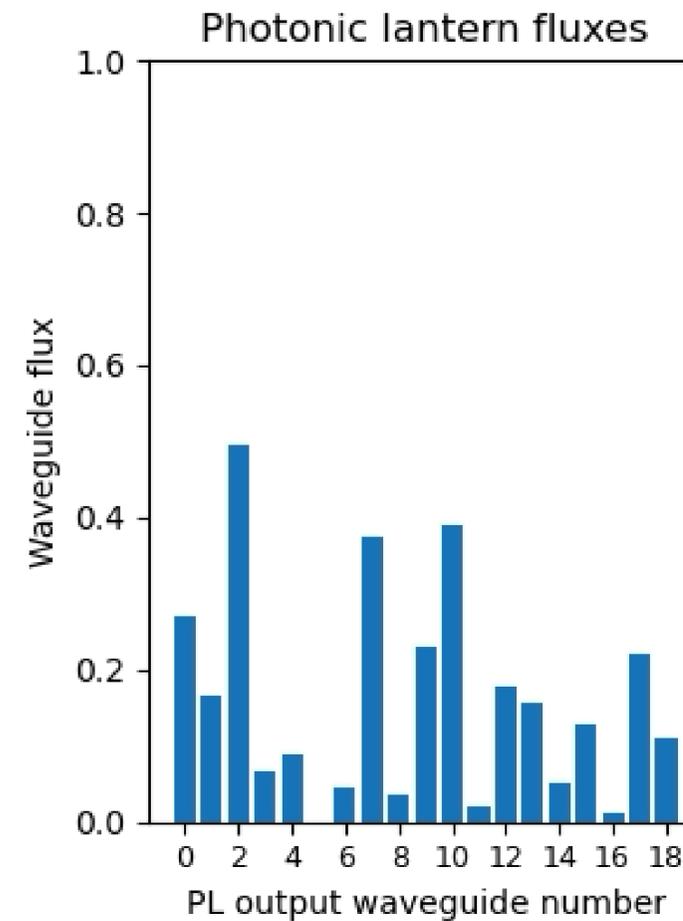   - LP02 good match to Airy disc, LP01 to apodised PSF
- Optimise AO PSF to excite only e.g. LP01 -> LP01 output fibre to spectrograph
- Light coupled into higher modes (due to WF error) in AO servo loop to keep LP01 maximised
- **Alternatively, do the opposite** - discard the light in LP01 or LP02 and do imaging with remaining fields ->
    - This removes the majority of the starlight from the imaging modes, reducing photon noise (~factor of 10) at the expense of inner-working-angle

Applications

- Spatially unresolved spectroscopy, e.g. radial velocity
- Long baseline interferometry (each telescope to one fibre, for photonic beam combiner)
- Fibre nulling, such as Vortex Fibre Nuller
- Optimal SNR imaging

To high-R spectrograph (or discard)

