








# **ESTIMATING DIFFERENTIAL PISTONS FOR THE EXTREMELY LARGE TELESCOPE USING DEEP LEARNING**

**... or how to make a Residual Network measure petaling from focal plane images**



**By Pierre Janin-Potiron  
(postdoc @ IPAG)**

# WITH GREAT POWER COMES GREAT INSTRUMENTAL RESPONSIBILITY

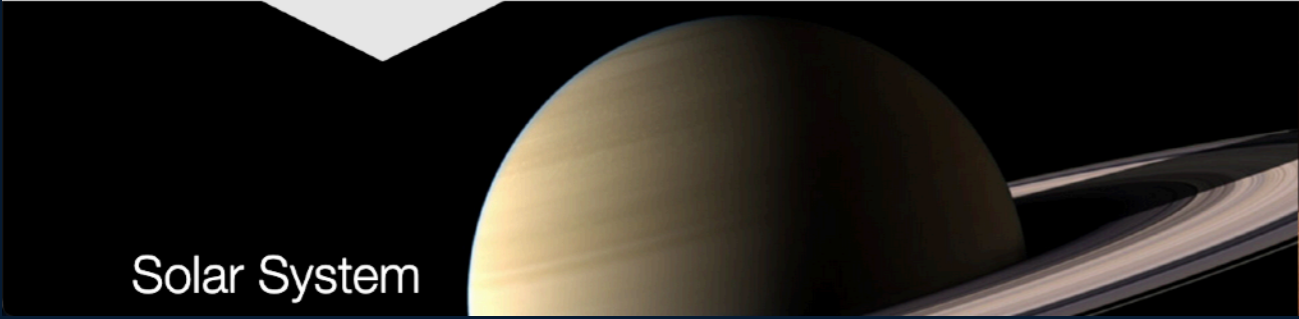
  Choose your language     

## Science with the ELT

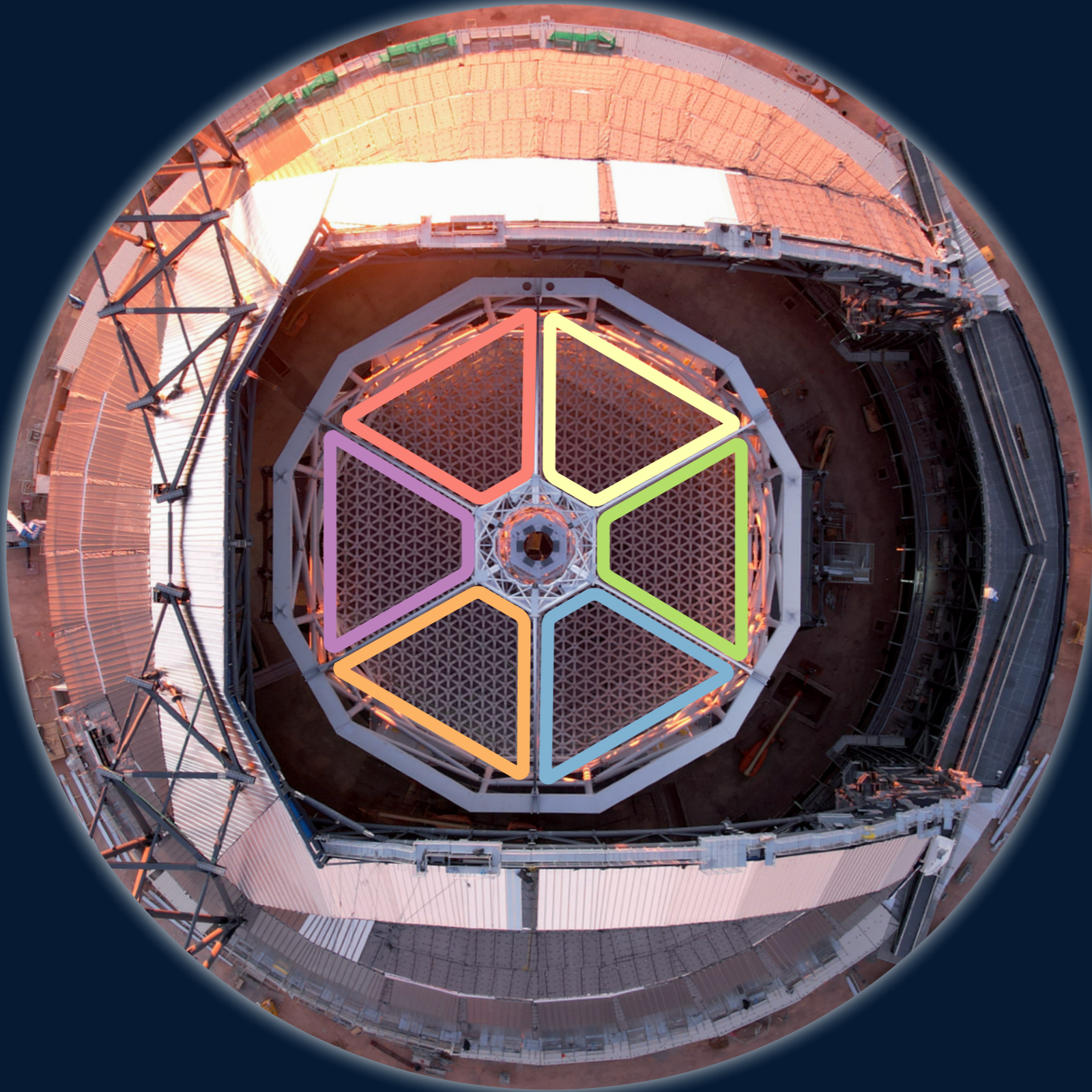
[ELT HOME](#) [ABOUT](#) [TELESCOPE](#) [INSTRUMENTS](#) [SCIENCE](#) [NEWS & MULTIMEDIA](#) [SUCCESS STORIES](#)

### Science

The ELT will tackle the biggest scientific challenges of our time, and will aim for a number of notable firsts, including tracking down [Earth-like planets](#) around other stars in the habitable zones where life could exist. It will also make fundamental contributions to [cosmology](#) by probing the nature of dark matter and dark energy. Other key science areas include the study of [stars](#) in our galaxy and beyond, [black holes](#), the evolution of distant [galaxies](#), up to the very first galaxies in the earliest epoch of the Universe. And discoveries that nobody [has ever even thought](#) about!



