N_2O $NCPA$ *
A new low order Wavefront Sensor and its first experimental results.

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Dr. T. Heritier
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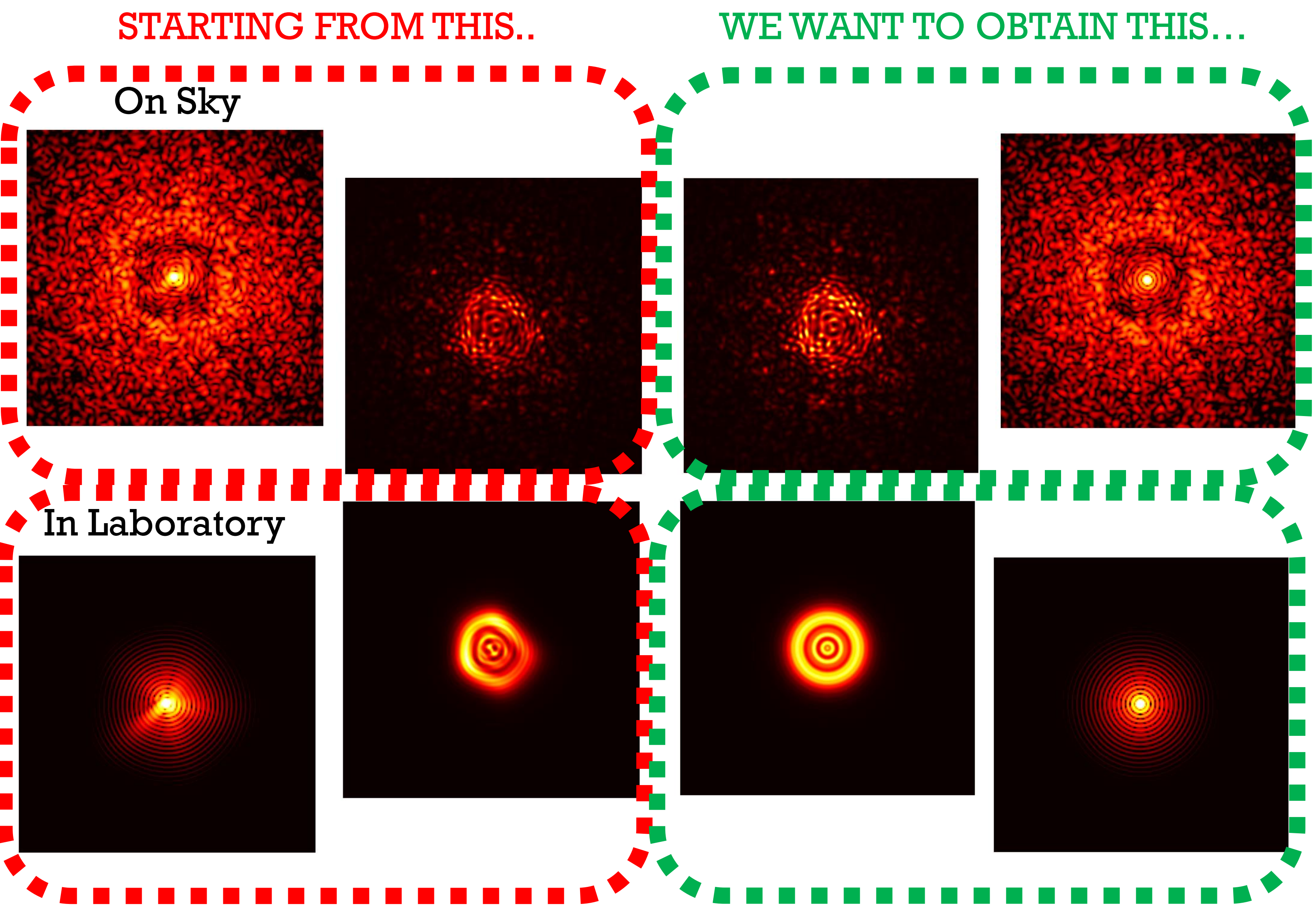
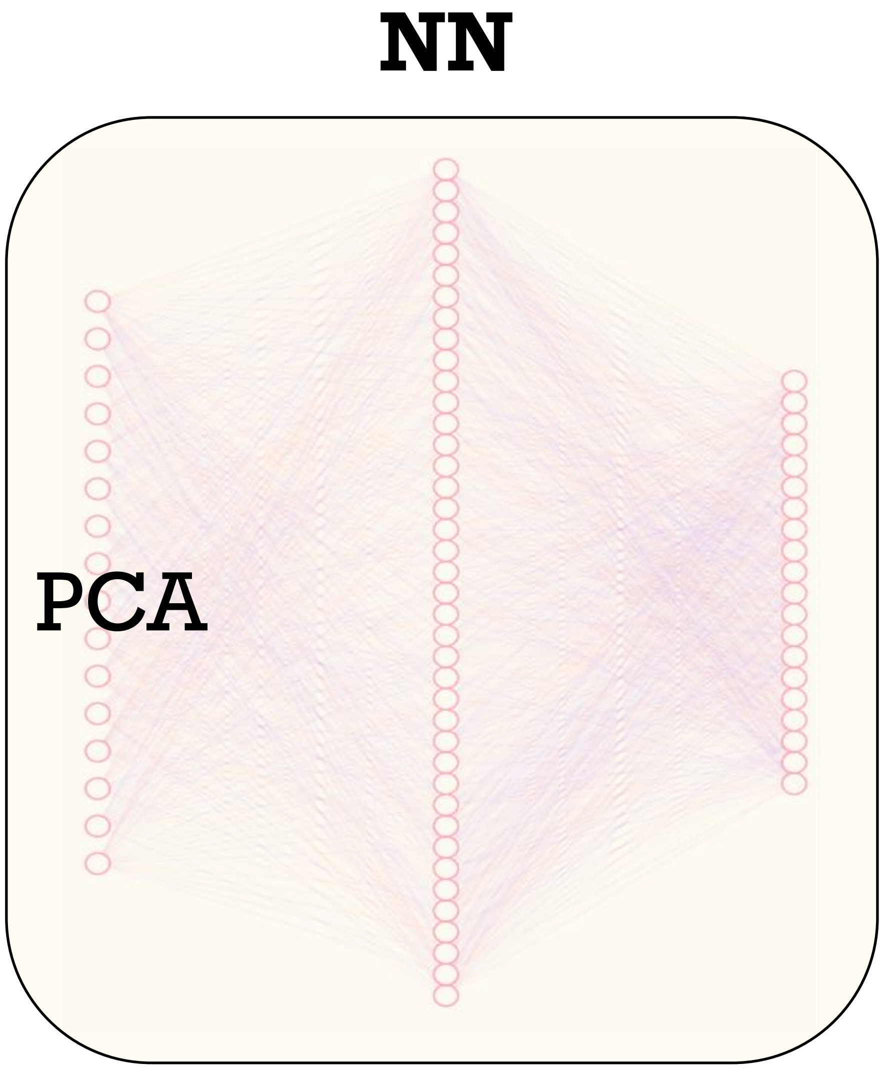
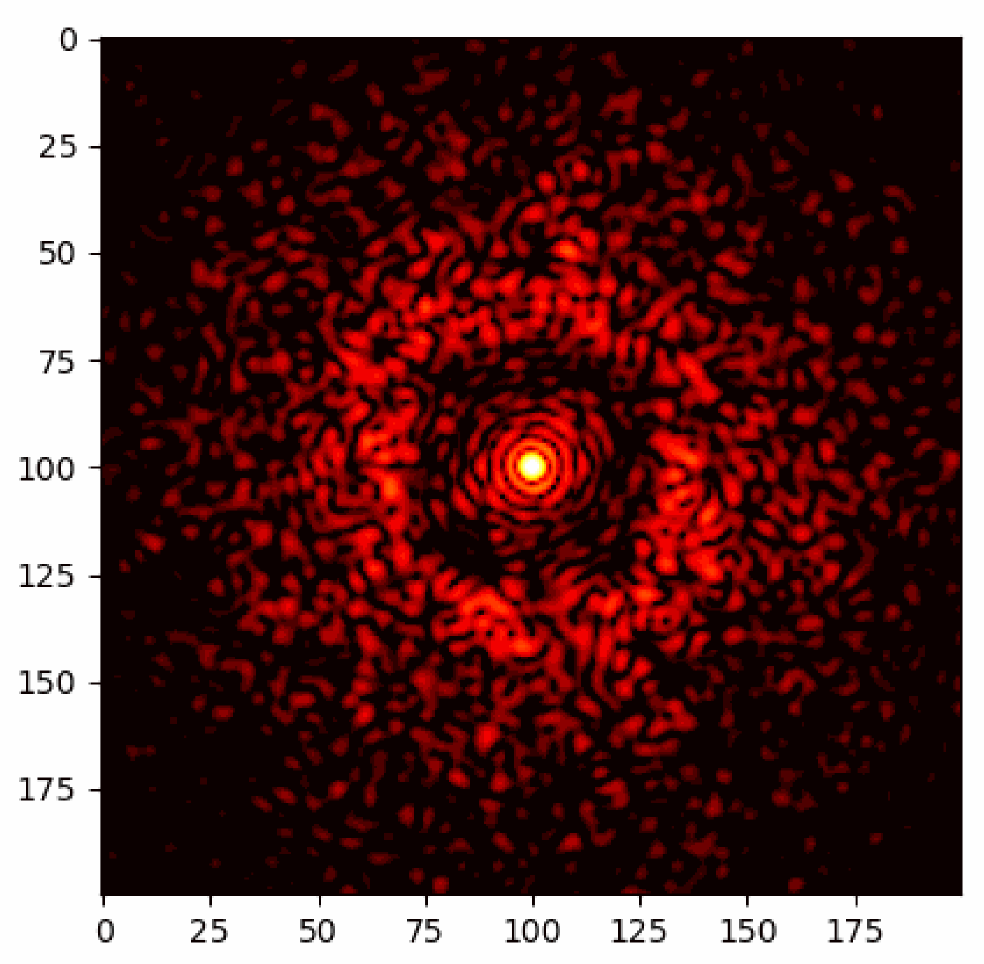
Short Summary

