

Deep Learning Wavefront Reconstruction With Collimated Lasers Using Experimental Data from the PPPP Bench

Nazim Ali Bharmal ¹,
Carlos González-Gutiérrez ²,
Huizhe Yang ^{1,3},
Jorge Rodríguez Muro ²,
Tim Morris ¹,
Francisco Javier de Cos Juez ²

¹ Centre for Advanced Instrumentation, Durham University, UK

² Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias, University of Oviedo, Spain

³ College of Advanced Interdisciplinary Studies, National University of Defense Technology, China



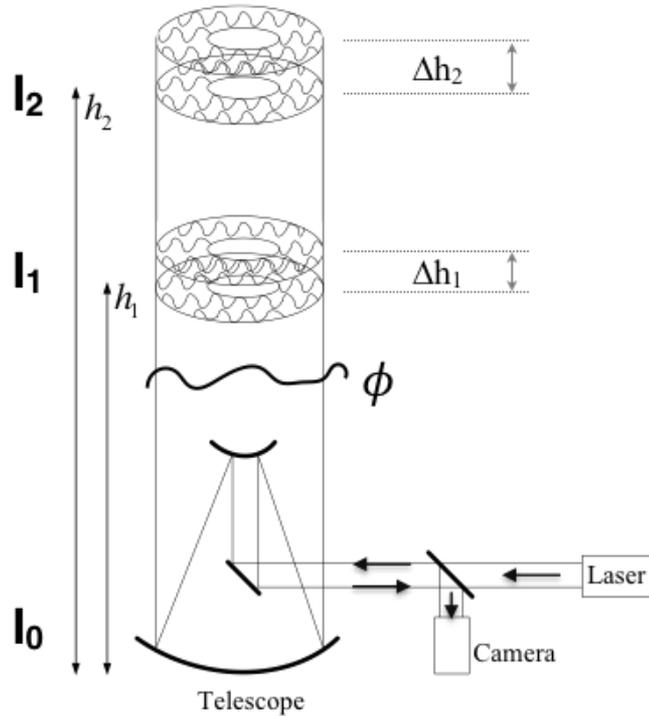
Outline

1. Alternative laser-based wavefront sensing, our technique
2. The PPPP bench, our source of experimental data
3. Results from ML, our analysis of the data
4. Next steps, our plans