**DIFFERENTIAL PISTON CAN COST UP TO 60% OF THE ELT'S  
SPATIAL RESOLUTION.**



**PETALS**

=

*piston on each  
subaperture*

# DIFFERENTIAL PISTON ORIGINATES FROM VARIOUS SOURCES

## ADAPTIVE OPTICS CONTROL LOOP

When wavefront sensors are almost blind to it

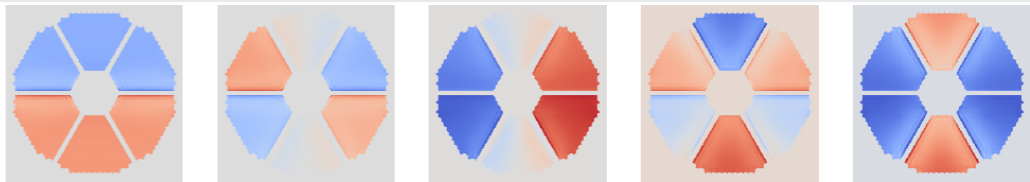
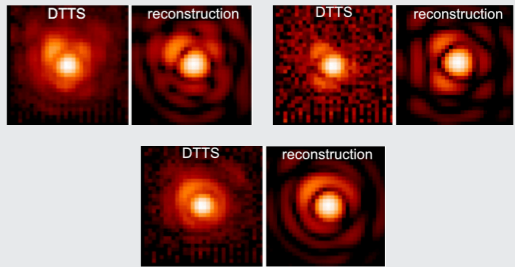
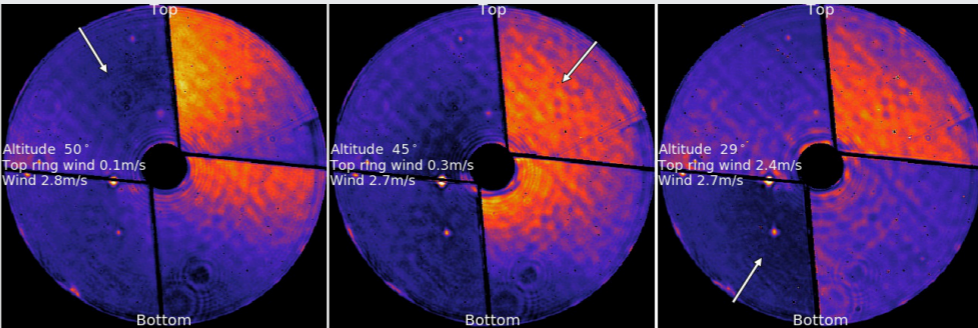


Fig. 2. Last eigenvectors of the interaction matrix: they are dominated by petal modes.

Bertrou-Cantou A. et al. (2020)

## LOW WIND EFFECT

When the wind does not blow fast enough.



Milli J. et al. (2018)

## THERMO-MECHANICAL EFFECTS

When physics finds every possible way to mess with you

**THERMO-OPD:**  
Statistical evaluation of discontinuity

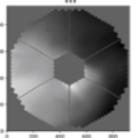
Discontinuity = Deviation from the most likely continuous extrapolation (maximum likelihood)

$m$  Real modal coefficients (projection of phase on basis)  
 $m'$  Extrapolated coefficients using a continuity constraint  
 $T_m$  Trust matrix (small weight on discontinuity modes,  $\rightarrow$  1-mm error)  
 $\Delta_k$  Laplacian regularisation (continuity = minimization of local curvature)  
 e.g. A. Obereder, AO4ELT7, (2023): Discrete Laplacian Operator

$$m' = E_m m$$

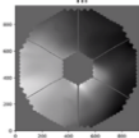
$$E_m = (\Delta_k^{-1} + T_m^{-1})^{-1} T_m^{-1}$$

Real projection



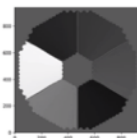
$m$

Continuous projection



$m'$

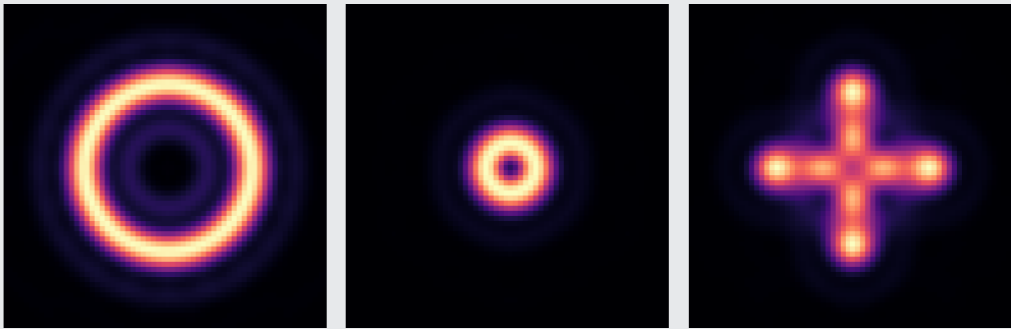
Difference



# DIFFERENTIAL PISTON IS ALREADY MANAGEABLE WITH CONVENTIONAL TECHNIQUES

## ADAPTATION OF THE CONTROL LOOP

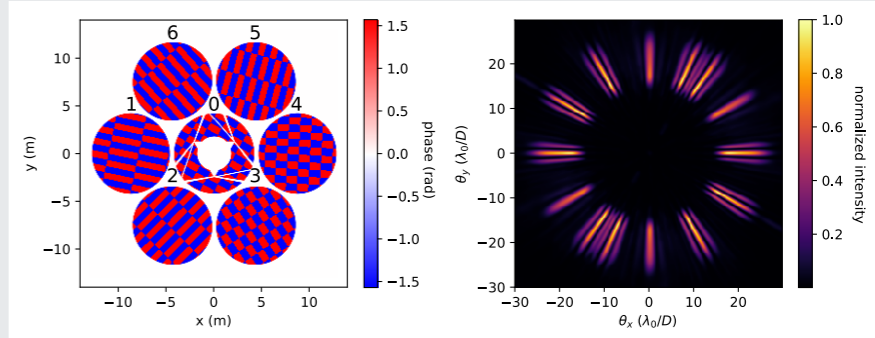
*Tune the sensitivity to petal modes*



Bertrou-Cantou A. *et al.* (2020)

## CREATE « NEW » WAVEFRONT SENSORS

*Specifically developed for petaling correction*



Haffert S. *et al.* (2022)

## ADAPTING THE ALGORITHM TO EXISTING WAVEFRONT SENSORS

*Differential piston information is already there, and that's where we talk about AI !*

**AI MODELS ARE ATTRACTIVE  
BECAUSE YOU LET ALL THE  
BORING COMPLEXITY BE IN THE  
MODEL ITSELF.  
SO WE BUILT ONE...**