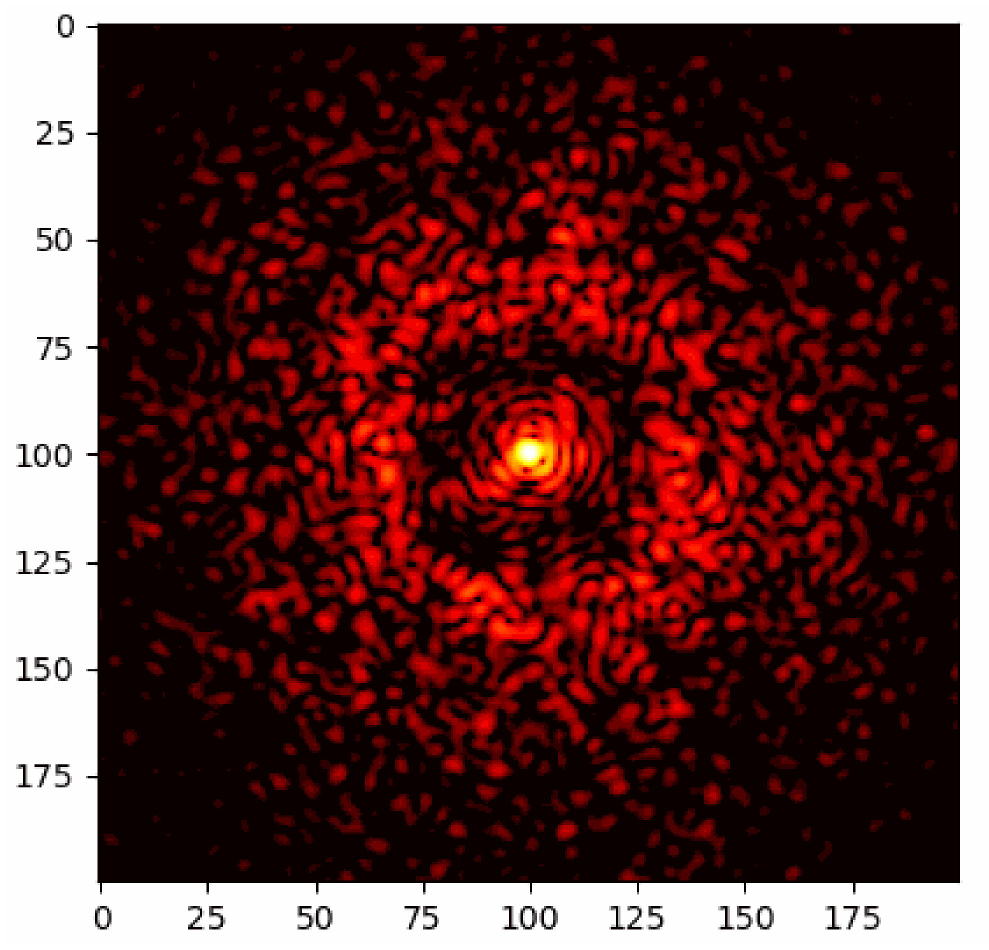




Use of extrafocal images

AO residual and NCPA





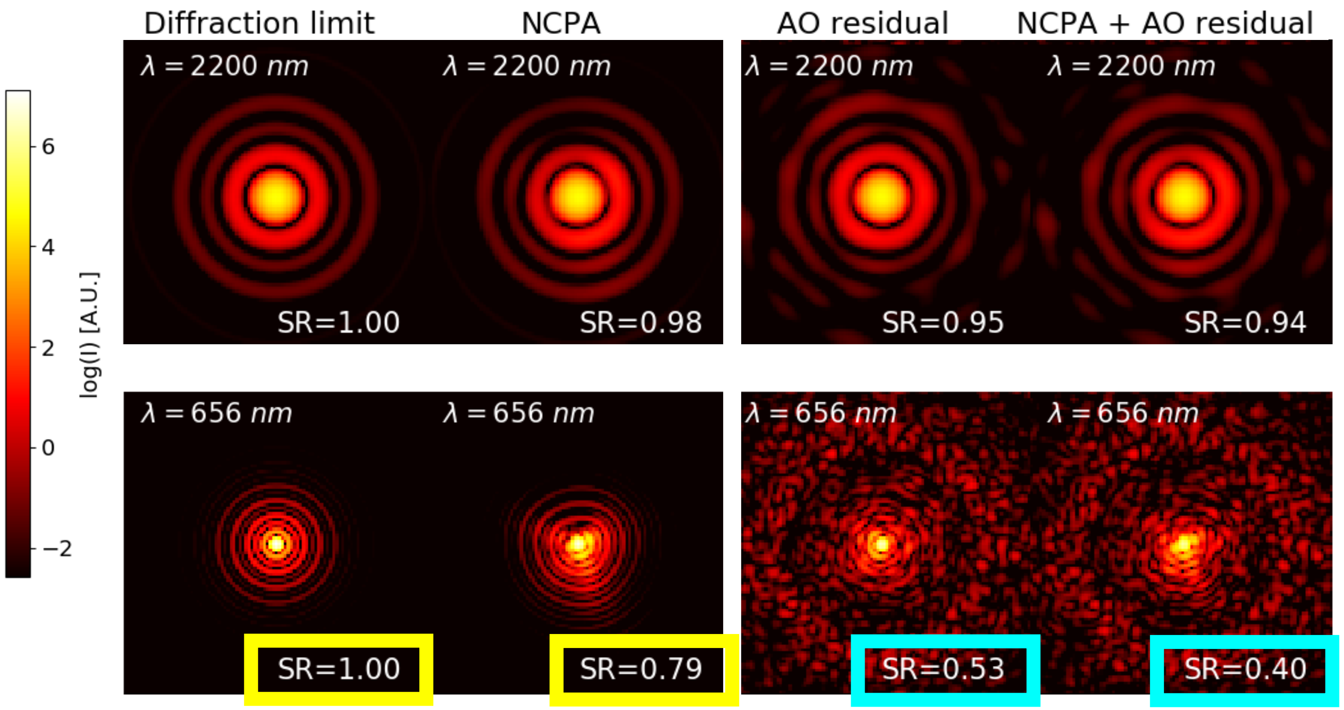
Simulated using the ESO library PO4AO by T.C.Heritier 2020

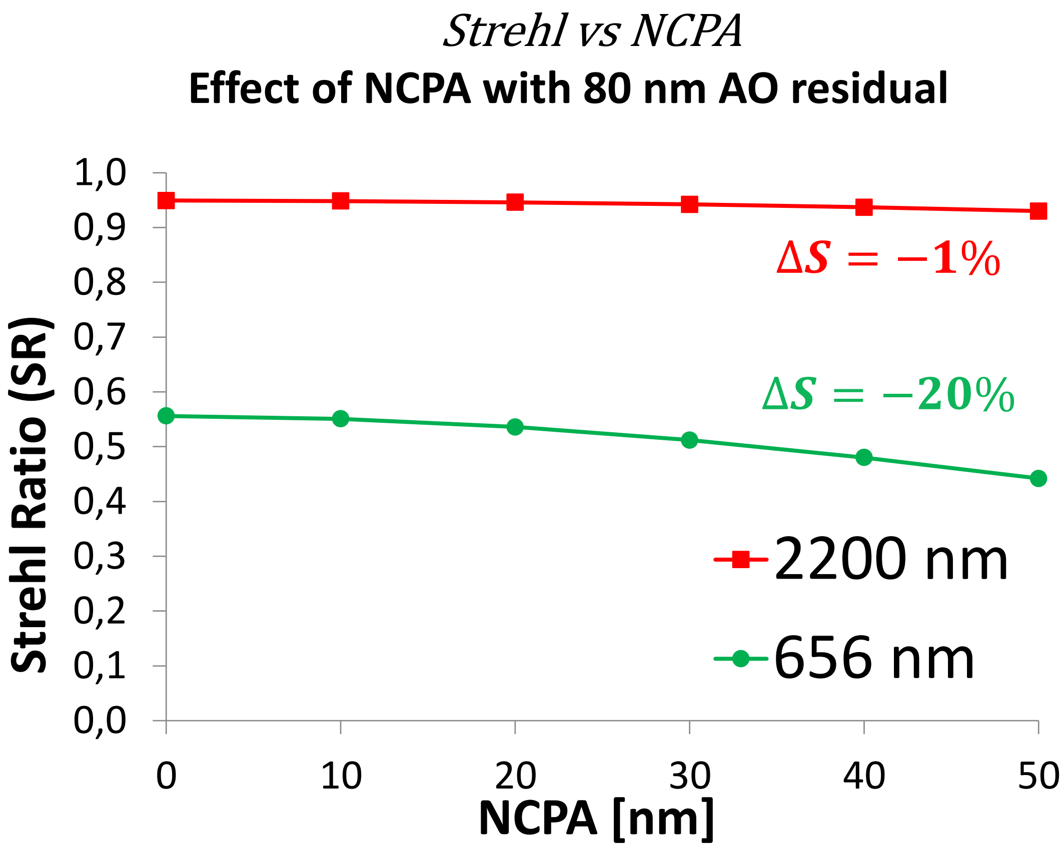
NCPA is critical in the visible $\lambda < 1\ \mu m$

TYPICAL BEST SCENARIO @LBT $AO\ residual \approx \mathbf{80}\ nm\ RMS$

Example: $NCPA \approx \mathbf{50}\ nm\ RMS$

||-------No AO residual-----||-----With AO residual-----||





Optical Propagation Simulations

Equivalent system with just 3 features needed: $\begin{cases} F_{\#} \\ \lambda \\ pixsize \end{cases}$

$E(x, y, 0) = A(x, y)e^{\phi(x,y)}$

$E(x', y', z') = FT\{E(x, y, 0)\}$

$E(x'', y'', z'') = FT\{E(x, y, 0)\} * \exp(-iz'')$

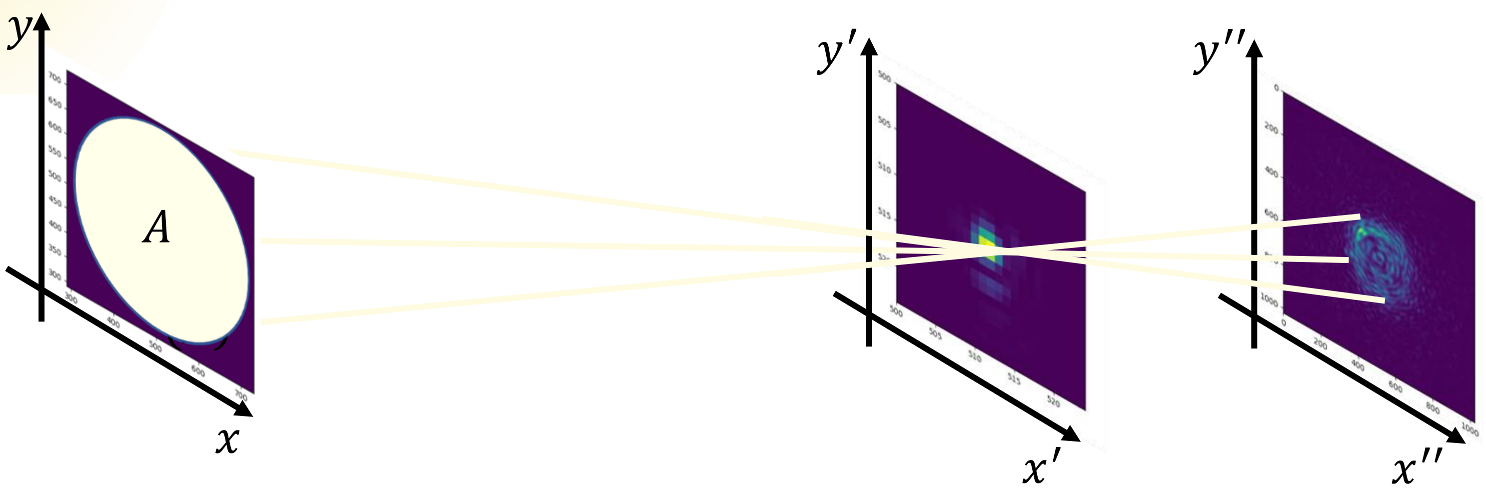
STOP

PUPIL PLANE

FOCAL PLANE

EXTRAFOCAL PLANE

PUPIL PLANE

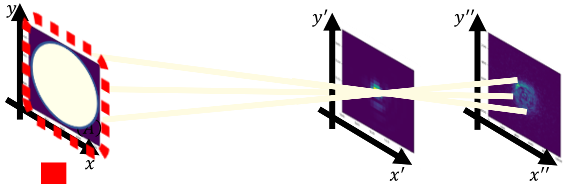


$\boldsymbol{E(x, y, z)}$ CAN'T BE MEASURED….

…We measure the POINT SPREAD FUNCTION

$PSF = I(x^j, y^j) = |E(x^j, y^j, z^j)|^2$

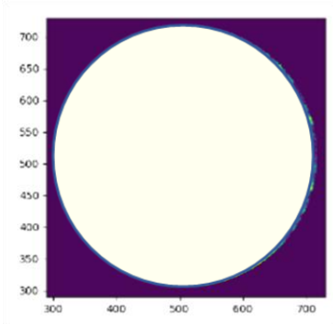
Phase: Zernike Polynomials or phase screen

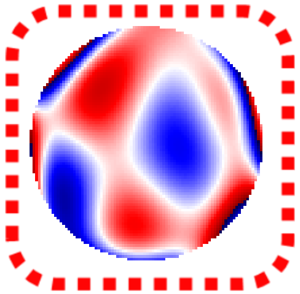


$$E(x, y, 0) = A \exp(i\phi)$$

Amplitude (A)

Phase (ϕ)