l = 0, m = 1   l = 1, m = 1   l = 2, m = 1   l = 0, m = 2

l = 3, m = 1   l = 1, m = 2   l = 4, m = 1   l = 2, m = 2

l = 0, m = 3   l = 5, m = 1   l = 3, m = 2   l = 1, m = 3

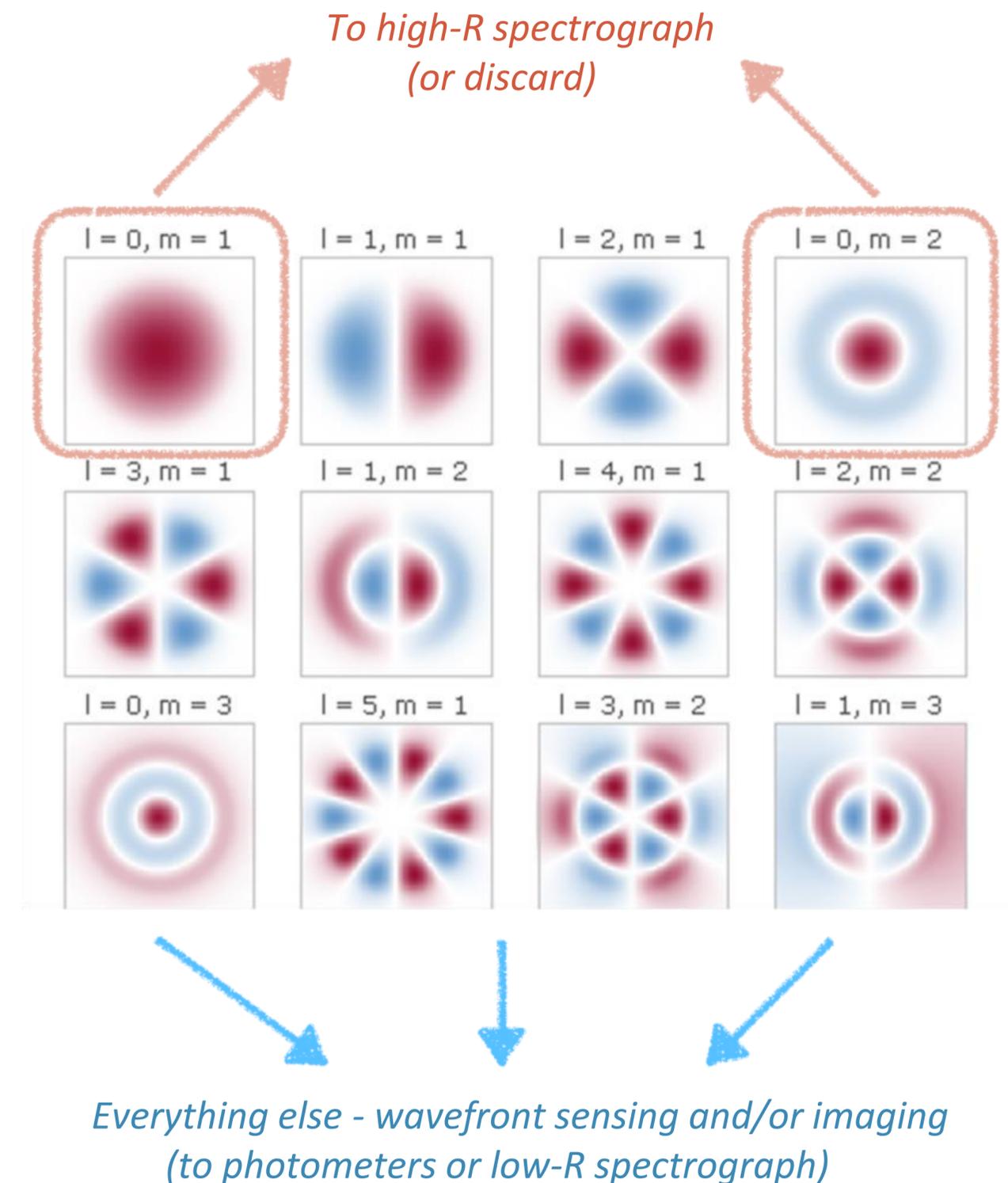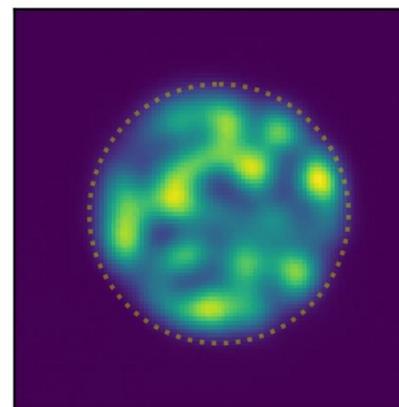*Everything else - wavefront sensing and/or imaging (to photometers or low-R spectrograph)*