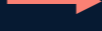
# BECAUSE WE WORK WITH 2D IMAGES, RESNET WAS THE NATURAL CHOICE

**5 RESIDUAL BLOCKS WITH SKIP CONNECTIONS**  
*Extracting piston-related features from the images*

**FLATTEN LAYER**

**3 FULLY CONNECTED LAYERS**  
*Mapping features to piston estimates*

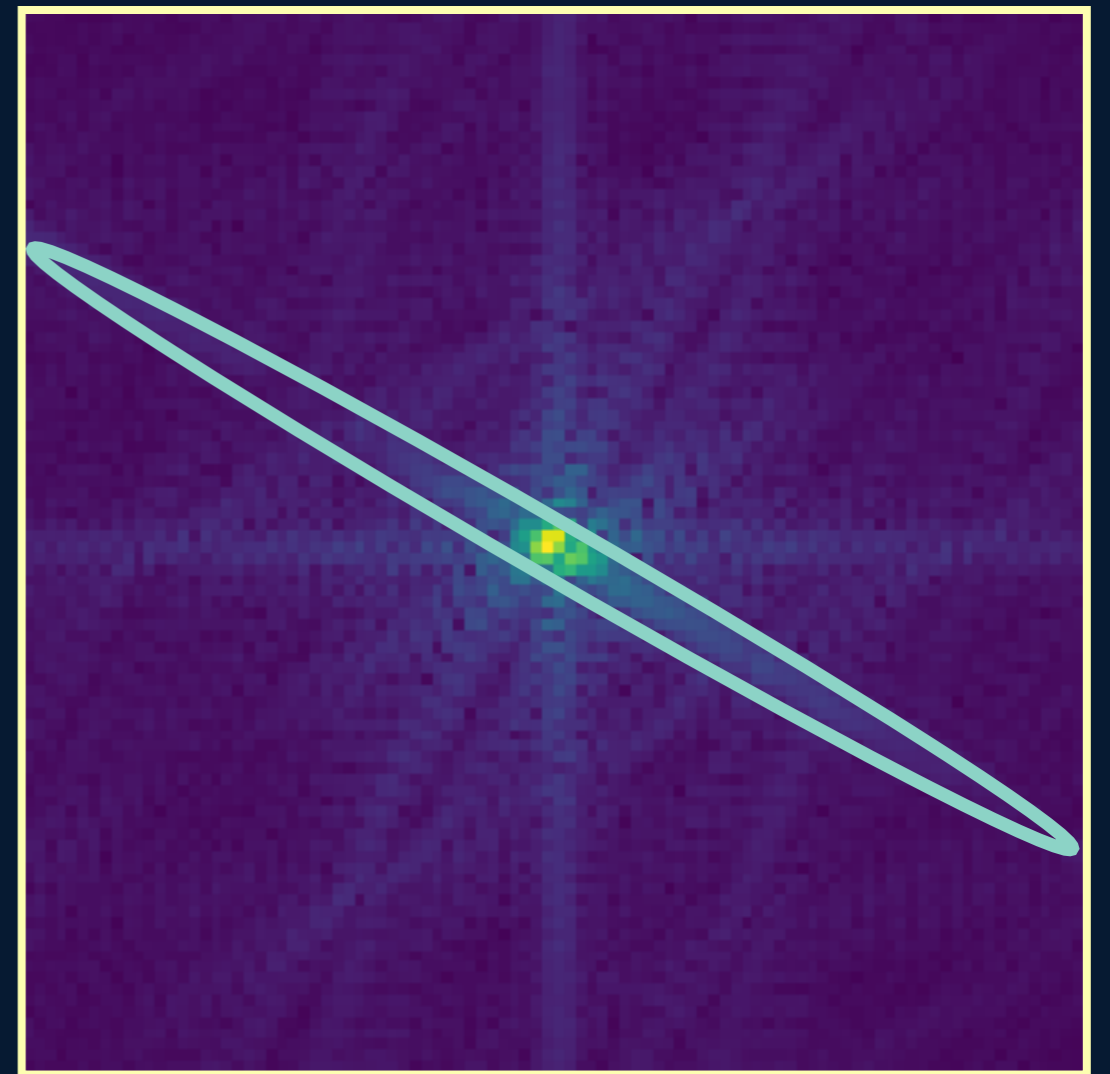
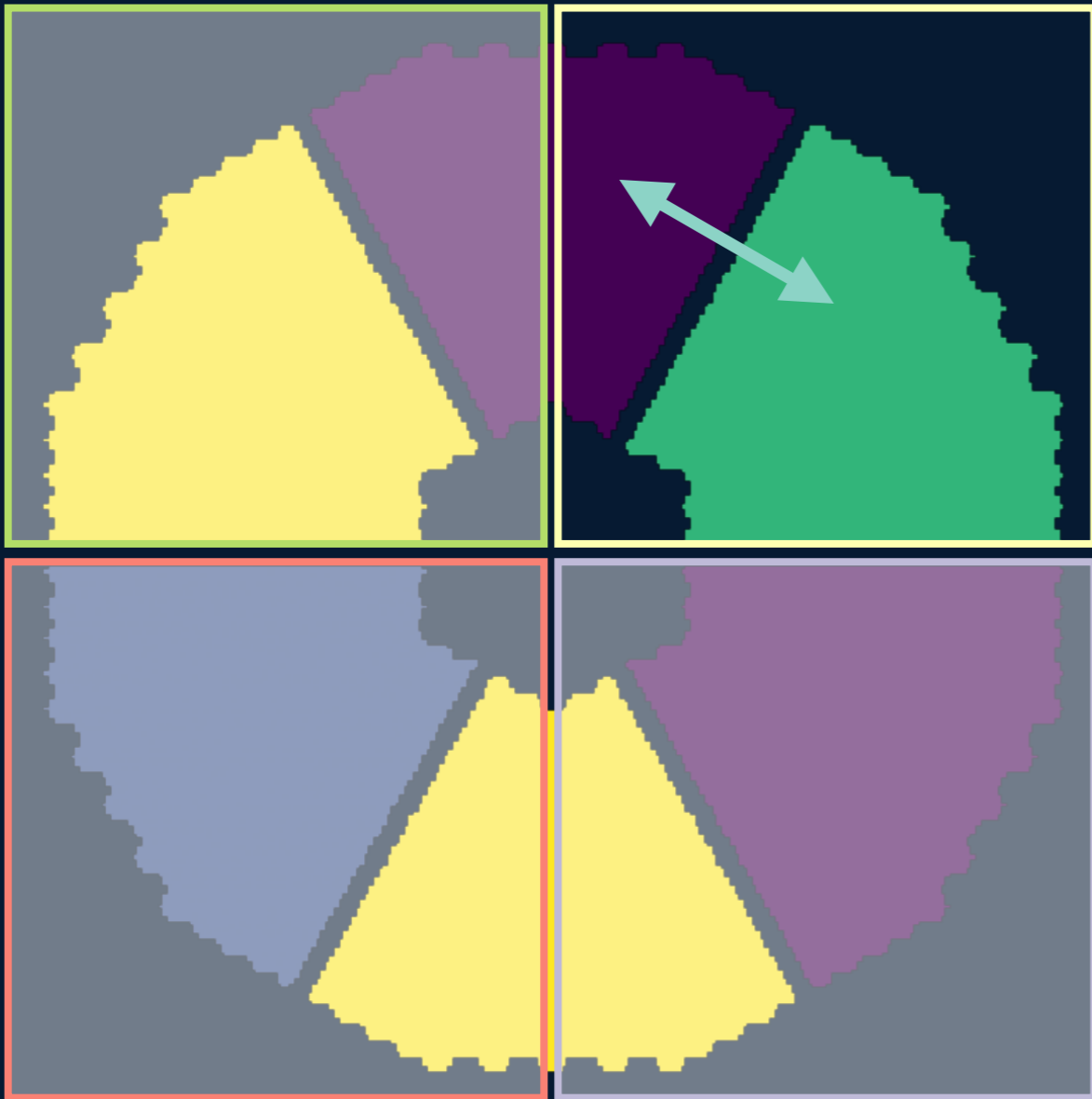
**OUTPUT LAYER**



```
-----  
Layer (type:depth-idx)      Output Shape      Param #  
-----  
DynamicModel                [1, 1]            --  
├─ModuleList: 1-1           --  
│   └─ABlock: 2-1            [1, 32, 96, 96]  --  
│       └─Conv2d: 3-1         [1, 32, 96, 96]  608  
│           └─ReLU: 3-2       [1, 32, 96, 96]  --  
│               └─Conv2d: 3-3 [1, 32, 96, 96]  9,248  
│                   └─Conv2d: 3-4 [1, 32, 96, 96]  96  
│                       └─ReLU: 3-5 [1, 32, 96, 96]  --  
│   └─BBlock: 2-2            [1, 32, 96, 96]  --  
│       └─Conv2d: 3-6         [1, 32, 96, 96]  9,248  
│           └─ReLU: 3-7       [1, 32, 96, 96]  --  
│               └─Conv2d: 3-8 [1, 32, 96, 96]  9,248  
│                   └─Identity: 3-9 [1, 32, 96, 96]  --  
│                       └─ReLU: 3-10 [1, 32, 96, 96]  --  
│   └─MaxPool2d: 2-3         [1, 32, 48, 48]  --  
│   └─ABlock: 2-4            [1, 64, 48, 48]  --  
│       └─Conv2d: 3-11        [1, 64, 48, 48]  18,496  
│           └─ReLU: 3-12      [1, 64, 48, 48]  --  
│               └─Conv2d: 3-13 [1, 64, 48, 48]  36,928  
│                   └─Conv2d: 3-14 [1, 64, 48, 48]  2,112  