1. A non-LGS method of wavefront sensing:

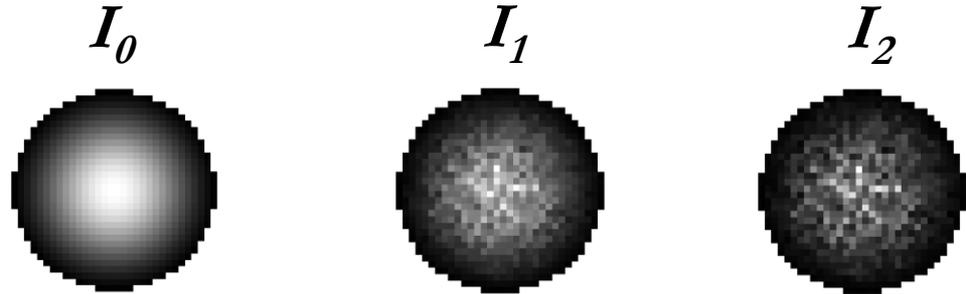


Mathematical model

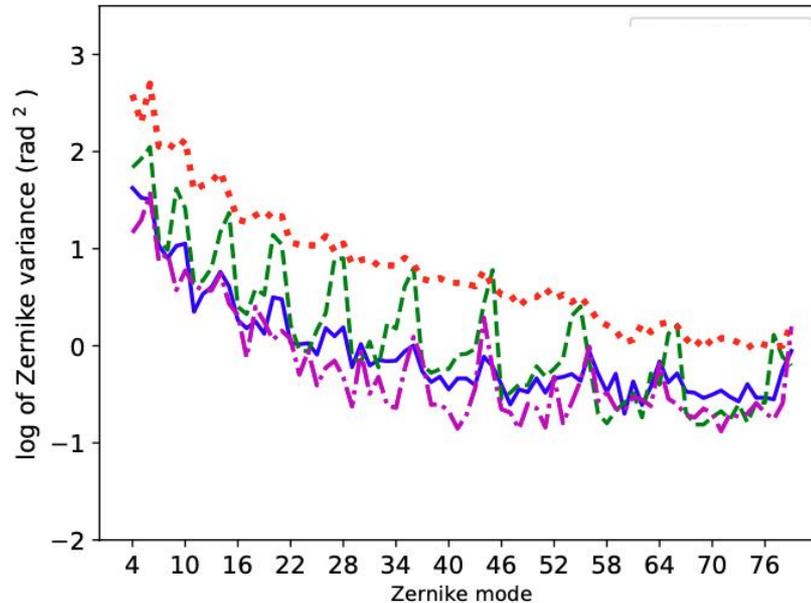
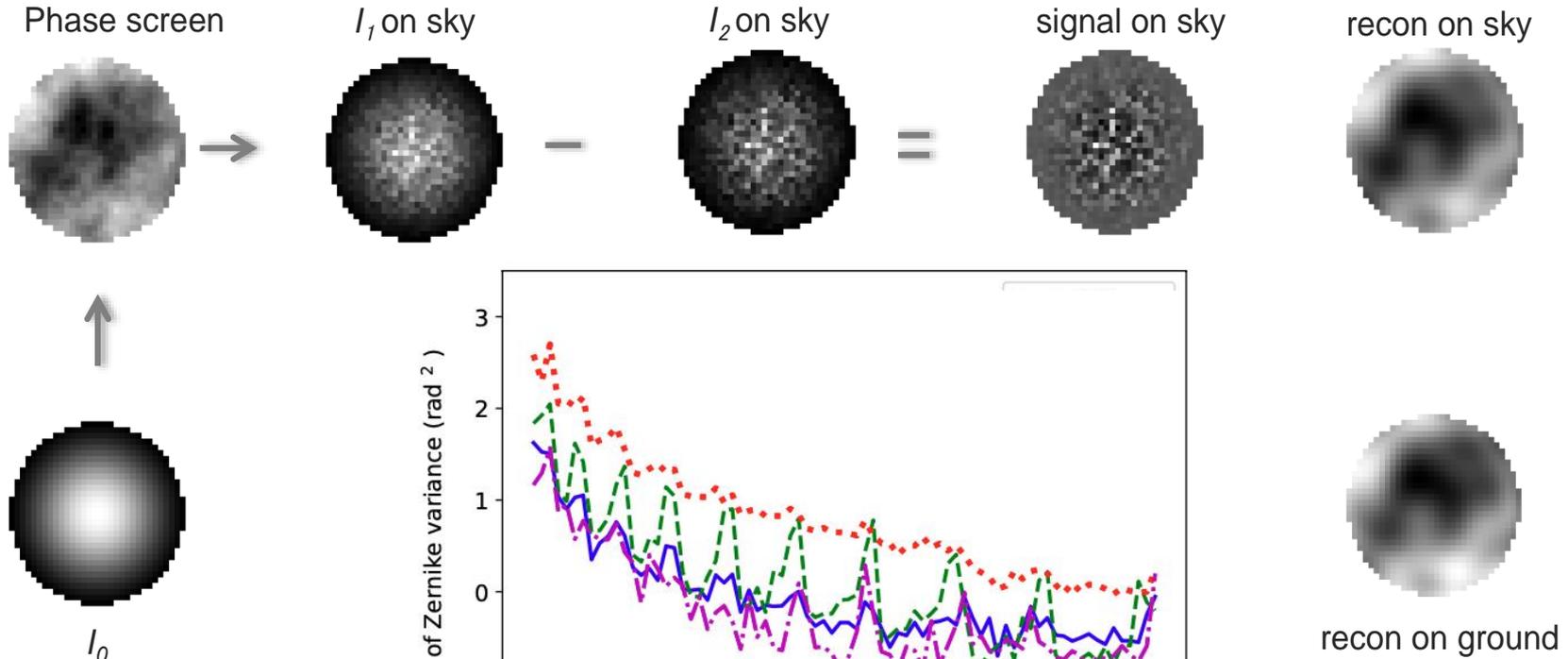


Transport of Intensity Equation (TIE),

$$k \partial_z I = k \frac{I_2 - I_1}{h_2 - h_1} = -\nabla I_0 \nabla \phi - I_0 \nabla^2 \phi$$