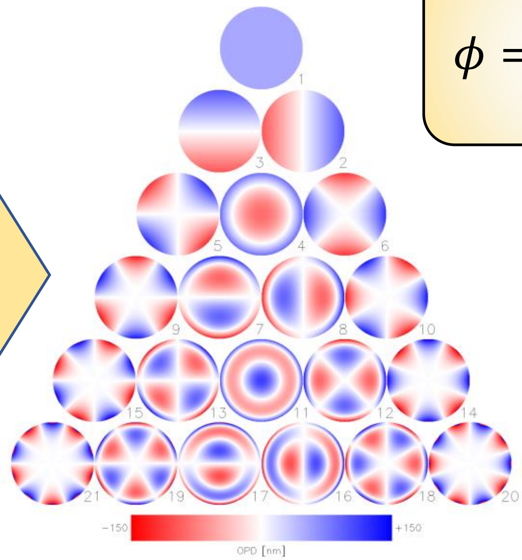




Constant

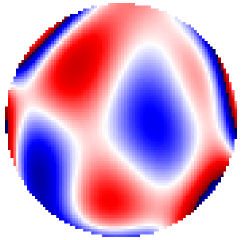
Variable

Zernike polynomials surfaces



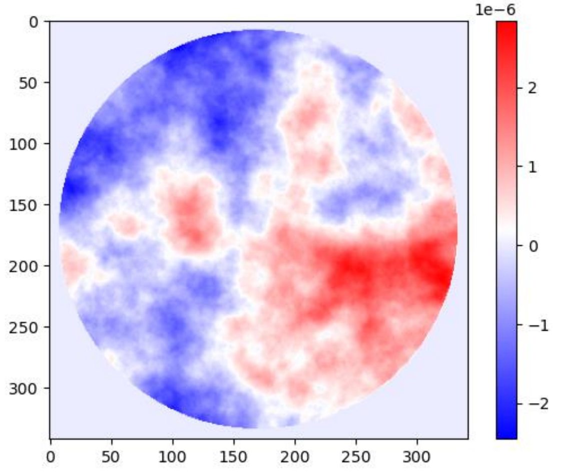
$$\phi = \sum_{i=1}^{\infty} c_i Z_i$$

$$\phi = \sum_{i=1}^{21} c_i Z_i$$

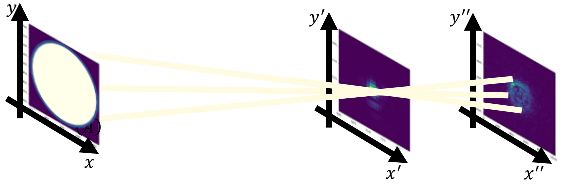


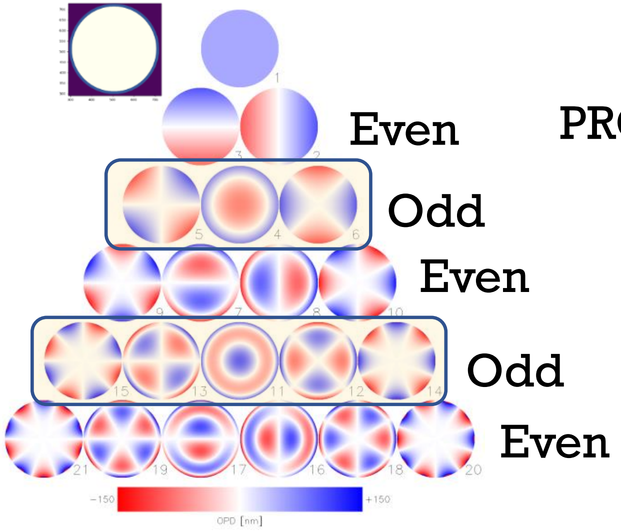
NCPA is encoded in the first Zernikes

Phase Screen to simulate Turbulence or AO residual

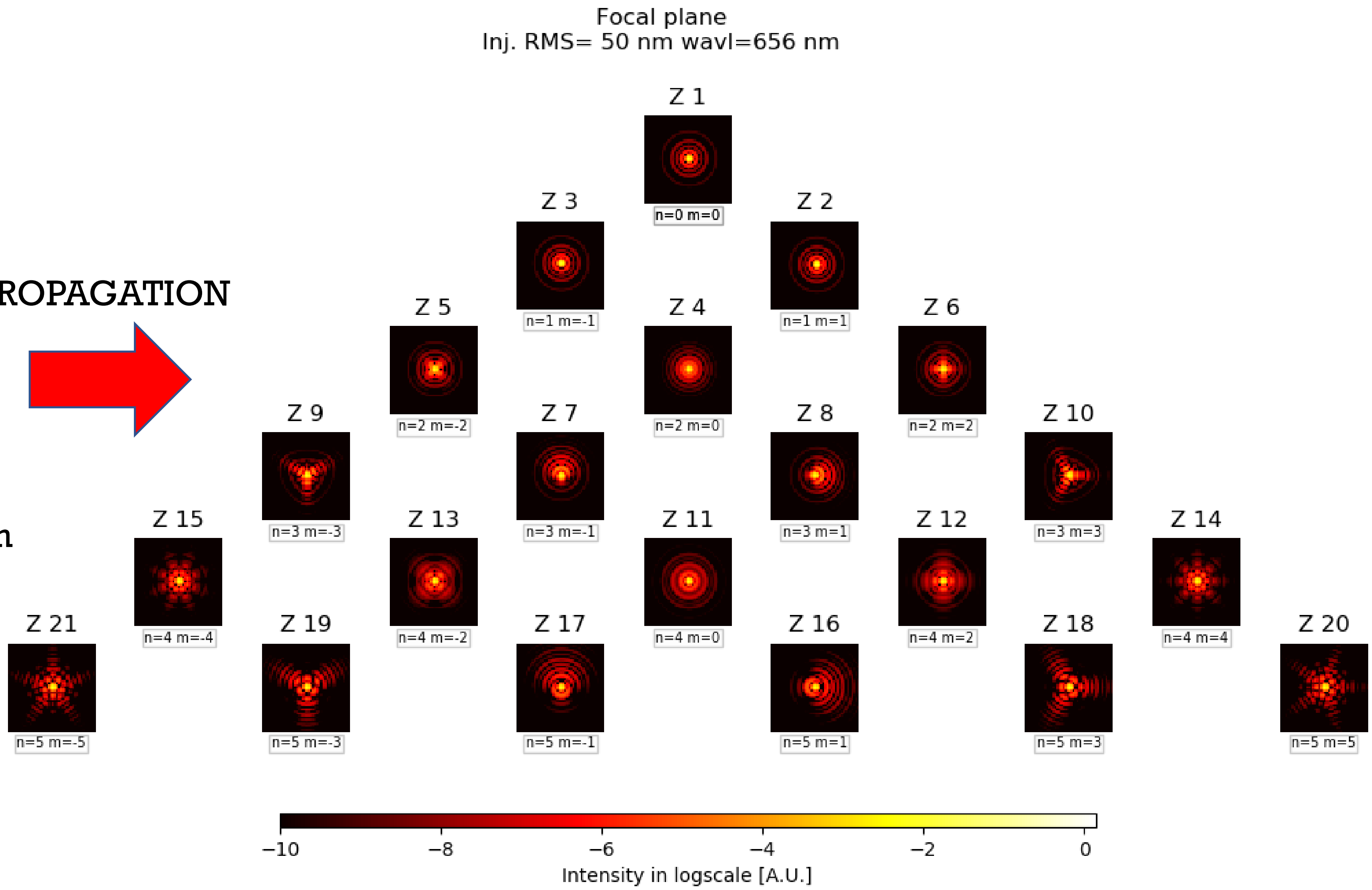


Can we use focal plane images to recognize aberrations?

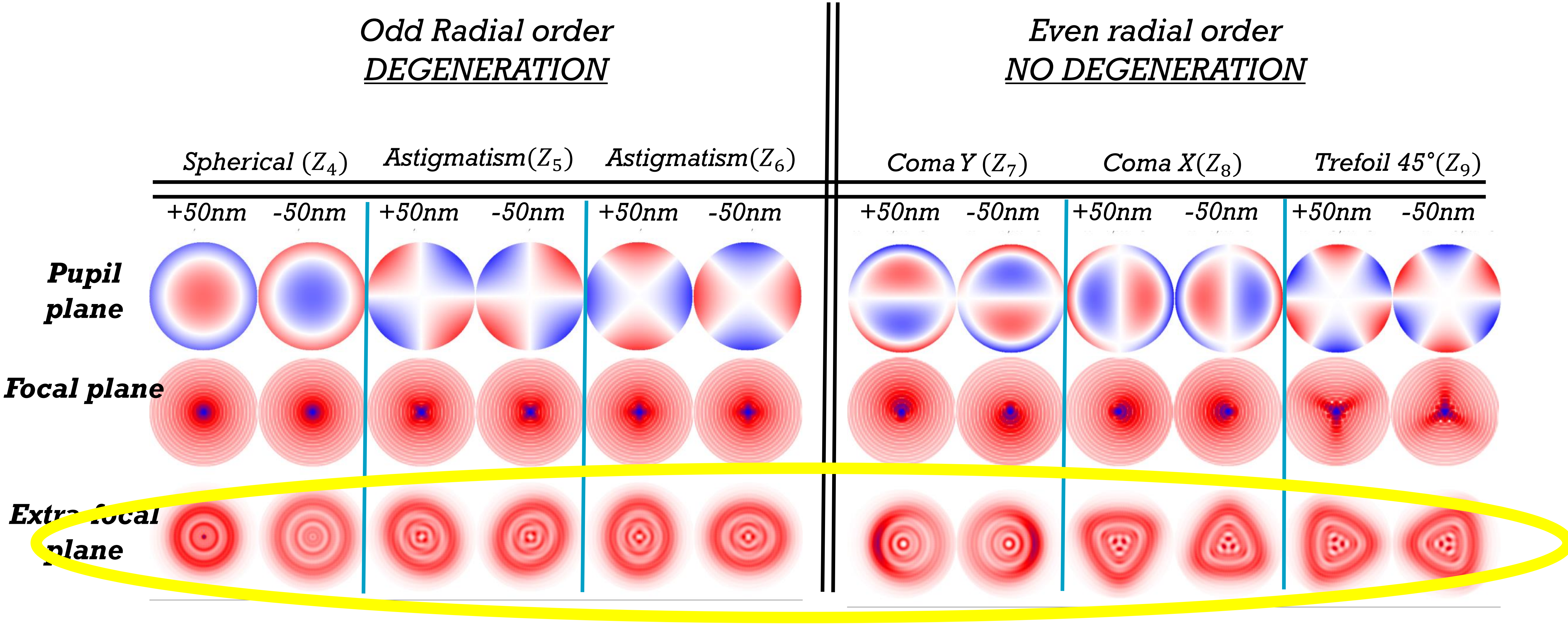




PROPAGATION



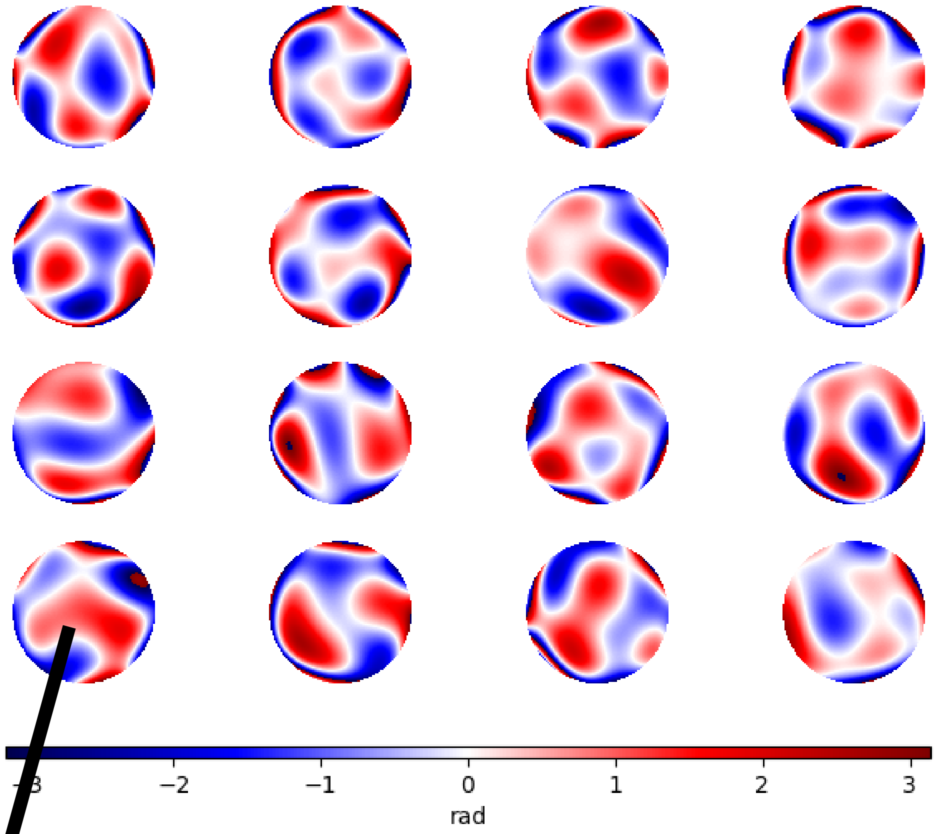
Degeneration or non degeneration? That's the problem



Simulated dataset (10 000 images)

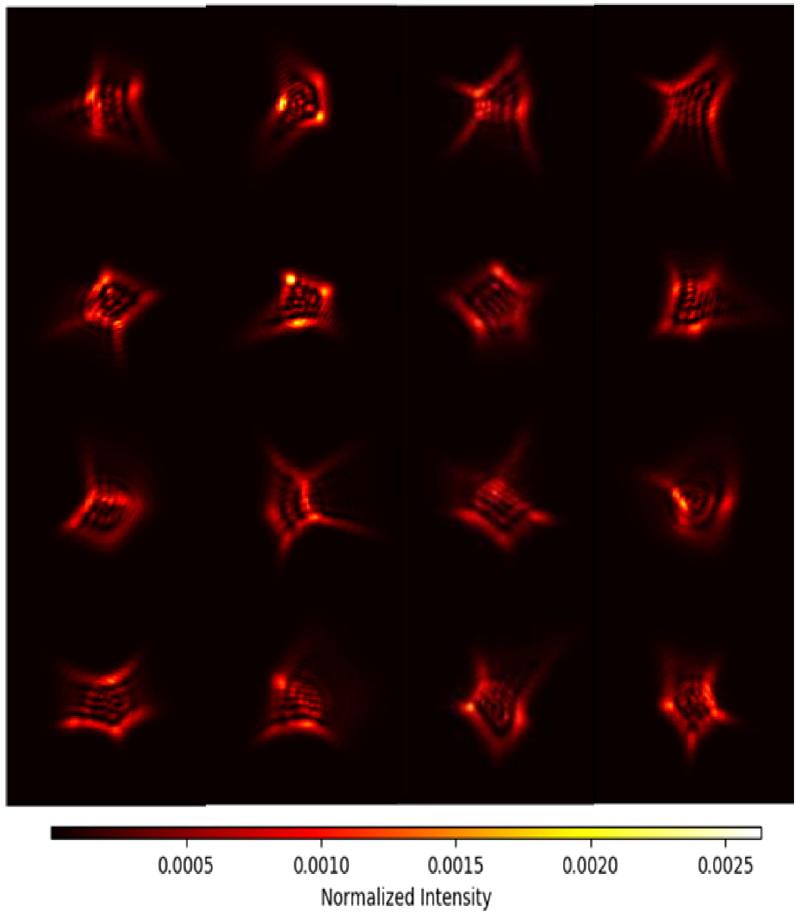
Simulations of 10000 Extrafocal plane images starting from the injection of different combination of 21 Zernike with $\pm 50\ nm$ UNIFORMLY RANDOM DISTRIBUTED