│                       └─ReLU: 3-15 [1, 64, 48, 48]  --  
│   └─BBlock: 2-5            [1, 64, 48, 48]  --  
│       └─Conv2d: 3-16        [1, 64, 48, 48]  36,928  
│           └─ReLU: 3-17      [1, 64, 48, 48]  --  
│               └─Conv2d: 3-18 [1, 64, 48, 48]  36,928  
│                   └─Identity: 3-19 [1, 64, 48, 48]  --  
│                       └─ReLU: 3-20 [1, 64, 48, 48]  --  
│   └─MaxPool2d: 2-6         [1, 64, 24, 24]  --  
│   └─ABlock: 2-7            [1, 128, 24, 24] --  
│       └─Conv2d: 3-21        [1, 128, 24, 24] 73,856  
│           └─ReLU: 3-22      [1, 128, 24, 24] --  
│               └─Conv2d: 3-23 [1, 128, 24, 24] 147,584  
│                   └─Conv2d: 3-24 [1, 128, 24, 24]  8,320  
│                       └─ReLU: 3-25 [1, 128, 24, 24]  --  
│   └─Conv2d: 2-8            [1, 128, 24, 24] 147,584  
│   └─ReLU: 2-9              [1, 128, 24, 24] --  
│   └─MaxPool2d: 2-10        [1, 128, 6, 6]   --  
│   └─Flatten: 2-11          [1, 4608]         --  
│   └─Linear: 2-12           [1, 16]           73,744  
│       └─ReLU: 2-13         [1, 16]           --  
│           └─Linear: 2-14    [1, 16]           272  
│               └─ReLU: 2-15  [1, 16]           --  
│                   └─Linear: 2-16 [1, 1]            85  
-----  
Total params: 611,285  
Trainable params: 611,285  
Non-trainable params: 0  
Total mult-adds (Units.MEGABYTES): 782.33  
-----  
Input size (MB): 0.07  
Forward/backward pass size (MB): 20.05  
Params size (MB): 2.45  
Estimated Total Size (MB): 22.57  
-----
```