Example of simulation, low-resolution



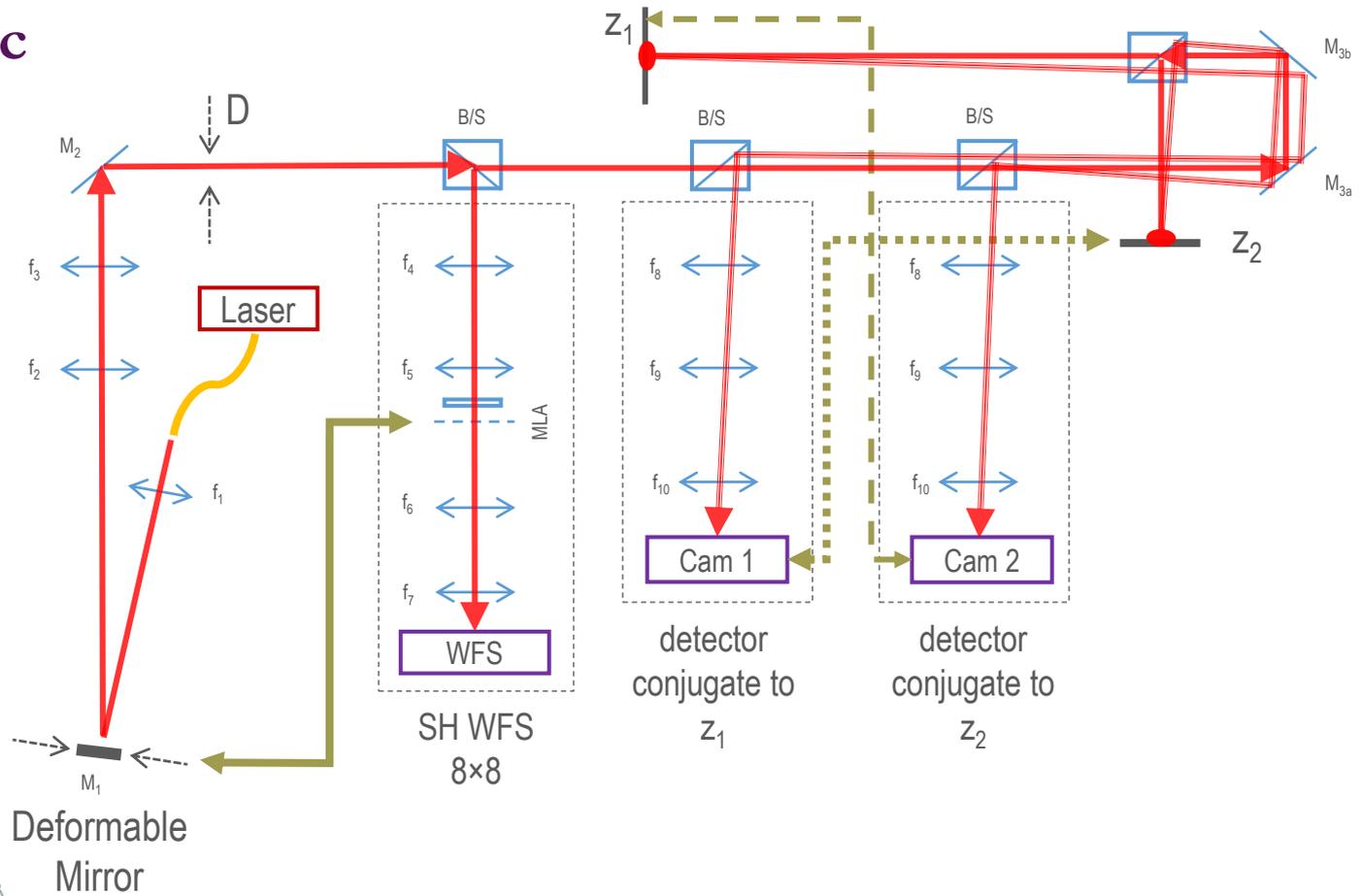
Simulation approach

1. Upward propagation → realistic → ✓
 - Fresnel diffraction, angular spectrum propagator + arbitrary height turbulent layers
 2. Downwards propagation → easy-to-implement assumption → ⊖
 - Simplify the situation by assuming,
$$I_{\text{seen}} \approx I(z) * \langle \text{kernel}(\theta) \rangle$$
 3. Reconstruction → realistic for a filled circular pupil → ☢
 - Modal, using Zernikes
- **Desire to improve fidelity via experimentation**
 - Include error sources, misalignments, and non-simulated effects