PUPIL PLANE→**PHASE**



Propagation

EXTRA-FOCAL PLANE→ **INTENSITY**

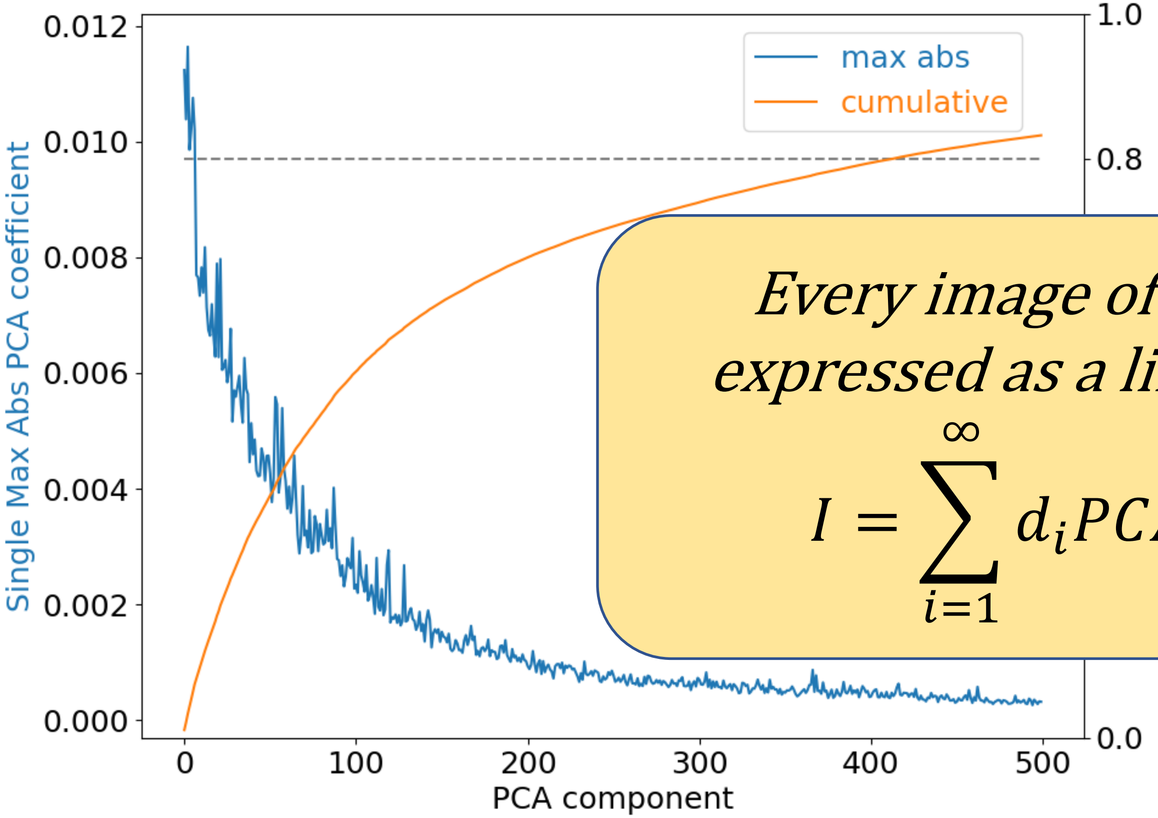


Each one is a linear combination: $\phi = NCPA = \sum_{i=1}^{21} c_i Z_i$

DEFOCUS = 10 mm

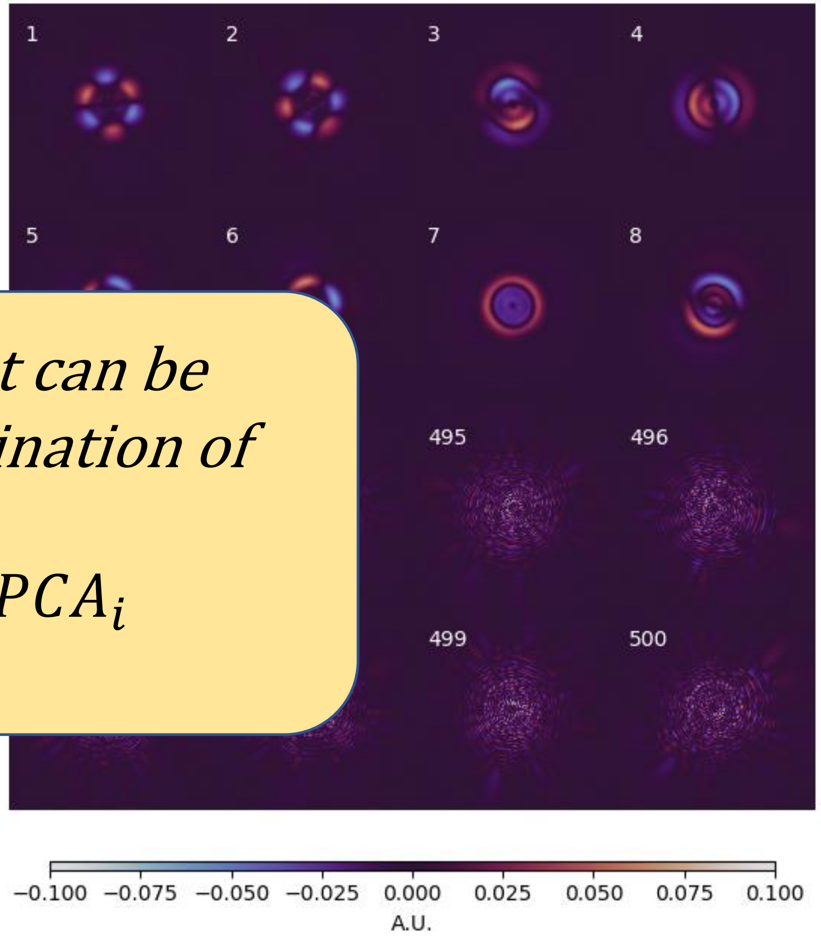
Principal Component Analysis (PCA)

- Returns basis of eigenimages that comes from the diagonalization of the covariance matrix for the defocused images dataset
- <u>Thousands of pixels</u> are now substituted with <u>few hundreds coefficients</u>
- Images can be projected on this basis



Every image of the dataset can be expressed as a linear combination of

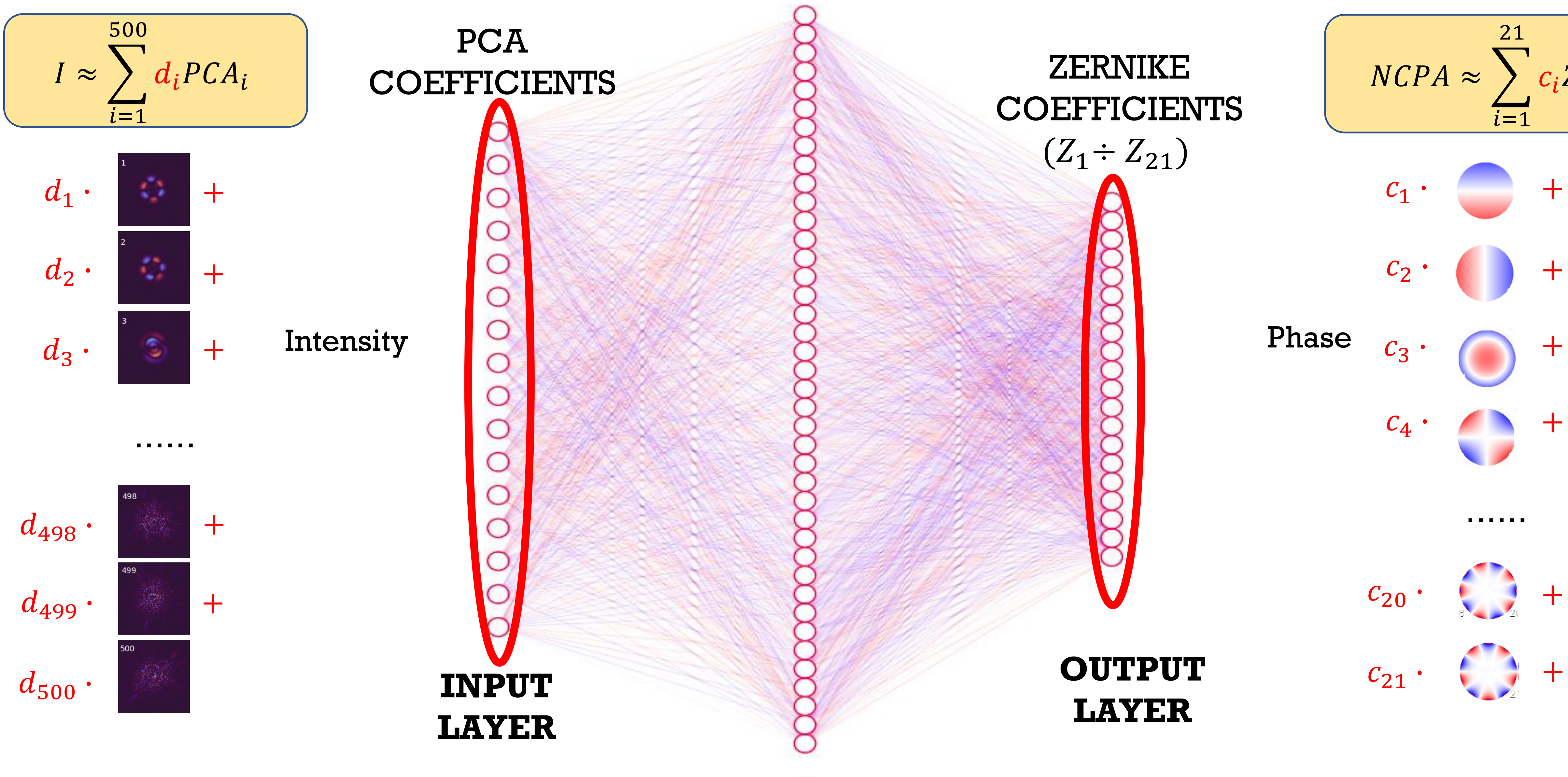
$$I = \sum_{i=1}^{\infty} d_i PCA_i \approx \sum_{i=1}^{500} d_i PCA_i$$