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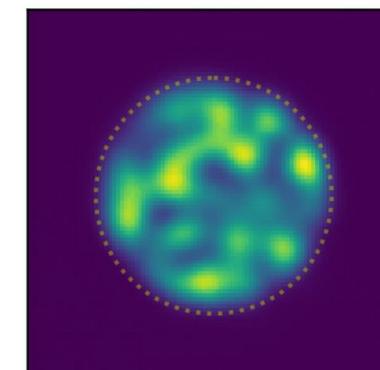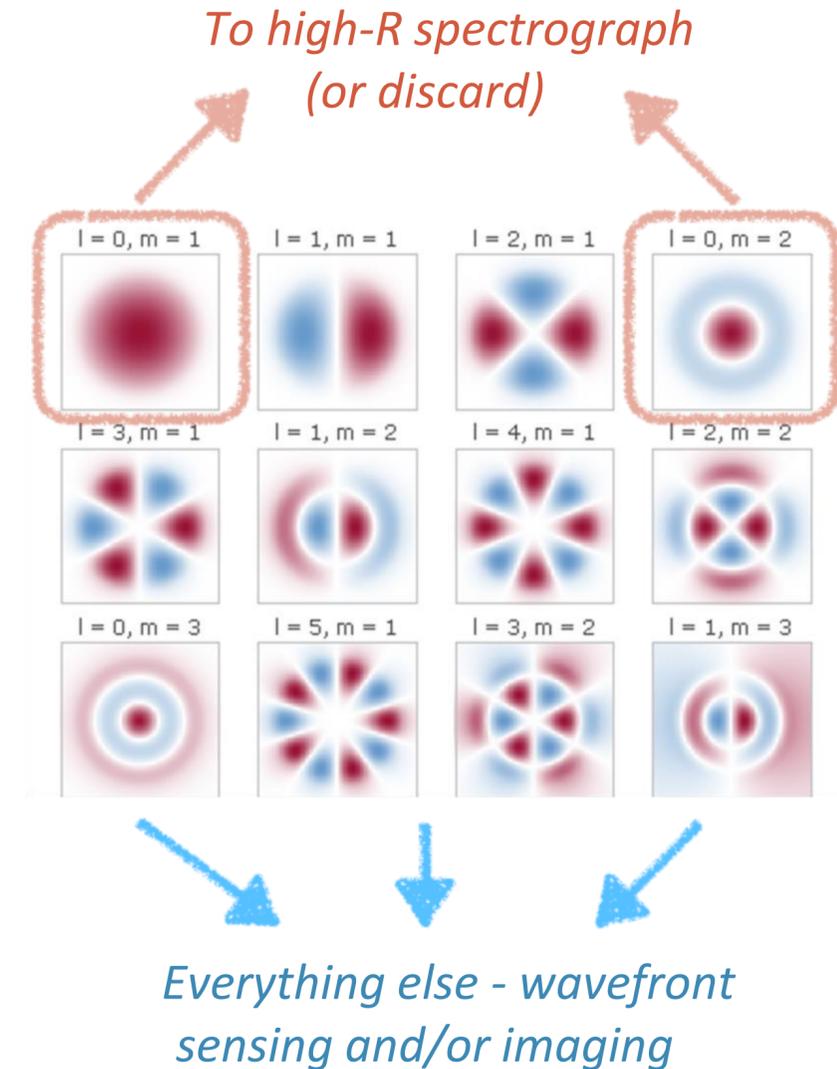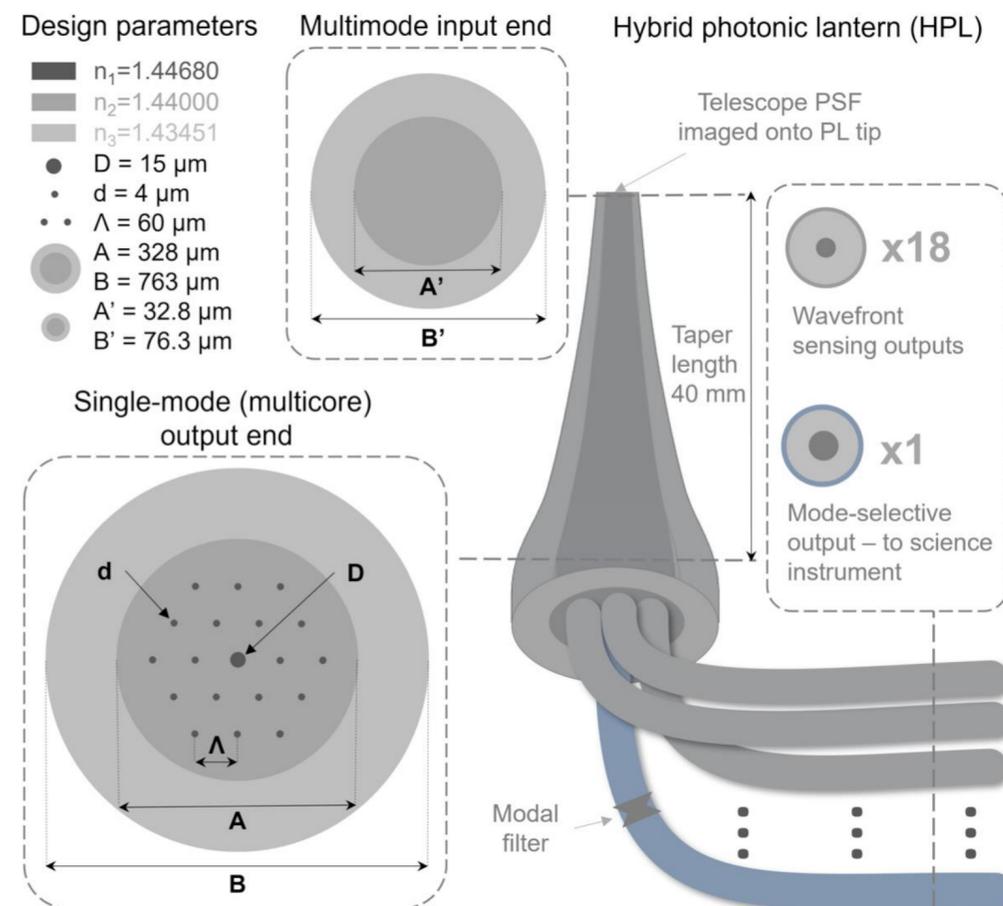
What the PSF looks like with Extreme AO vs fiber mode fields

- All mode fields span ~the same spatial region (the physical fibre core)

- Superposition of modes can describe any image (up to spatial frequency sampled by those modes)