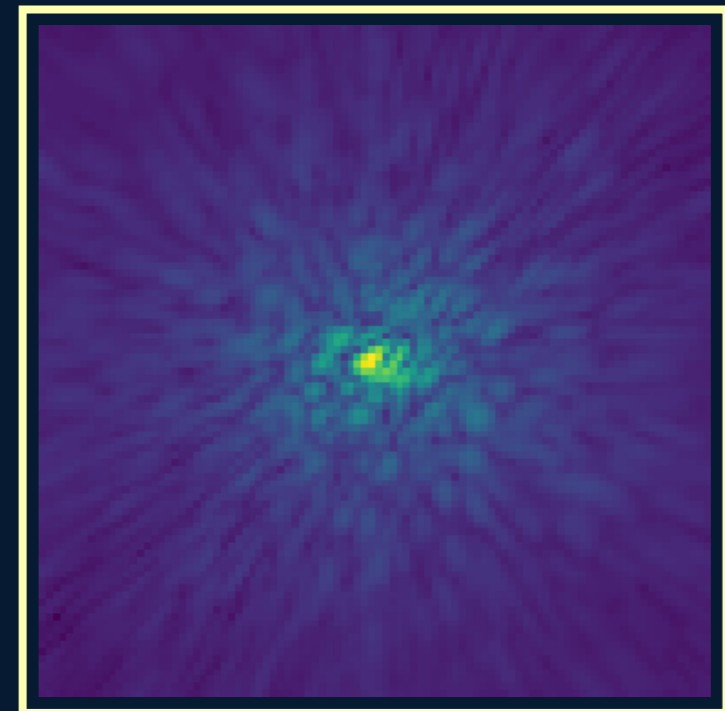
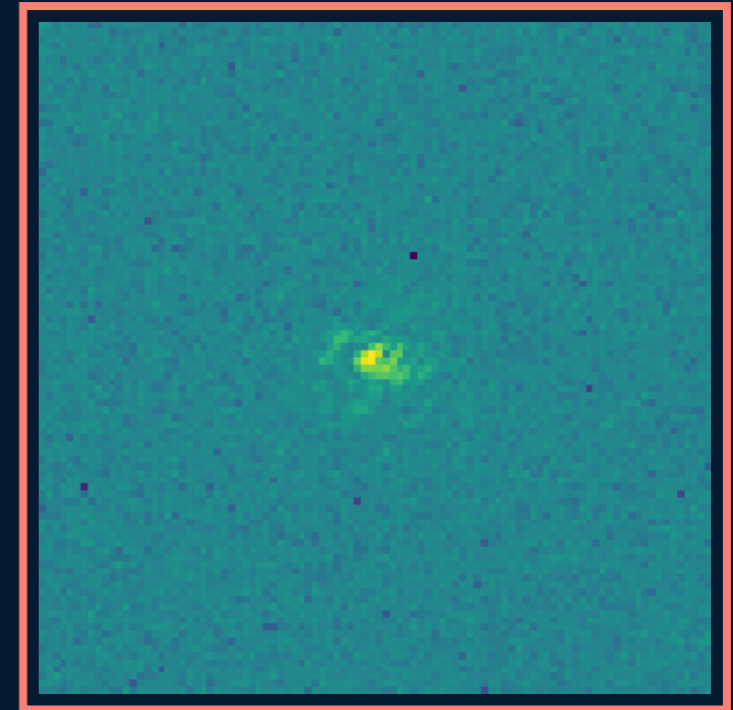
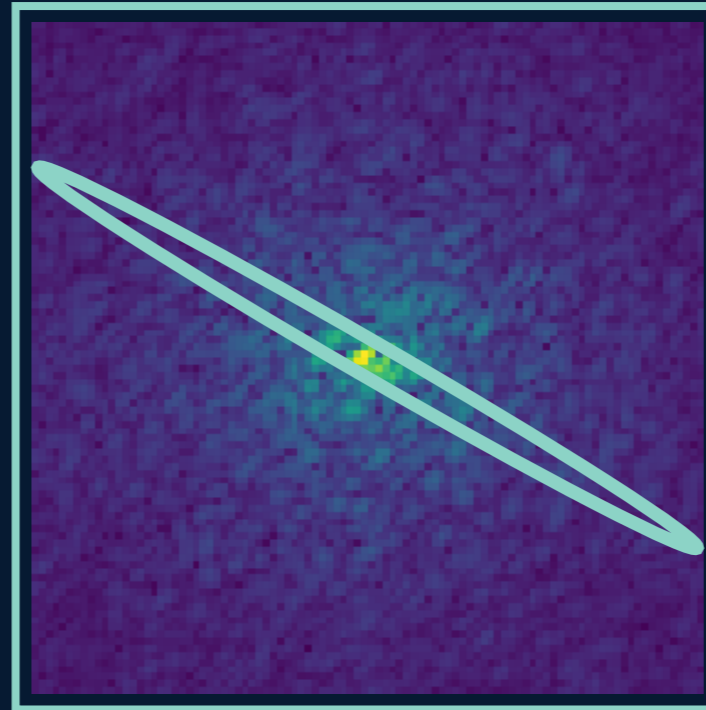
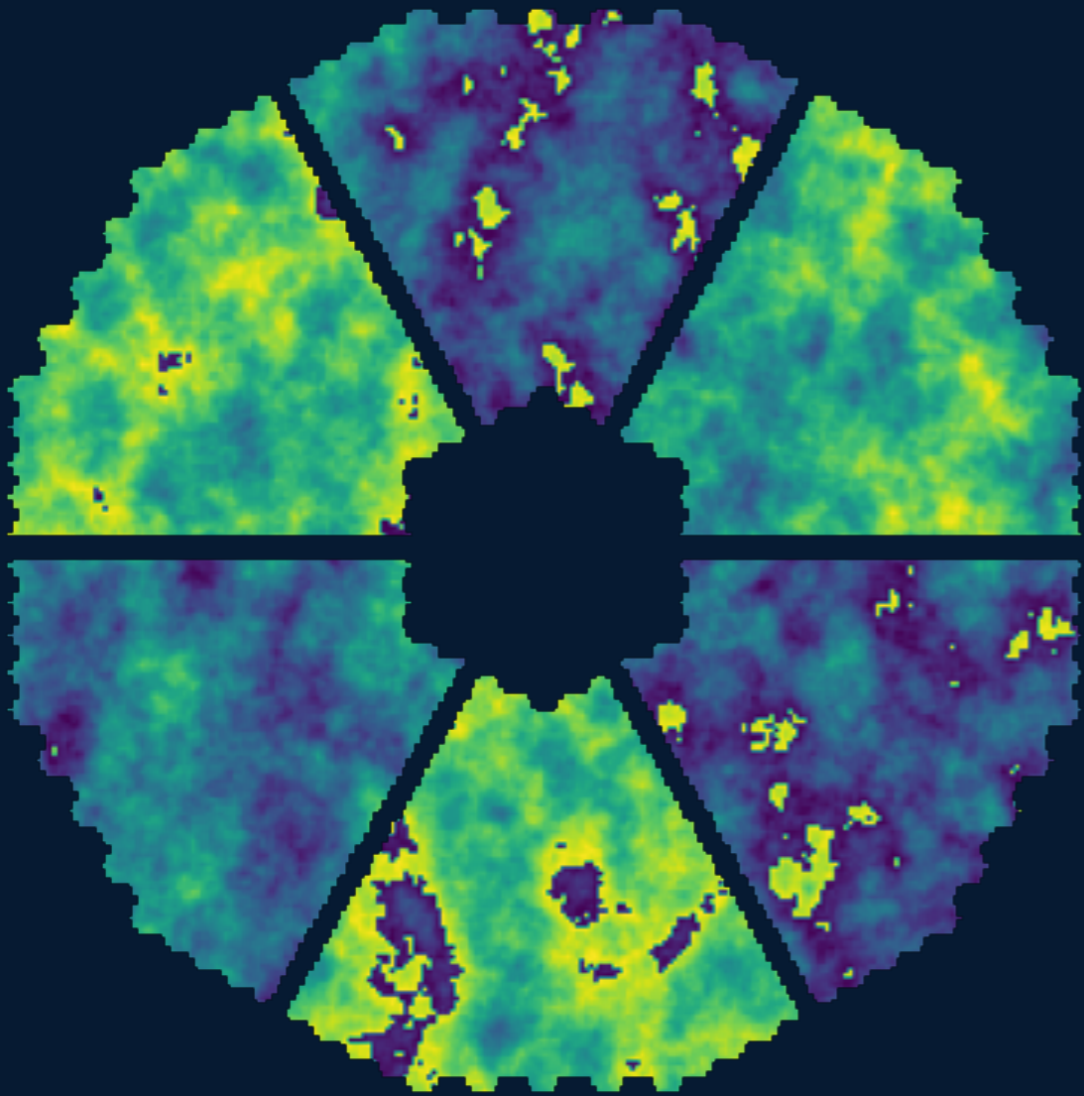
# WE SIMULATE PSF USING FOURIER OPTICS AND CONFIRM VALUABLE INSIGHTS