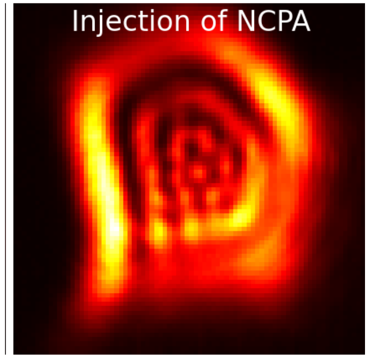
Neural Network

$$I \approx \sum_{i=1}^{500} d_i PCA_i$$

$$NCPA \approx \sum_{i=1}^{21} c_i Z_i$$



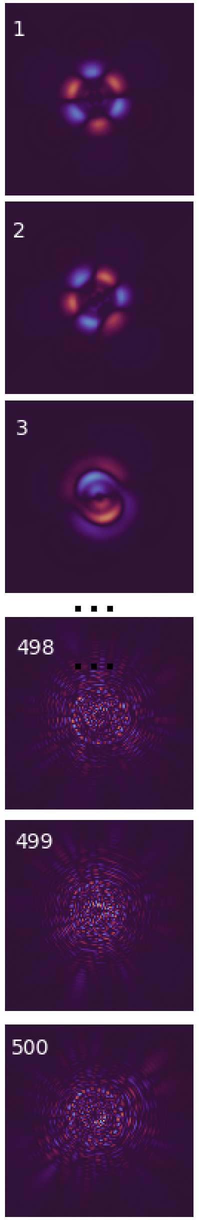
NN usage on 1 image



SIMULATED

OR

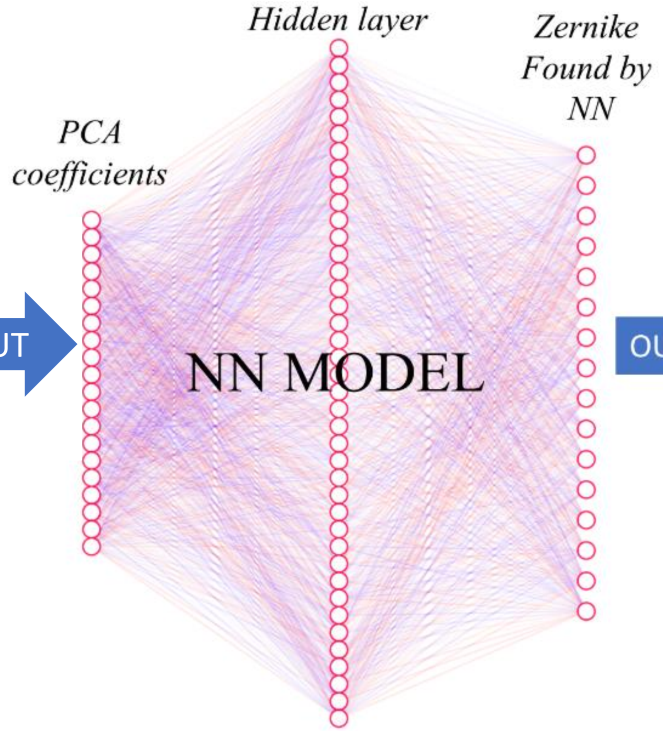
EXPERIMENTAL



PROJECTION

d_1
d_2
d_3
...
d_{498}
d_{499}
d_{500}

INPUT



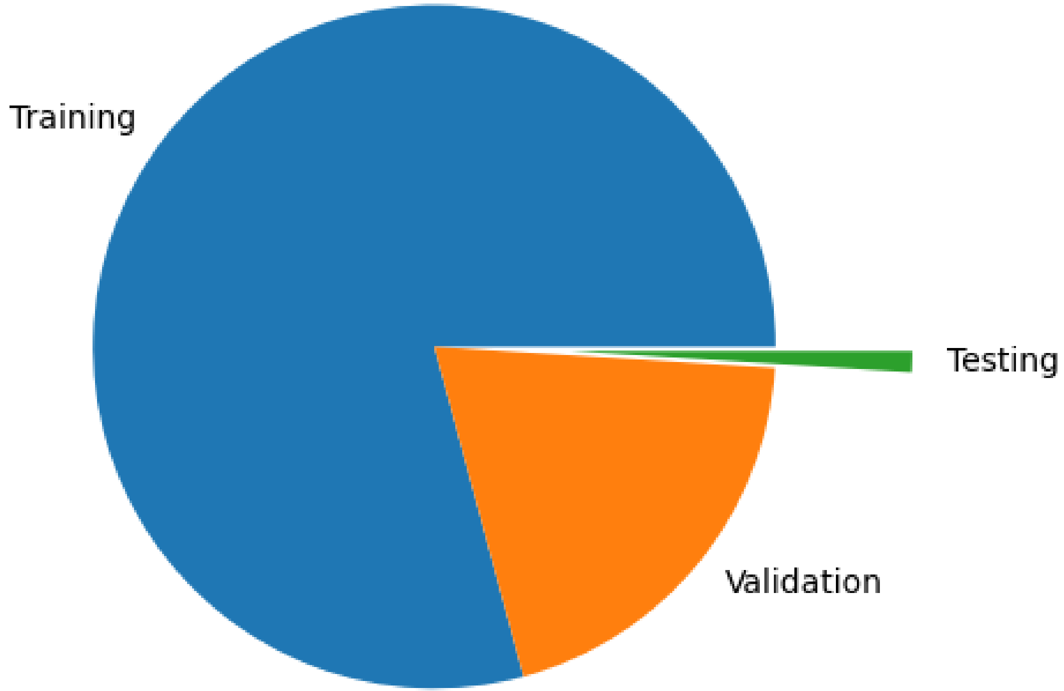
OUTPUT

c_1
c_2
c_3
c_4
c_5
c_6
c_7
c_8
c_9
c_{10}
c_{11}
c_{12}
c_{13}
c_{14}
c_{15}
c_{16}
c_{17}
c_{18}
c_{19}
c_{20}
c_{21}

Training, Testing and merit figures

Results come from simulated images:

- Train-set **10 000** images
- Test-set **100** images



We need merit factors to evaluate the efficiency of the NN reconstruction:

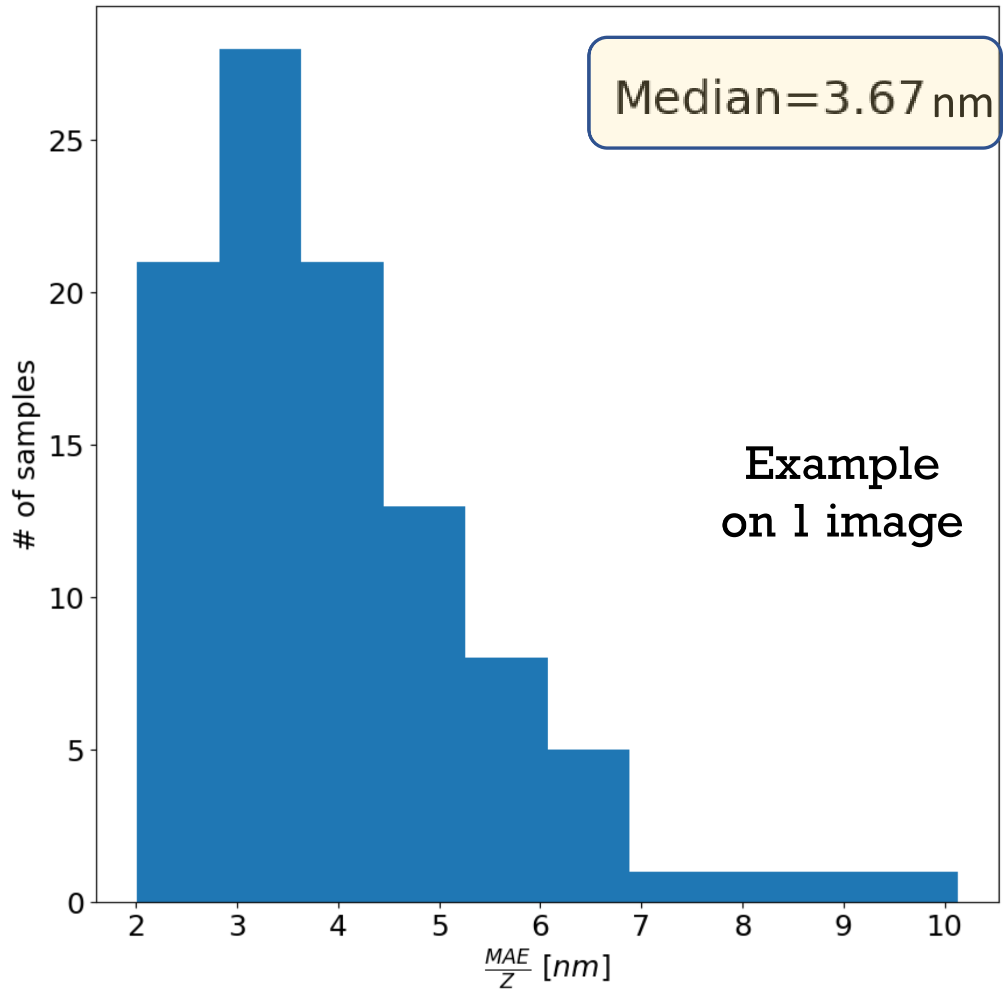
$$PE = \frac{MAE}{Z} = \frac{\sum_{i=1}^{N} \left| Z_{injected,i} - Z_{predicted,i} \right|}{N}$$

$$WFE = \sqrt{(AO_{residual})^2 + \sum_{i=1}^{N} \left(Z_{injected,i} - Z_{predicted,i} \right)^2}$$

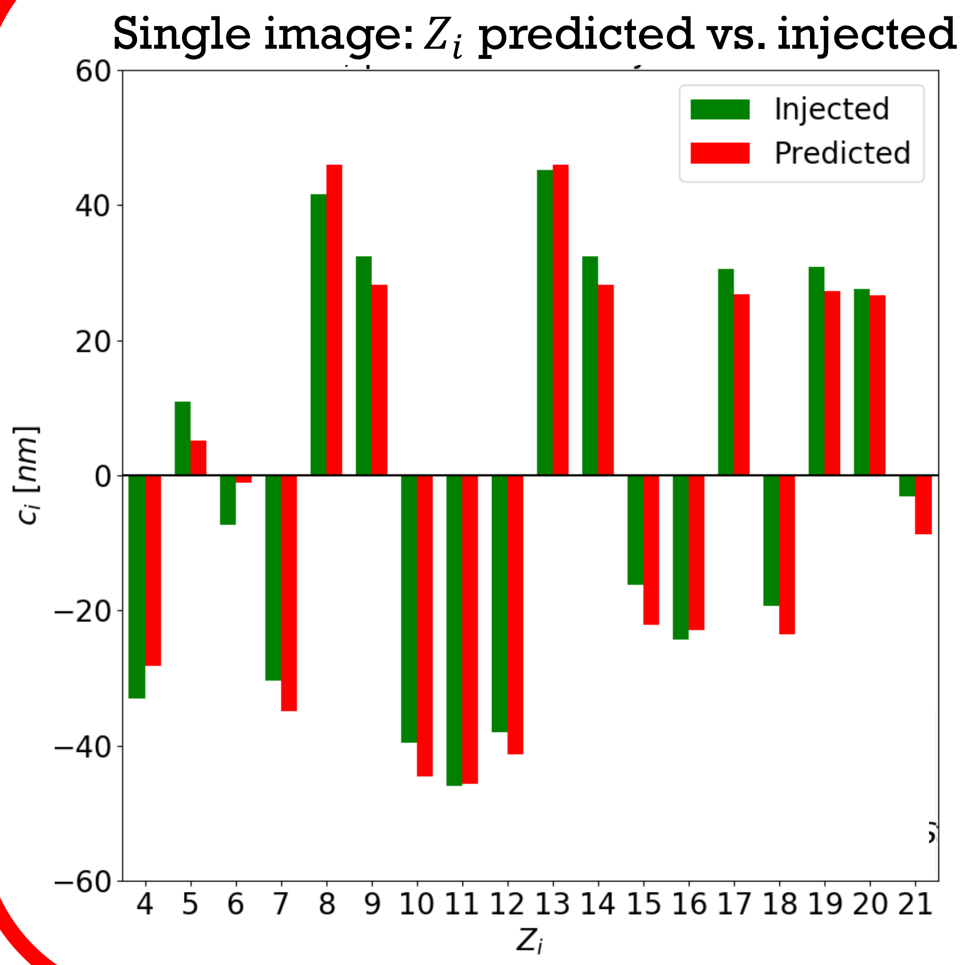
$$SR = \exp\left(- \left(\frac{2\pi * WFE}{\lambda} \right)^2 \right)$$