- LP01 biased towards centre. If hybrid mode selective, could remove (or optimal suppress in data analysis) these modes.
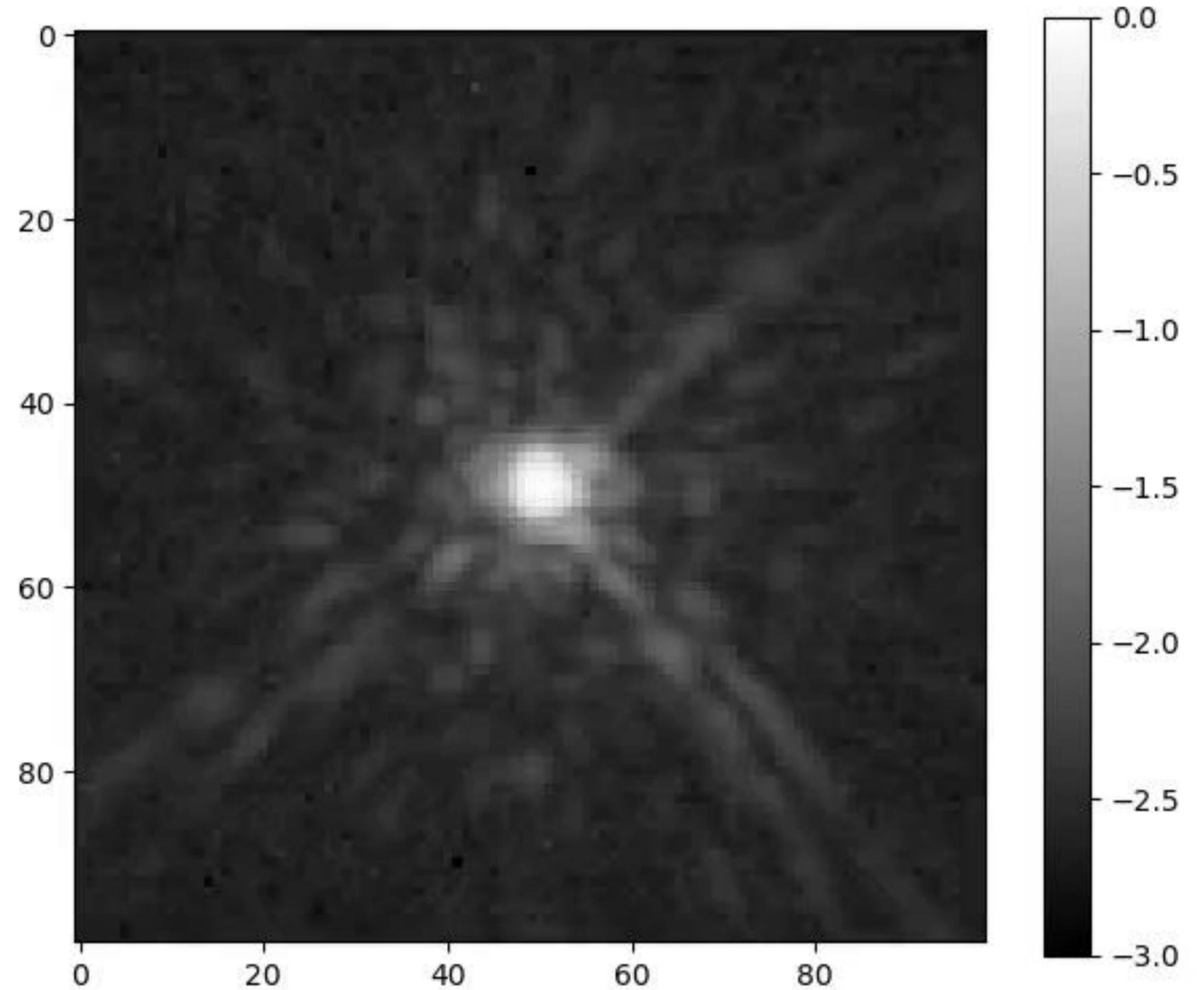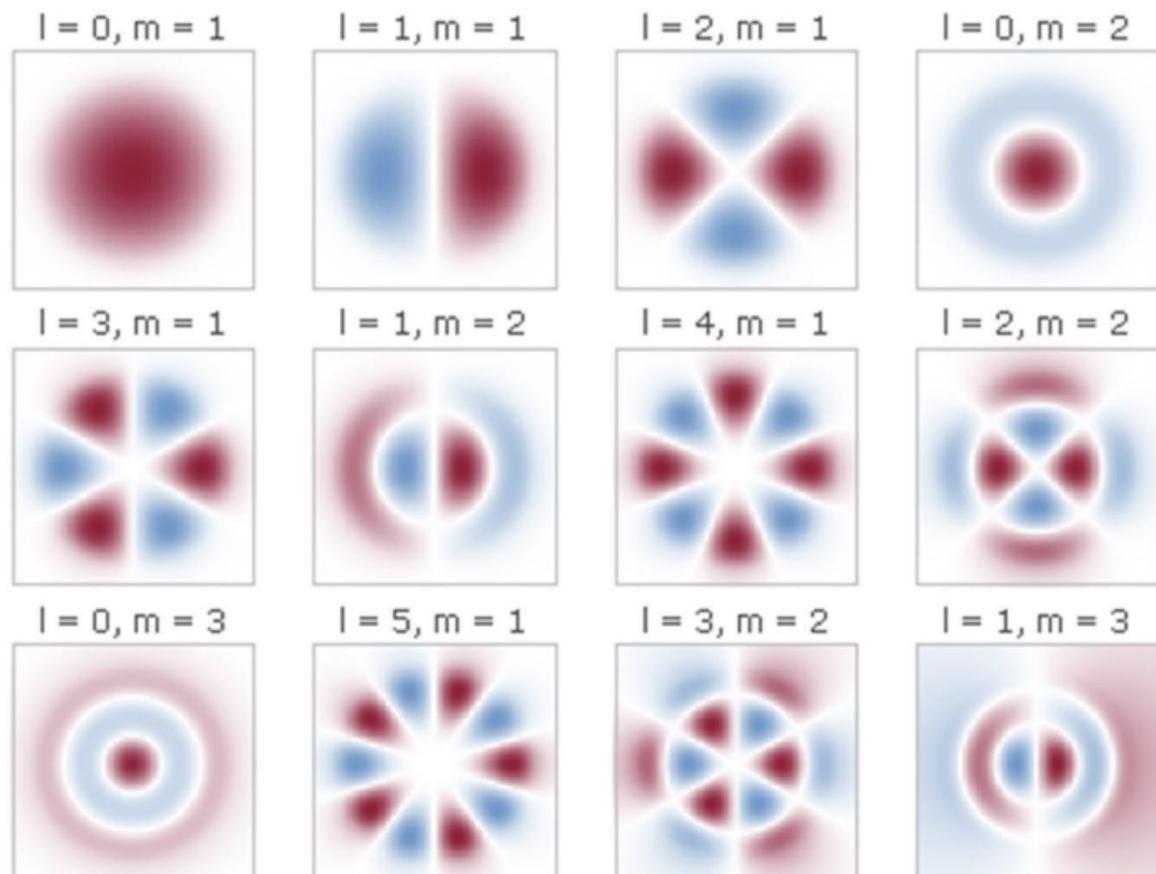
Transfer matrix