*The pupil is divided into four quarters to break symmetry (and because the 2x2 SH-WFS is a thing).*



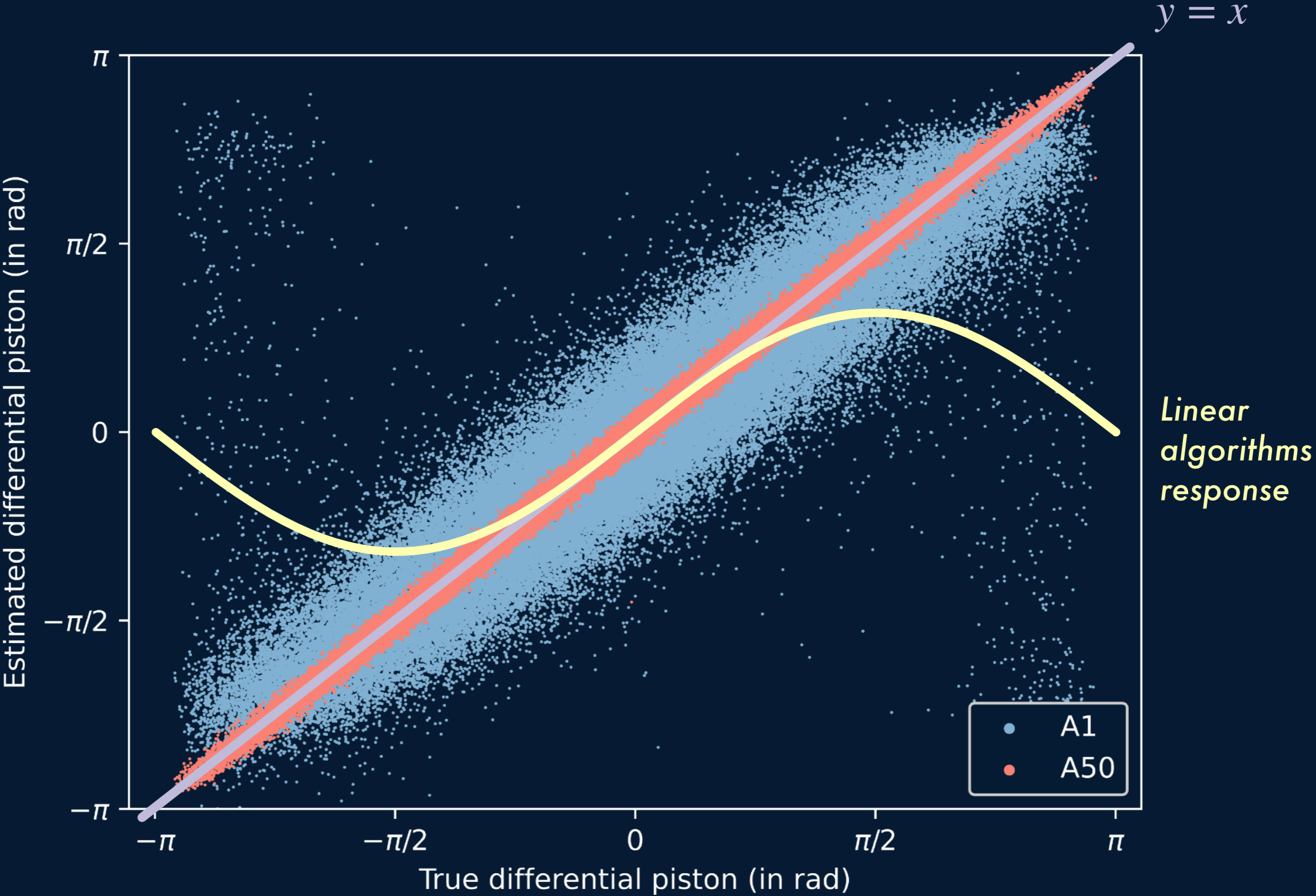
*The differential piston diffraction pattern exhibits a preferred direction.*

# WE AIM TO BE AS CLOSE AS POSSIBLE TO THE REAL PSF AND ADD ADAPTIVE OPTICS RESIDUALS, NOISE AND CHROMATISM TO THE IMAGES



*Residual turbulence speckles, detector noise, and chromatic blur all overlap with the differential piston signal.*