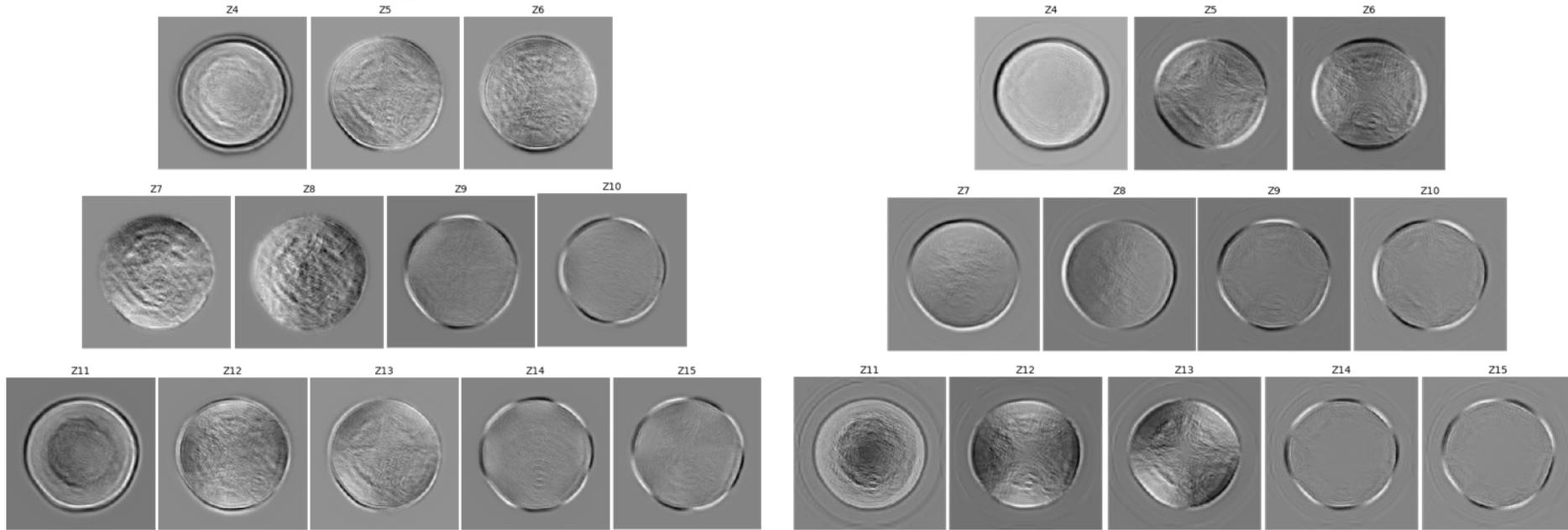
2. The PPPP bench



Schematic

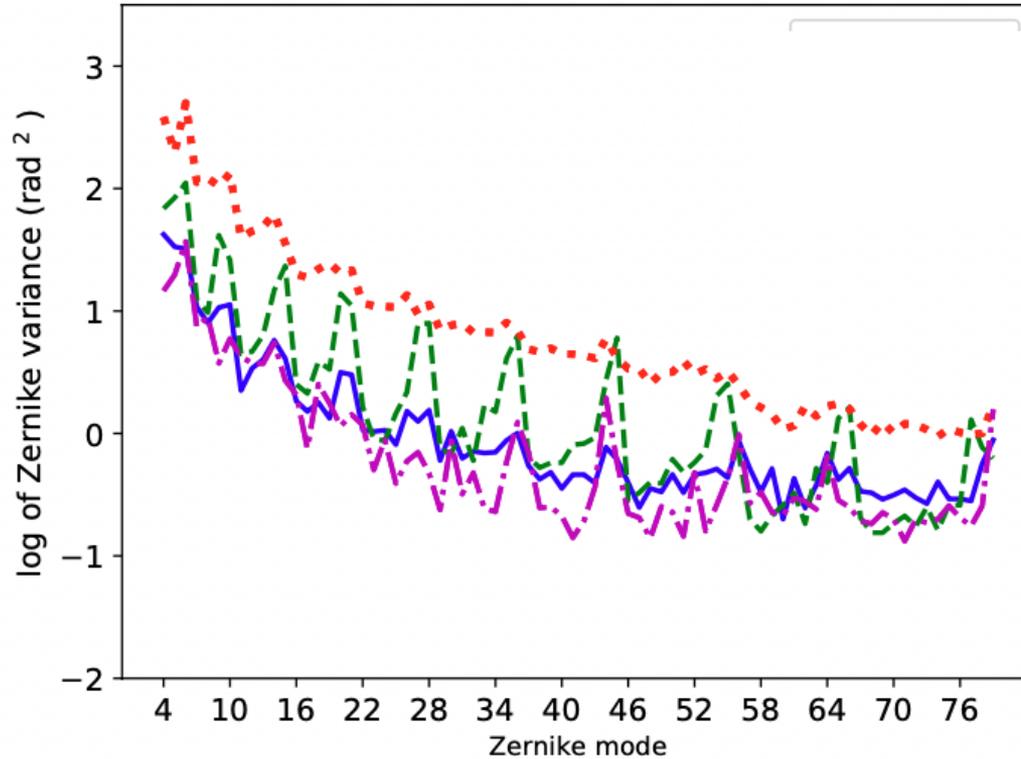


Modal DM response



- Choice to use:
 - measured IM and its inverse
 - forward model
- Both work well → **linear algebra**