- Complex transfer matrix produced by BPM simulations -
  - Excite each input mode (found with FEM) one at a time, calculate complex overlap integral of all output waveguides
- Performance evaluated by mode selectivity of MS waveguide (LP01) to input LP01 mode. <0.1% crosstalk (simulation)
- Devices currently being fabricated for lab tests

Broadband test (1)

- Input modes excited by randomly selected set of amplitudes (0 < A< 1) and phases (0 < φ < π).

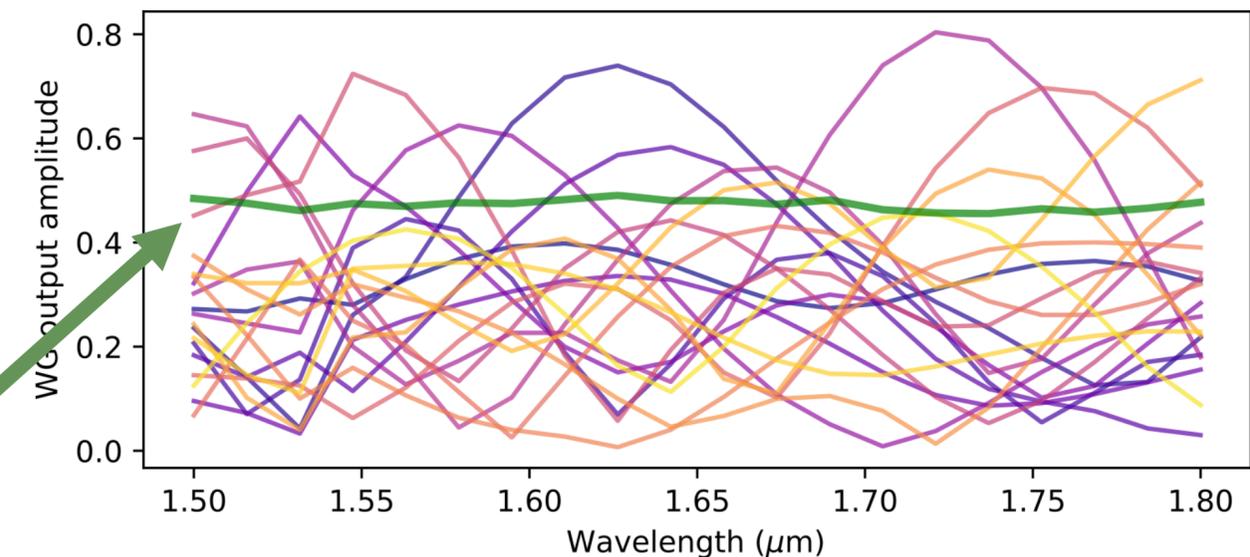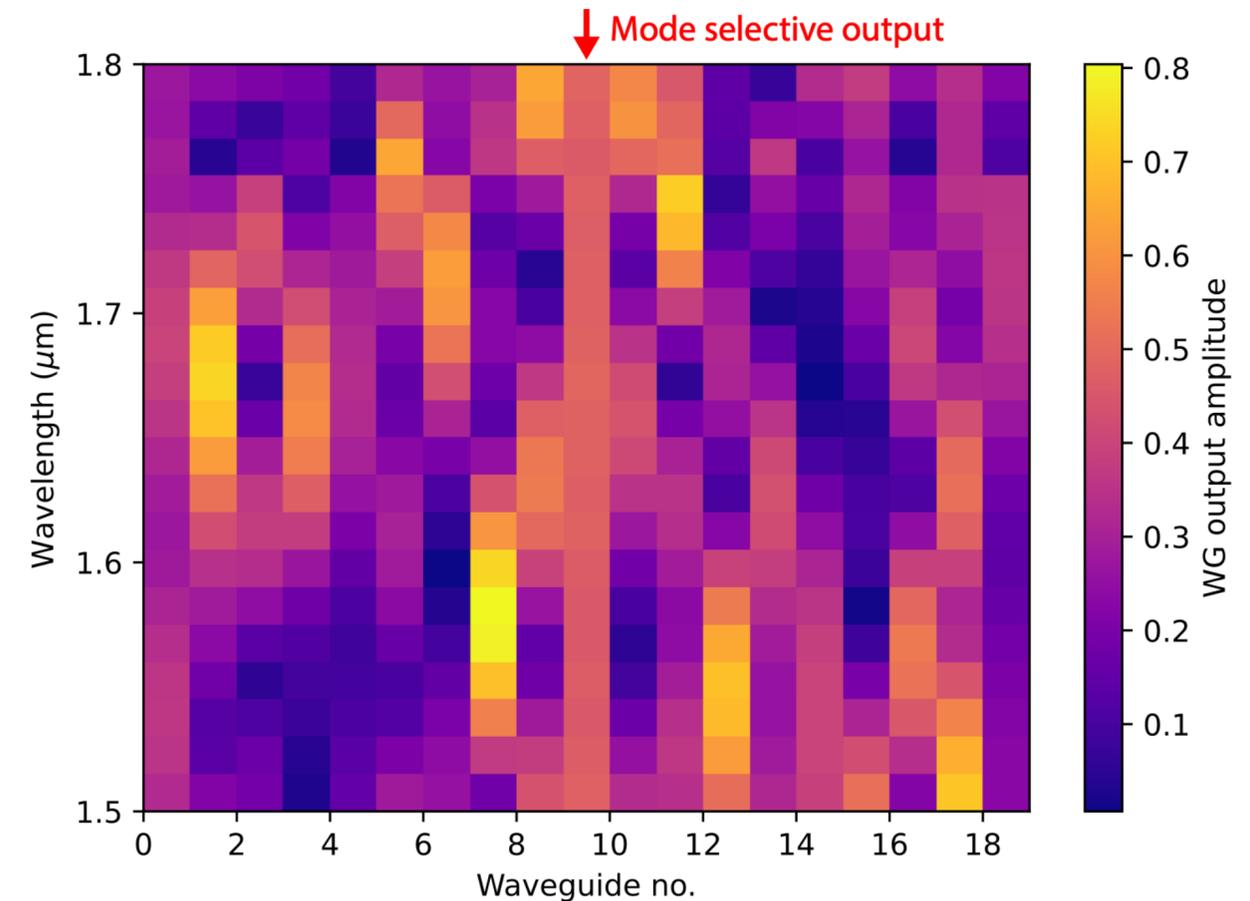- Standard outputs show the expected strong, non-linear amplitude modulation as function of wavelength