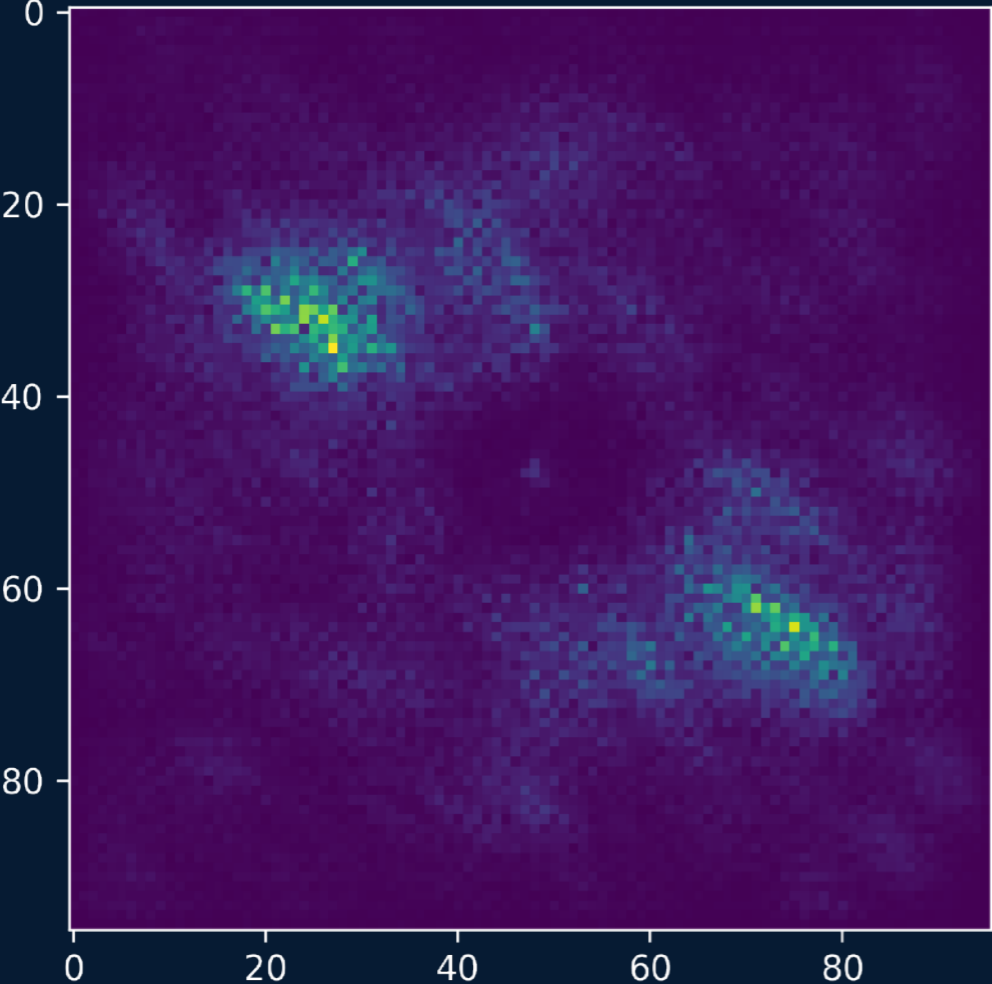
# AND THE NETWORK PERFORMS PRETTY WELL



Full details in Janin-Potiron P. *et al.* (2025)