Neural networks for higher SNR



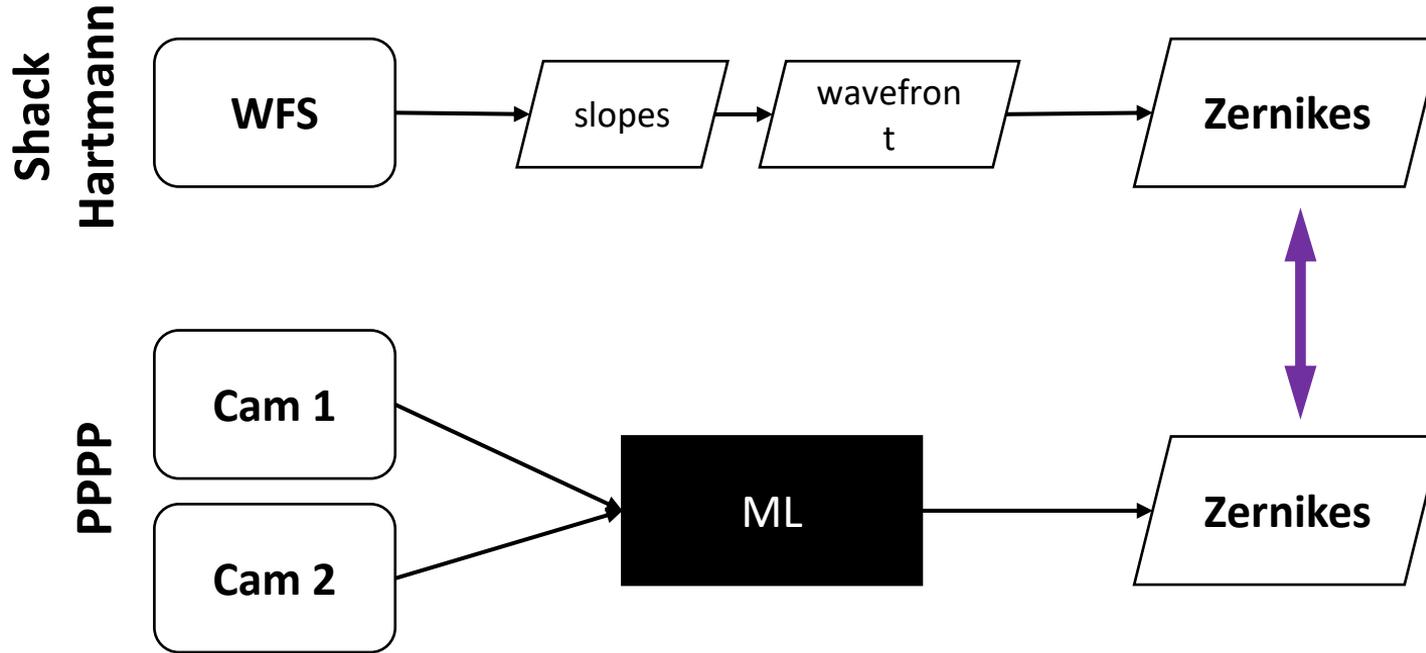
3. Neural Network architecture for Machine Learning

- Already demonstrated *in simulation* that a neural network architecture is superior to the linear solution,
 - (Except for unrealistic laser powers.)
- Can use existing image-based processing
- Wanted to confirm that NN-based ML algorithm works with hardware.