  - Interference between different modes with different propagation constants

- Mode-selective output has constant achromatic amplitude

  - Enabled by minimal cross-terms in transfer matrix

- Simulate time series

  - Input mode coefficients move in random walk (Gaussian sampling distribution, 0.1 rad / step)

- When used in adaptive optics:

  - Reference set to maximally excite LP01 input mode, and hence maximise output from the MS output, driven by feedback from the WFSing fibers

For optimal injection case - maximise green line by minimising other WFS outputs

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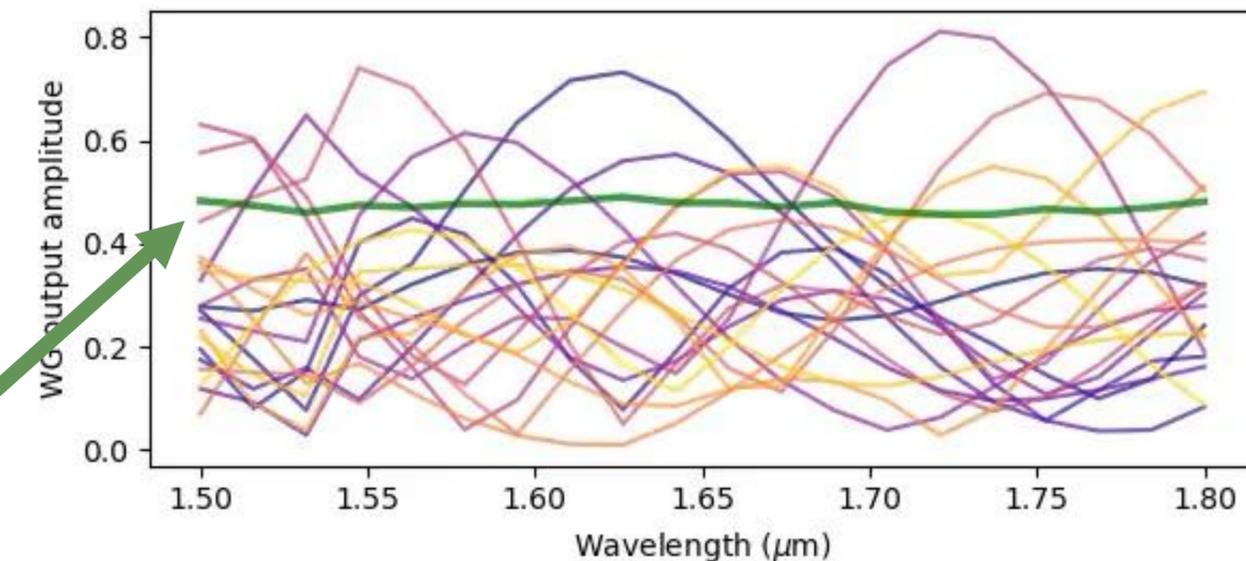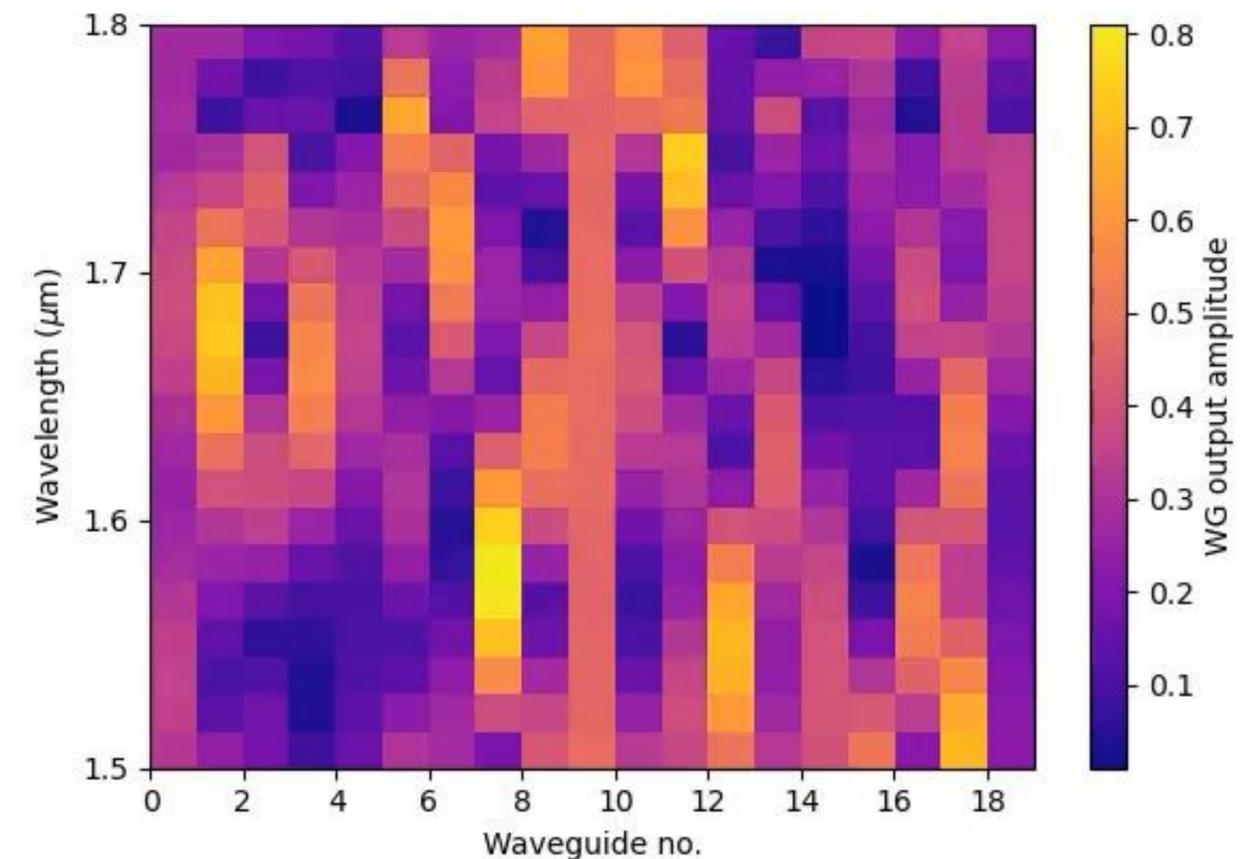
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Next step… Complete spectro-imaging and wavefront sensing

Concept

- Use all the modes for imaging!

- Like IFU, but modes, not pixels

  - More optimal than pixels, ranked by spatial frequency

  - Output fluxes from SM fibres projected back into image space in data reduction

Full wave

- Image reconstruction with access to full complex amplitude at focal plane

- Optimal speckle rejection

- >2x as many SM guides as MM modes

- Photon-noise limited, full aperture imaging at ~0.5l/D (interferometric criteria)