Ideal case: ONLY NCPA

TESTSET: distribution
of prediction error for 100 images

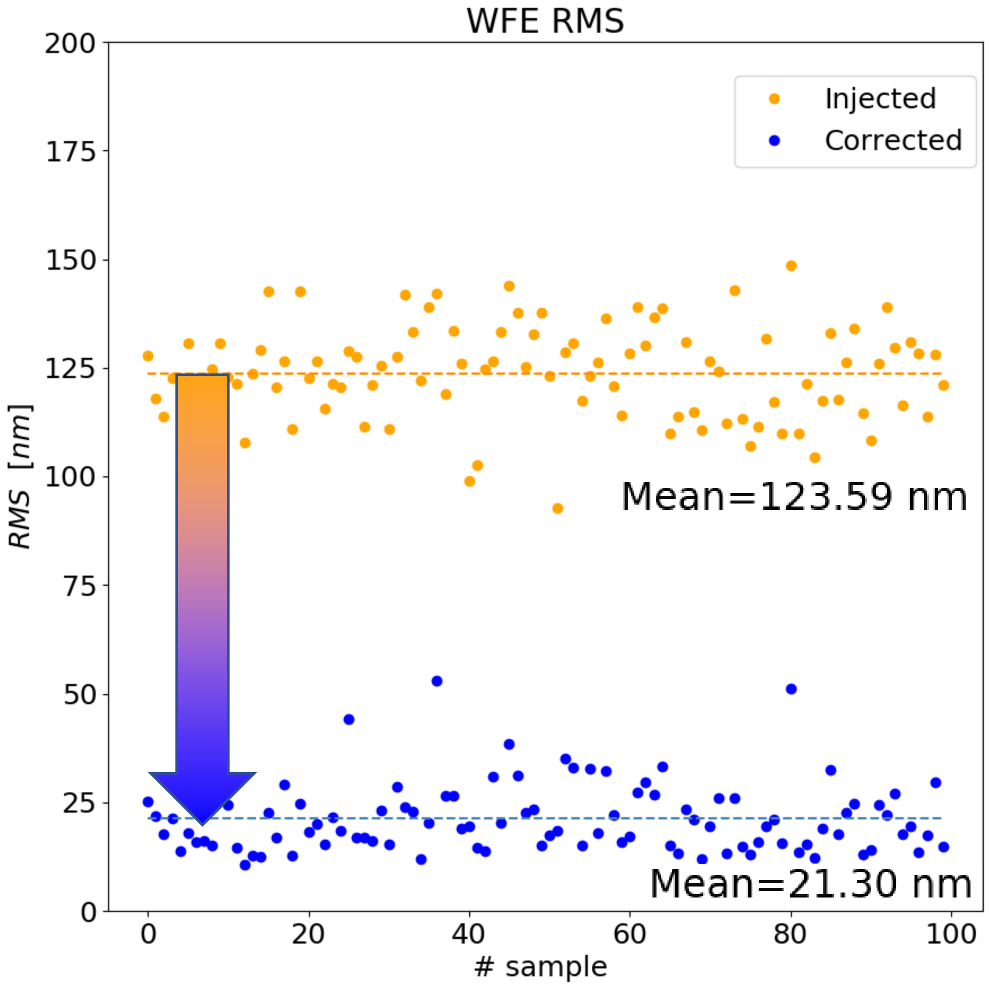


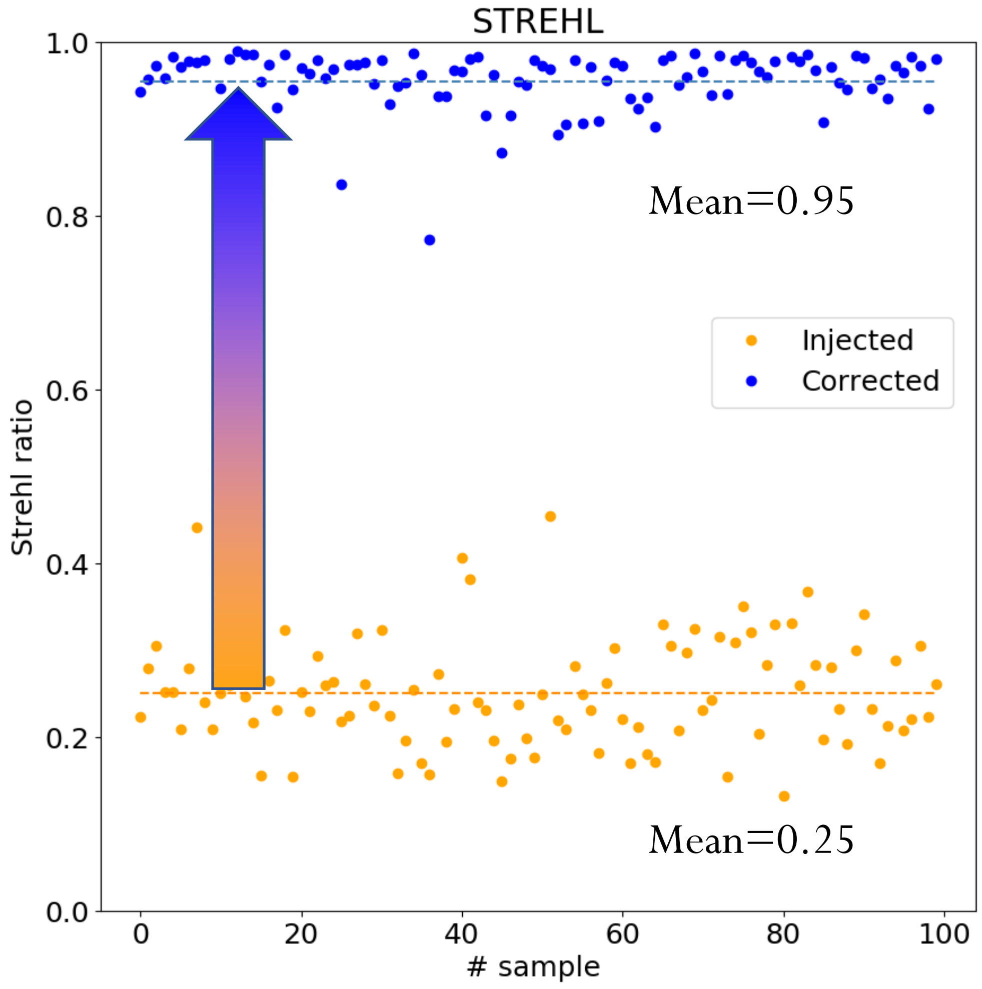
Example
on 1 image



SIMULATIONS

Simulation of correction: from 123 to 21 nm WFE



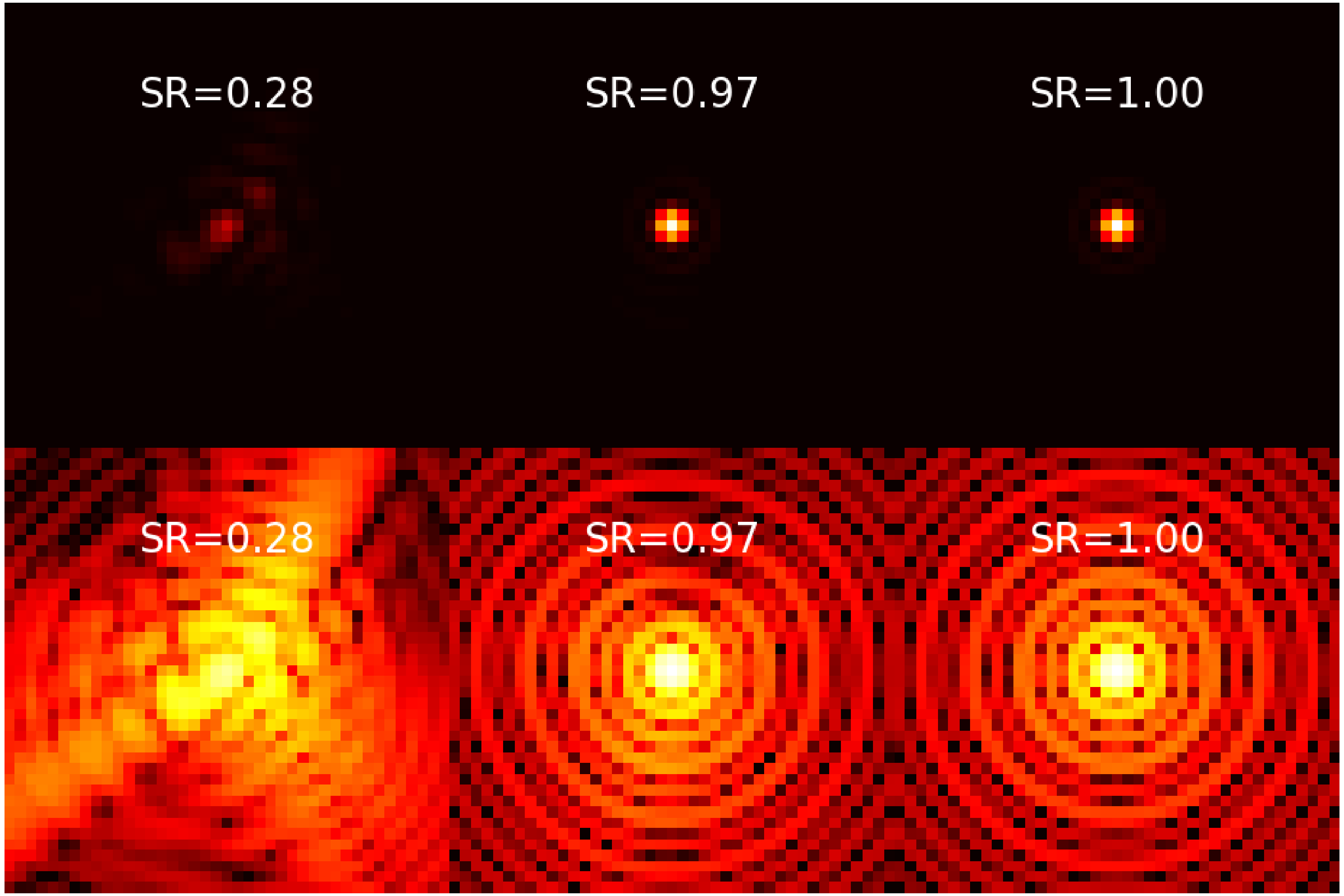


Effects in the focal plane

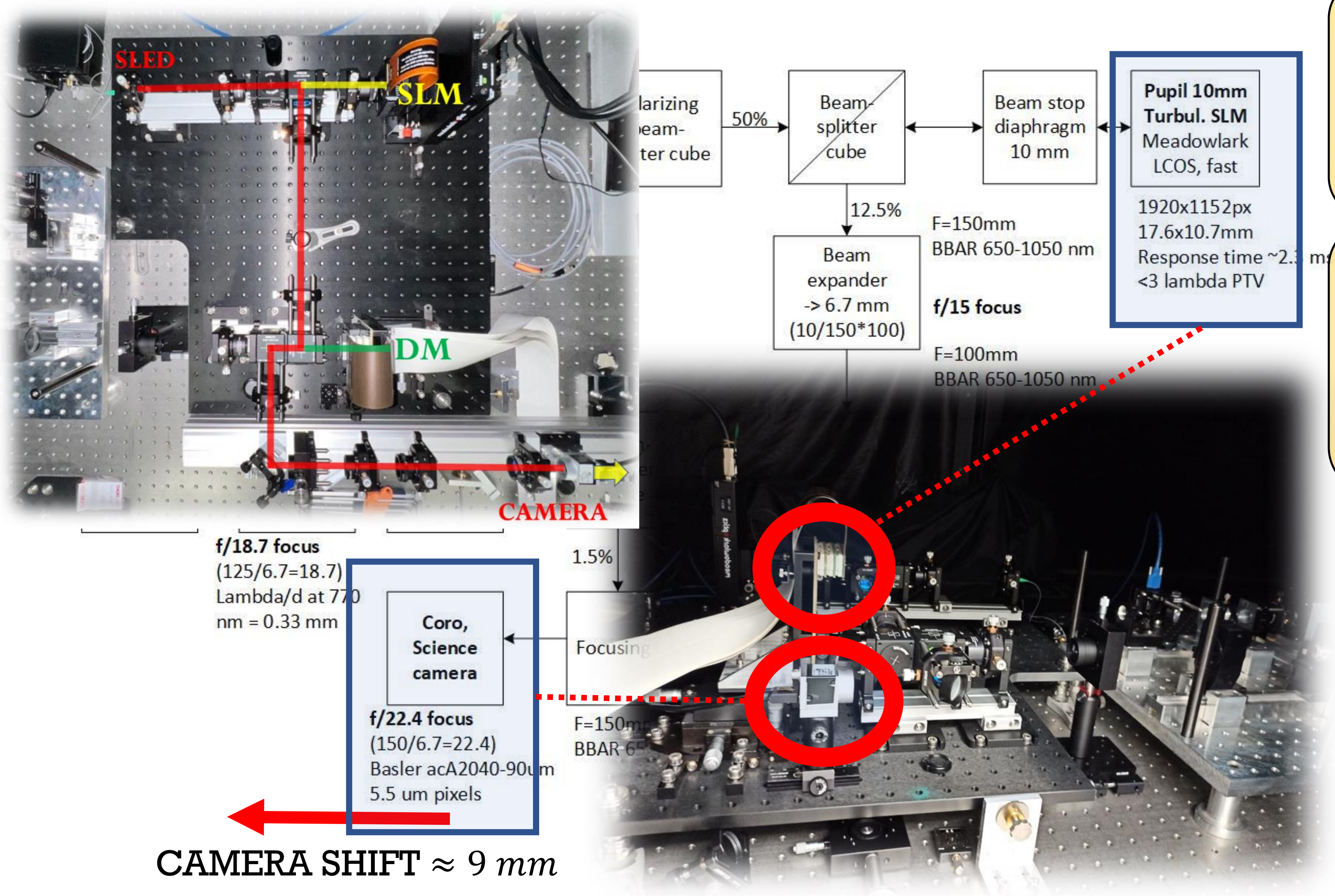
	Example: 1 image of the TEST-SET	After NN Prediction/Correction	Diffraction Limit

Linear scale

Log scale



EXPERIMENTAL: GHOST bench



CAMERA SHIFT $\approx 9\ mm$

Laboratory setup:

$\lambda = 770\ nm$

$f\# = 22.4$

$pixsize = 5.5\ \mu m$

$defocus = 9\ mm$

I used the Spatial Light Modulator (SLM) to inject:

1. Aberrations
2. AO residual (still working)

Experimental work to control bench and train the new NN

Move manually the camera out of focus and test the NN

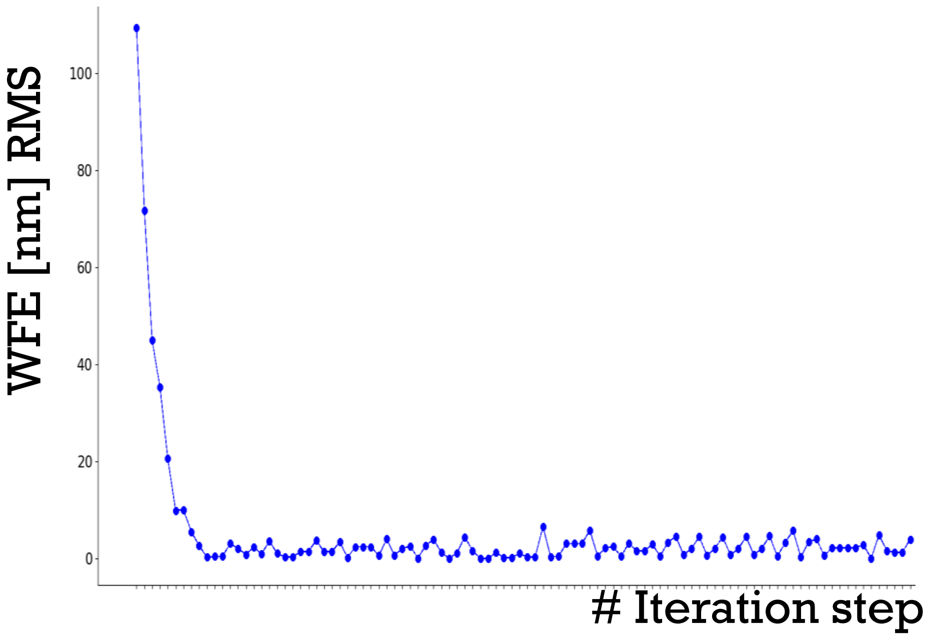
Use of iterative process of correction

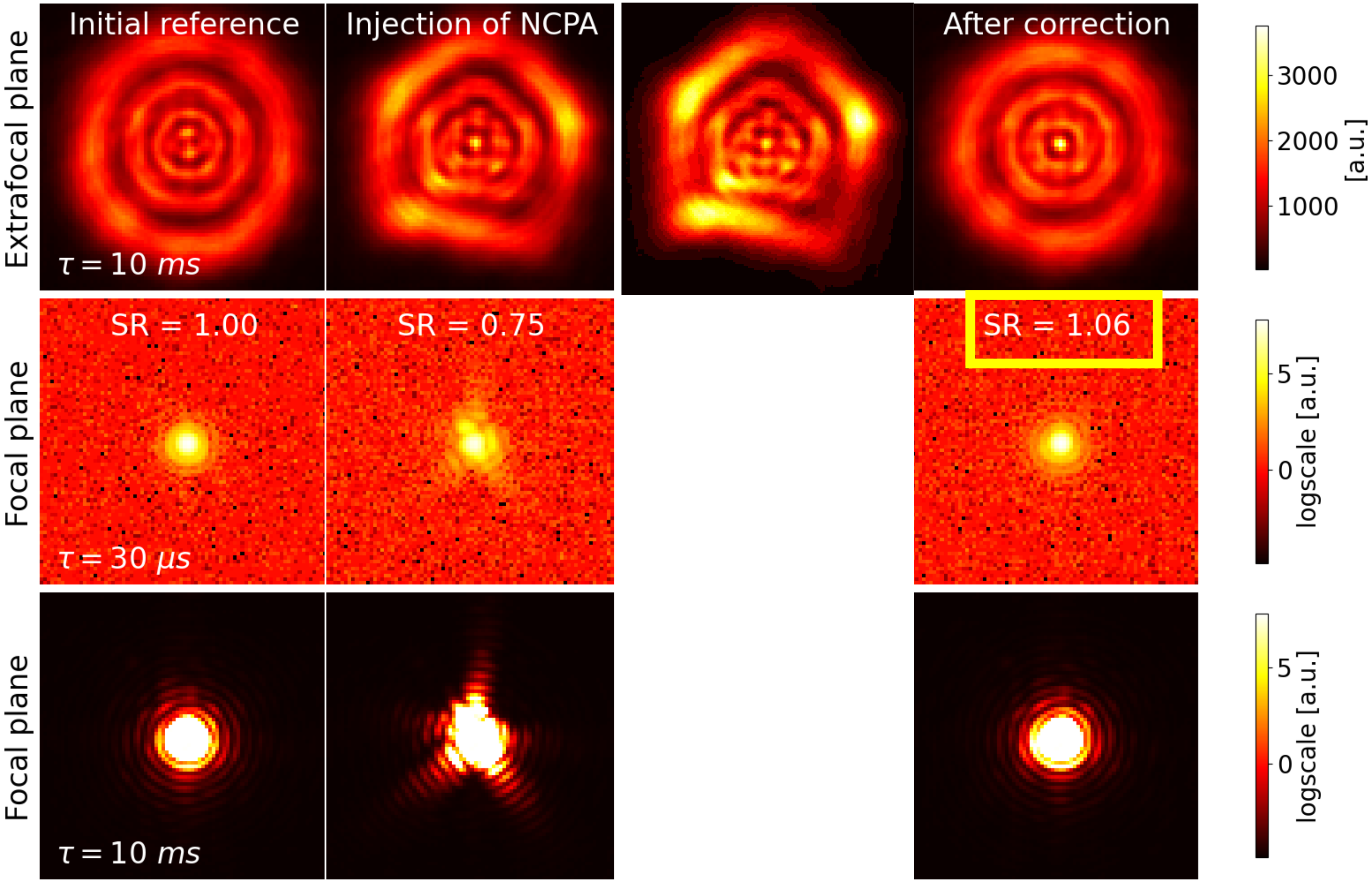
EXPERIMENTAL

Results on the GHOST bench with Iterative process

I chose a set of coefficients randomly in the range [-50,+50] nm for the 21 Zernike polynomials and then:

1. NCPA is injected through the SLM
2. We perform a measurement with NN
3. We can inject back in the SLM the values measured by NN





WE PERFORM BETTER AND FASTER THAN HUMAN

With AO closed loop residual turbulence

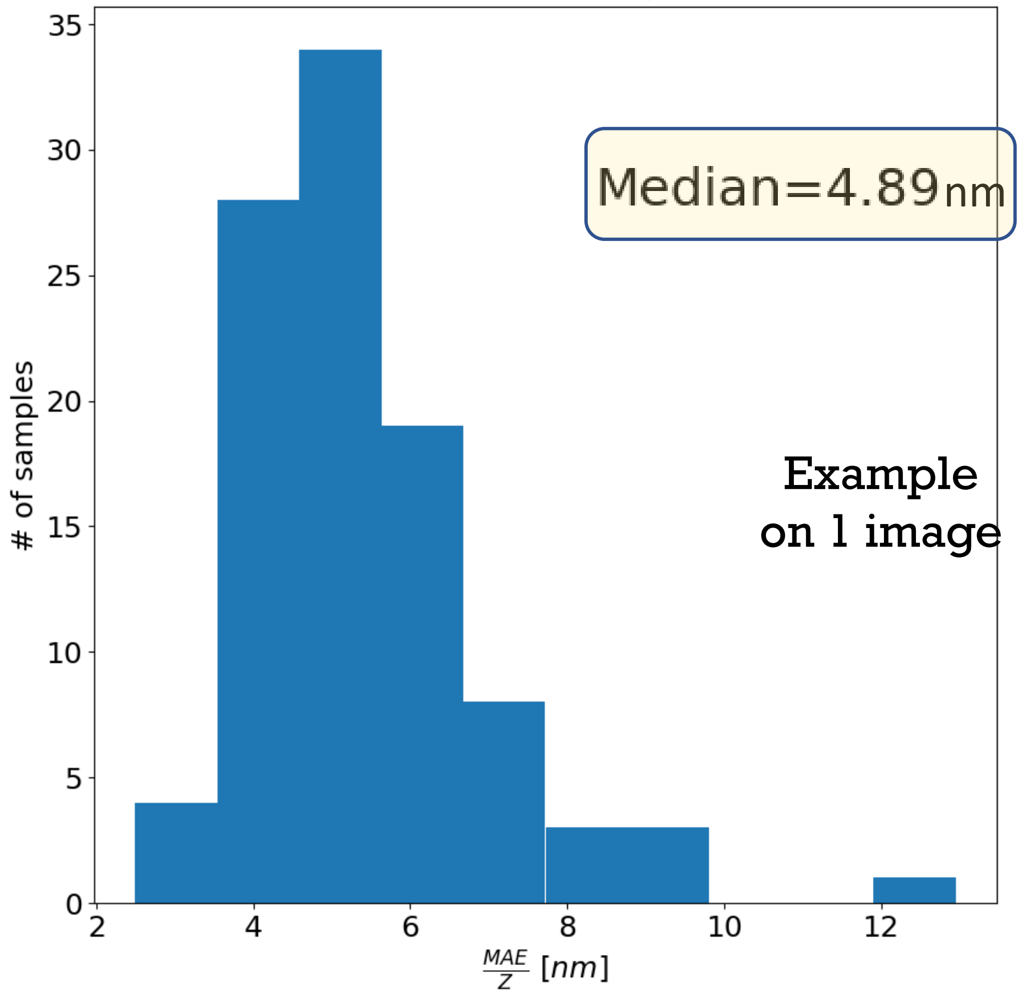
Three possible approaches to mitigate NCPA using NN:

1. AO Residual + random NCPA
2. AO residual + Fixed NCPA
3. Iterative correction using the AO loop

SIMULATIONS

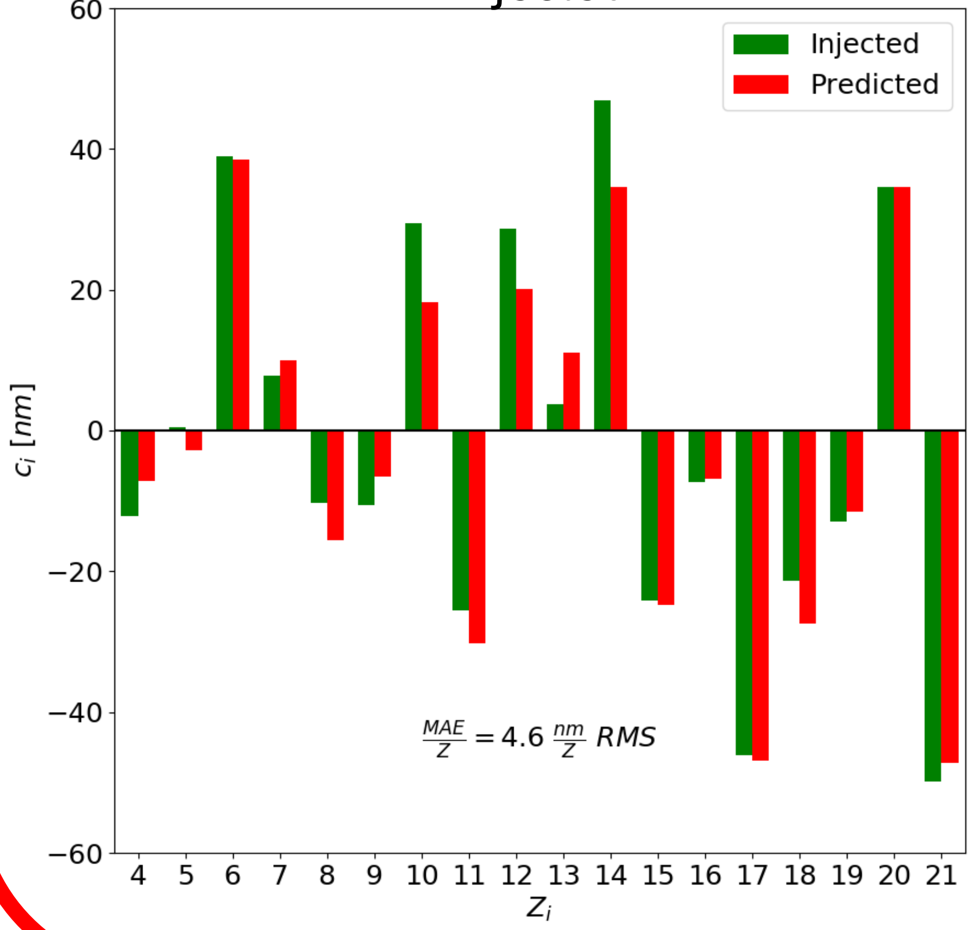
1. AO Residual + random NCPA

TESTSET: prediction error distribution for 100 images



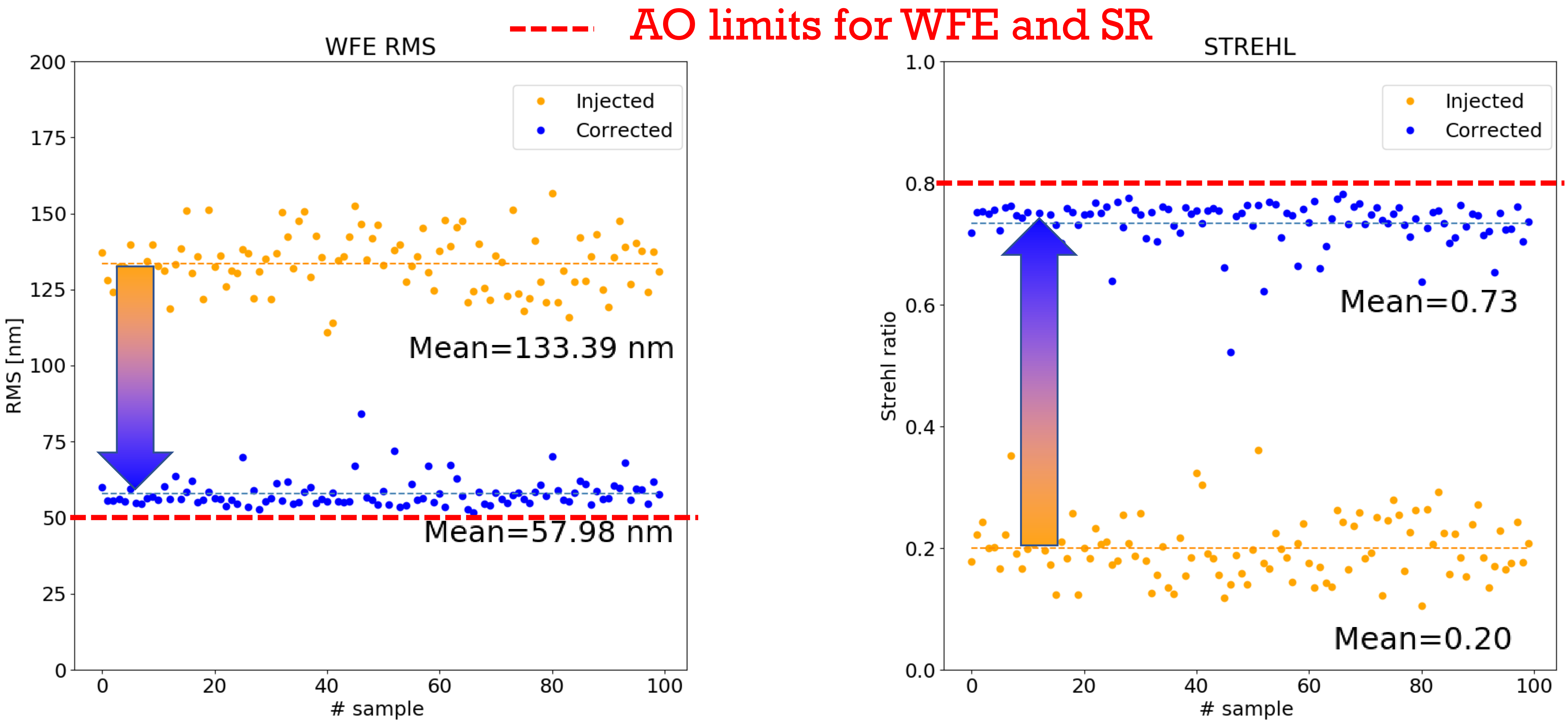
Example on 1 image

Single image: Z_i predicted vs. injected



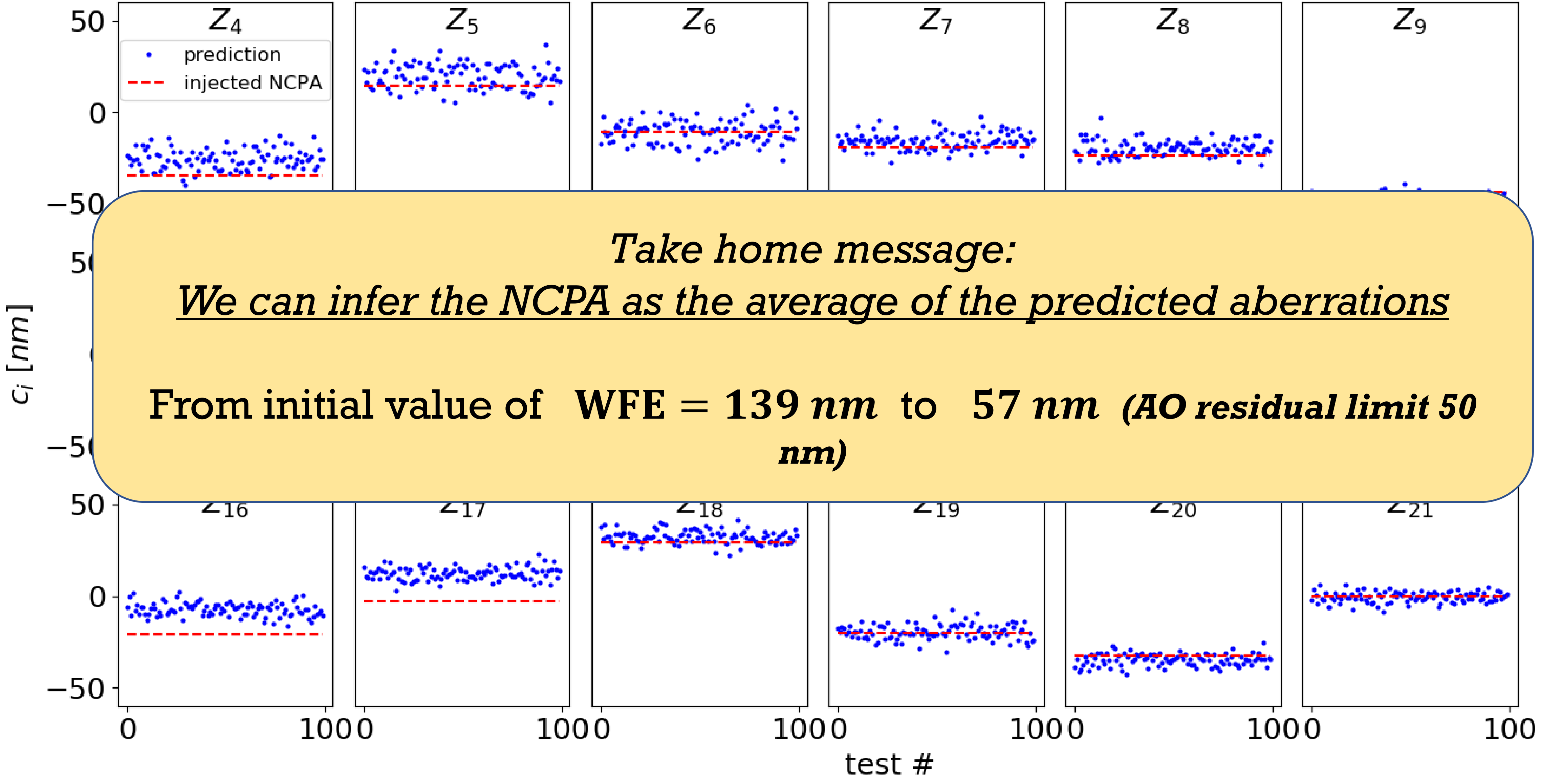
SIMULATIONS

1. AO Residual + random NCPA
From 133 nm to **58** nm WFE RMS



2. AO residual + Fixed NCPA

#100 fast exposures with fixed NCPA…. From 139 to **57** nm WFE RMS



Take home message:

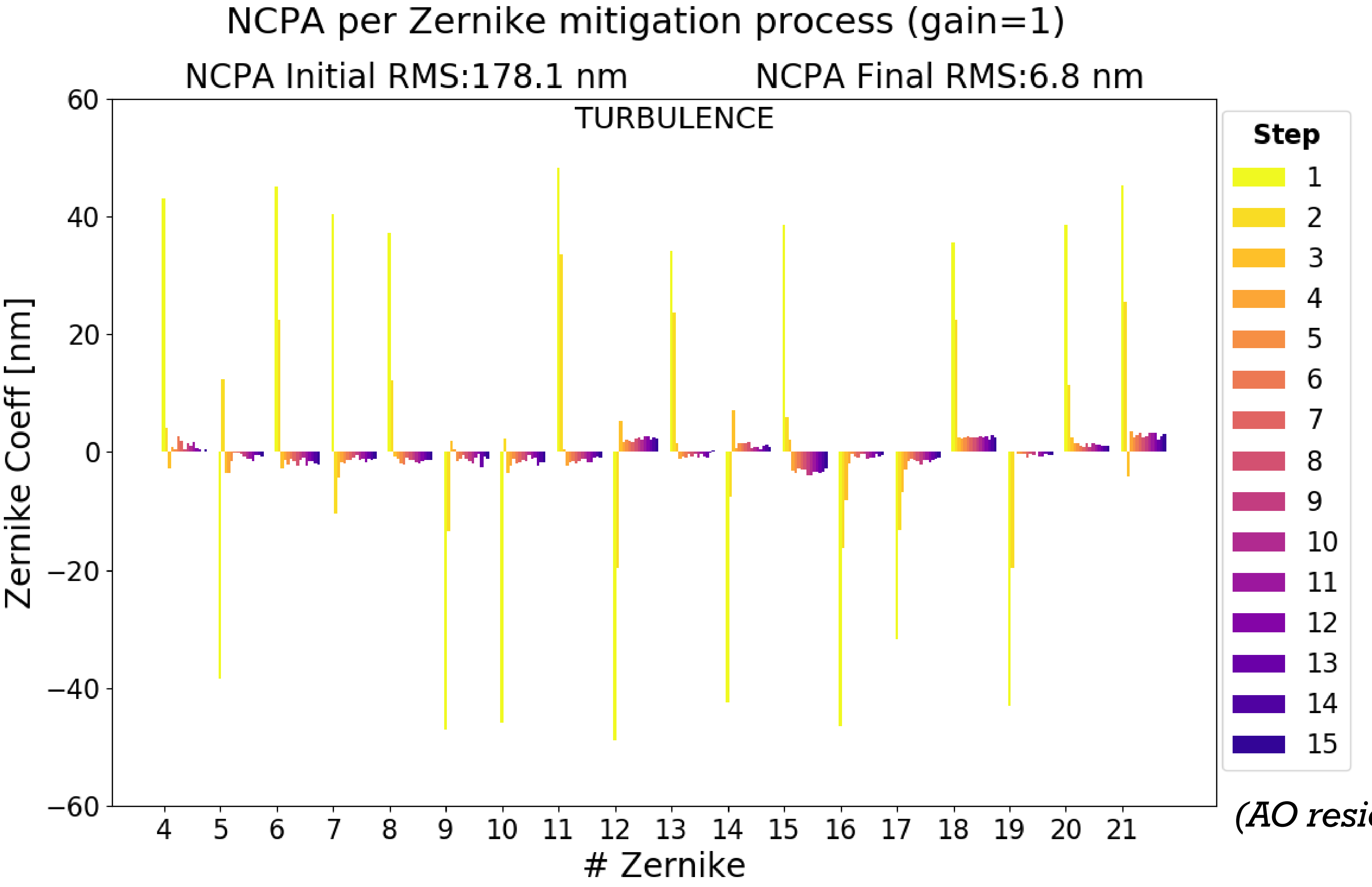
<u>We can infer the NCPA as the average of the predicted aberrations</u>

From initial value of **WFE = 139 *nm*** to **57 *nm*** ***(AO residual limit 50 nm)***

SIMULATIONS

3. Iterative correction using the AO loop

From 184 nm to 50.5 nm WFE RMS



(AO residual limit 50 nm)

EXPERIMENTAL

Experimental Results

ON-GOING ???
let's see

CONCLUSIONS

- This new proposed algorithm based on NN and PCA coefficients **WORKS**….. correctly identify relations between defocused images and wavefront phase at the pupil plane.

IDEAL CONDITION

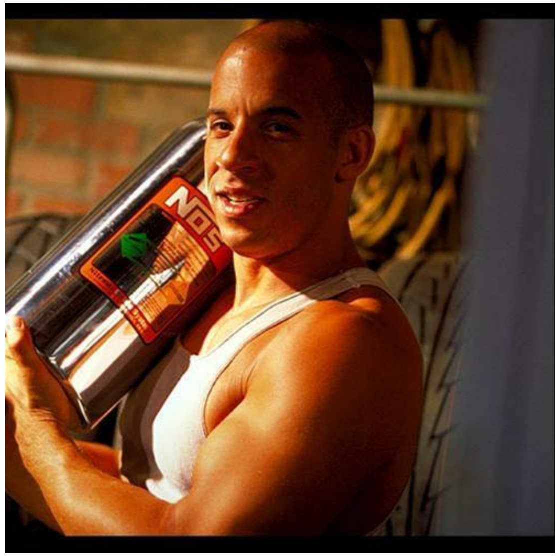
- It is possible to use it to mitigate completely all the static/quasi static aberrations in **CONTROLLED** conditions (such as Laboratory condition, the instrument has a calibration/reference source, characterizing optical elements or the entire optical path)
- Compared to MANUAL trial-and-error approach:
  1. **FASTER** …< 1 minute → NN prediction on one image < 1 ms
  2. **BETTER**… **7%** more in terms of maximum in the **peak** compared to values found MANUALLY by an EXPERT in optics.

TURBULENCE CONDITION

- It is possible to use this algorithm to minimize NCPA using the NN on:
  1. A single image
  2. Series of images in frozen flow condition with the same NCPA (FAST IMAGING APPROACH)
  3. Single or series of images but with the real time correction thanks to some Active Optical Elements
     (such as DM,DL or SLM …. typically on AO system)

* N^2ONCPA stands for «**Neural Network 2 Optimize NCPA**»

But if you switch apex with pedic it probably brought to your mind N_2O brute formula for Nitrous Oxide (NOS) used in cars to boost the output of the engine for a limited duration… **BECAUSE WE WANT TO REMOVE THE NCPA FASTLY**
Or the anesthetic used in surgery… **BECAUSE WE WANT THE ABERRATIONS TO GO TO SLEEP**



Thank you for the attention

<u>ORIGINAL IDEA:</u>

Terreri et al 2022, A&A, **Neural networks and PCA coefficients to identify and correct aberrations in adaptive optics**, DOI:10.1051/0004-6361/202142881

<u>EXPERIMENTAL RESULTS:</u>

Terreri et al. 2022, SPIE Proceedings, **Experimental verification of NN and PCA for NCPA mitigation**