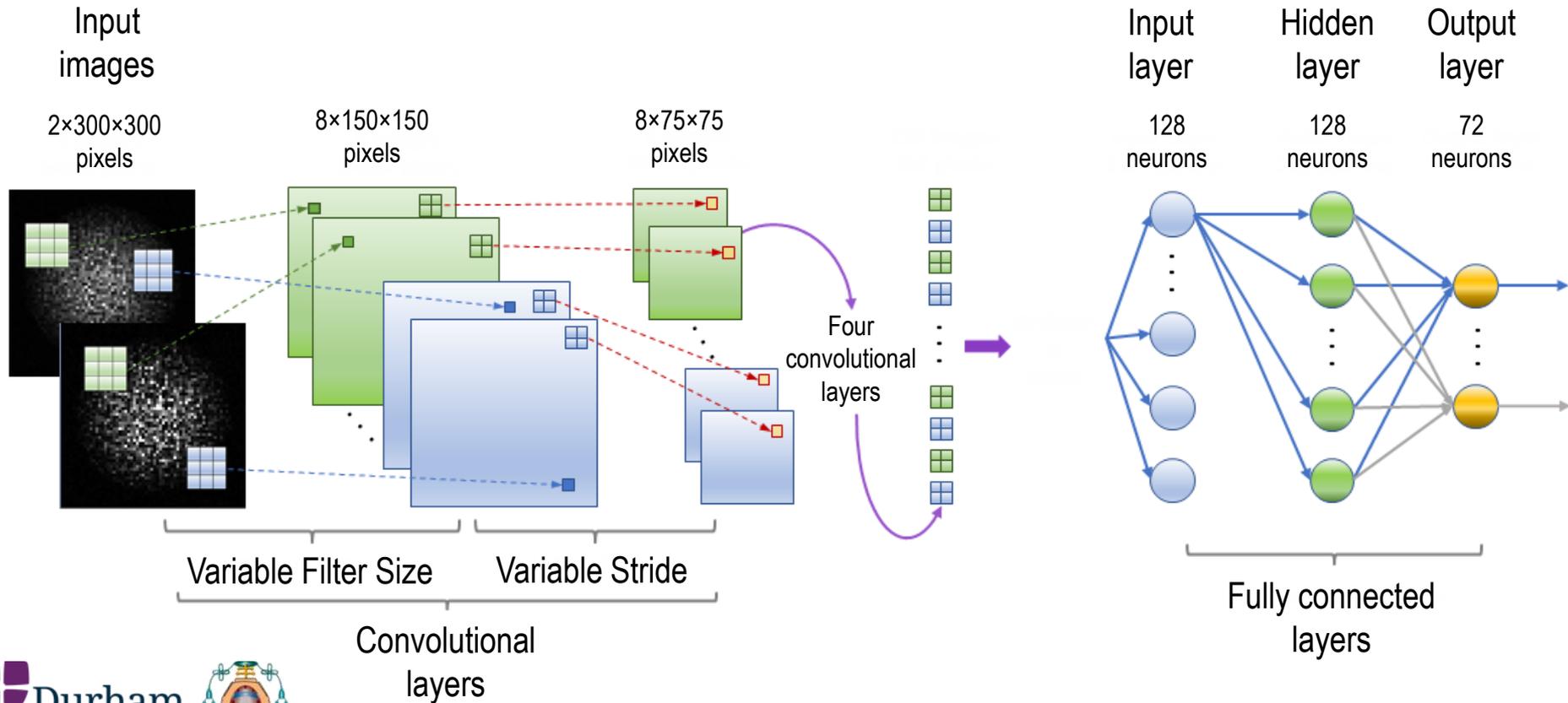
Limitations

1. Only one source of aberrations, low-order modal DM
2. Fixed propagation distances & zero turbulence altitude
3. Slow to operate, and need ca. 10^5 frames
4. Ignoring return propagation aberrations

Comparison of data inputs and outputs



Neural Network architecture



Results

Images subset		Output residual relative WFE			
Training	Testing	Two images	One image, closer	One image + WFE back propagation	Difference of images
Complete	Complete ≡ training	32.8%	30.0%	12.4%	14.6%
Random	Random ∉ training			12.4%	
<i>Estimated noise component</i>				14.1%	

4. Future experiments with *WIVERN*

- The PPPP bench reached its natural lifetime and has been dismantled
- Future experiments will use *WIVERN*, a novel concepts experiment[†] which has:
 - 1 arcminute FoV,
 - Laser projection through turbulence (two way) as far as $\lesssim 100\text{km}$,
 - Phase screens between surface and 20km,
 - Built-in DM—AO experiments such as pre-compensation, and
 - Well-defined software-based RTC.

[†] emulating a 4m telescope

Future goals

- I. Recreate PPPP for investigating tomographic sensing.
 - Currently at design stage for *WIVERN*.

- II. Determine performance limits with ML wavefront retrieval.
 - Enabled by faster ($\times 100$) and more accurate data from *WIVERN*.

- III. Integrate tip/tilt sensing (or not).