- Outputs used for WFS (realtime), spectro-imaging (offline)
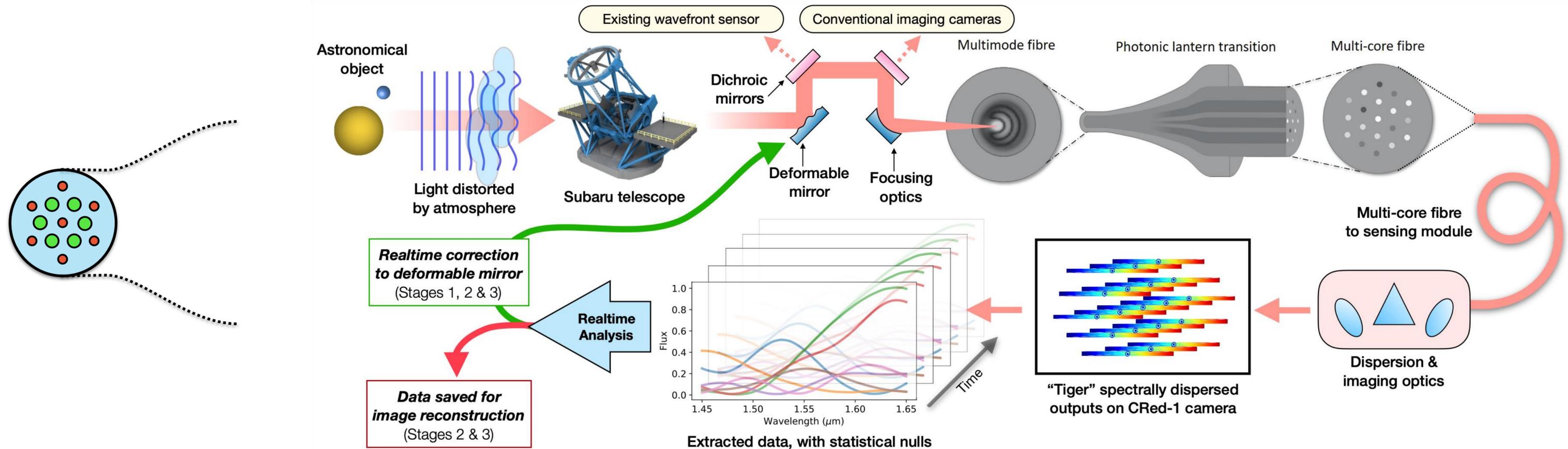
Conclusion

- 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 and on-sky tests show promising results

- PL-WFS allows
  - No NCP aberrations, sensitivity to blind modes
  - Wavelength-dispersed WFSing
  - Also allows reconstruction of PSF!

- Hybrid mode-selective photonic lantern
  - One mode (eg LP01) mapped directly to one output fiber over a broad bandwidth
  - Remaining fibres used for wavefront sensing
  - Ideal for optimal injection into a SMF, with truly zero NCPA and at same wavelength as science
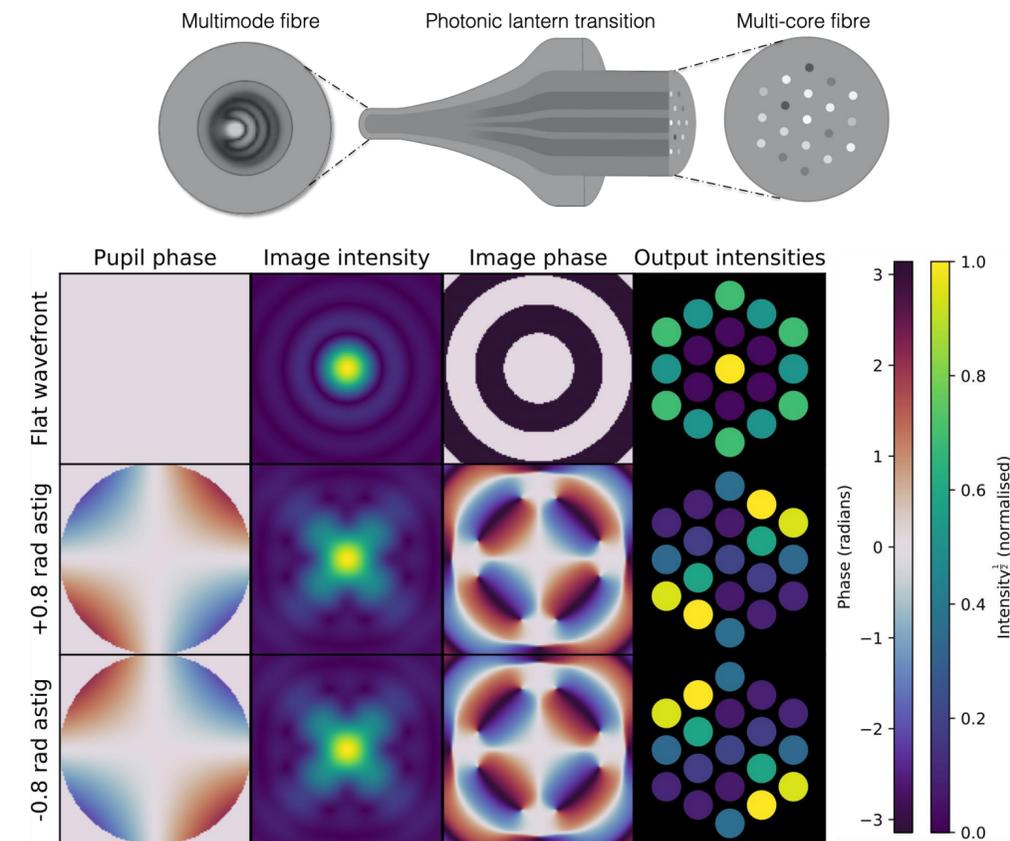
Next step - complete E field reconstruction for combined imaging + WFSing. Imaging with optimal speckle suppression!