# THE LEARNINGS ARE EXPLAINABLE

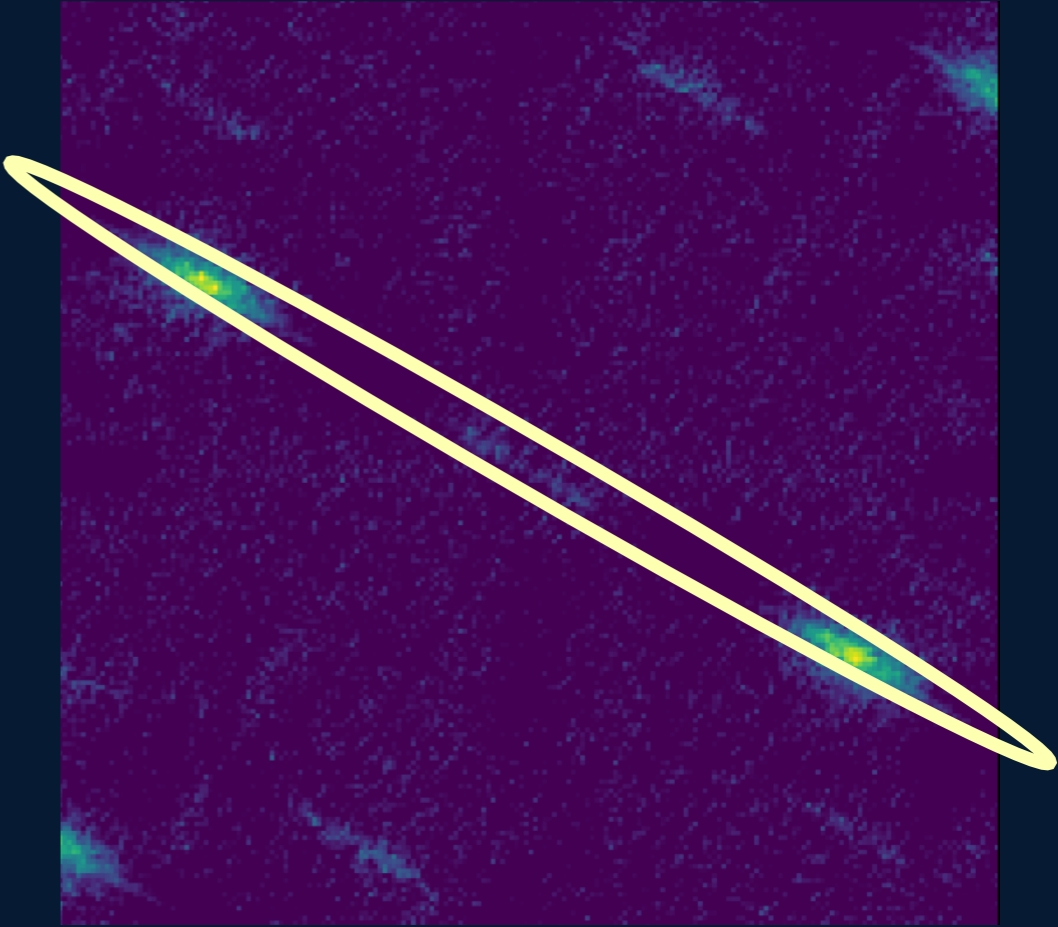
Average Saliency Map



*“which pixels need to be changed the least to affect the class score the most”*

*Simonyan et al. 2014*

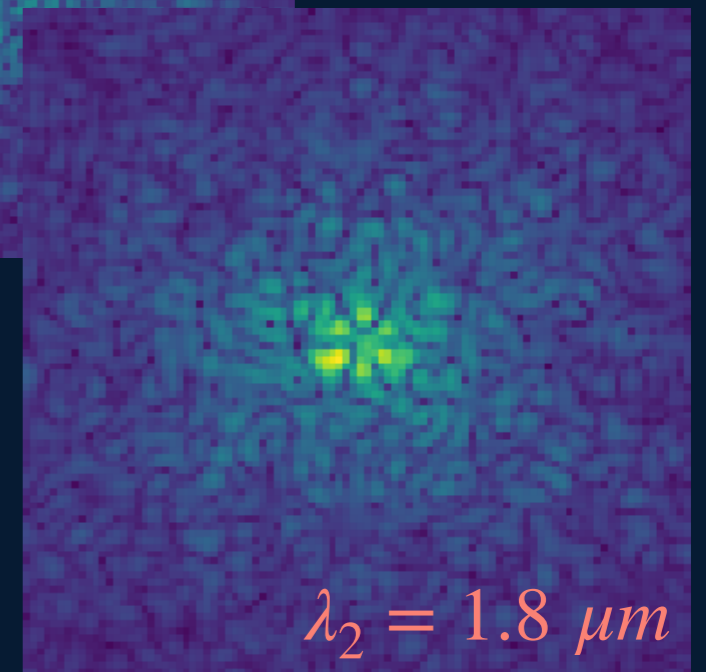
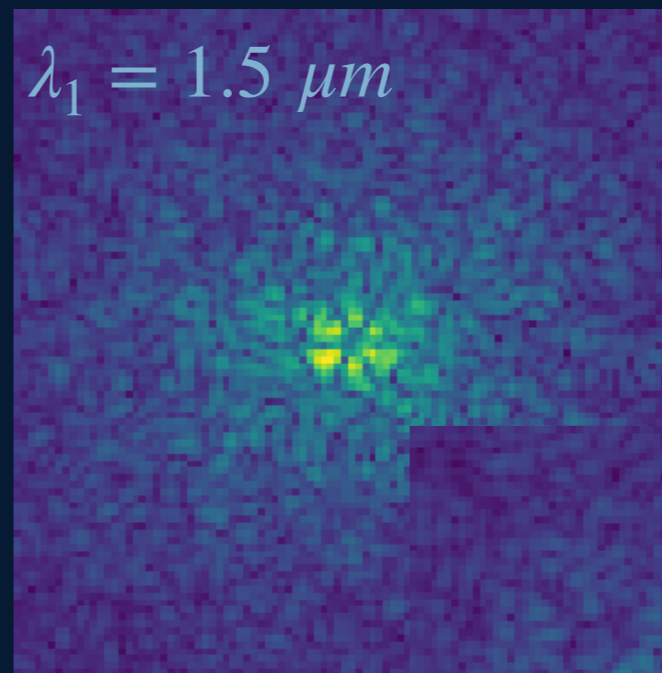
Speckle SNR estimator



*“which pixels show a higher piston-to-turbulence variance ratio”*

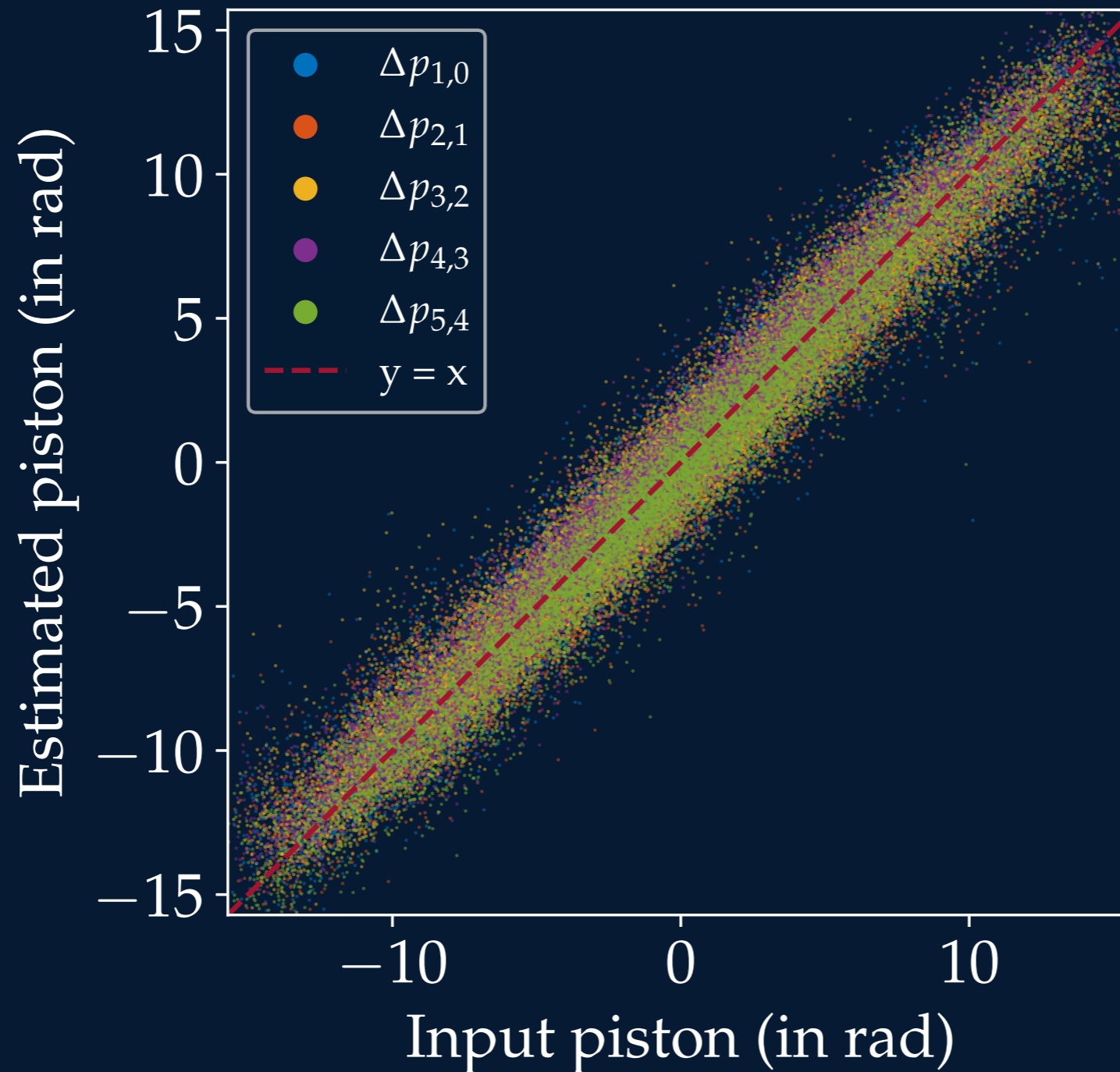
*Janin-Potiron et al. 2024*

# CAN WE RECOVER ALL SIX PISTONS FROM TWO COLORED DEFOCUSSED IMAGES?



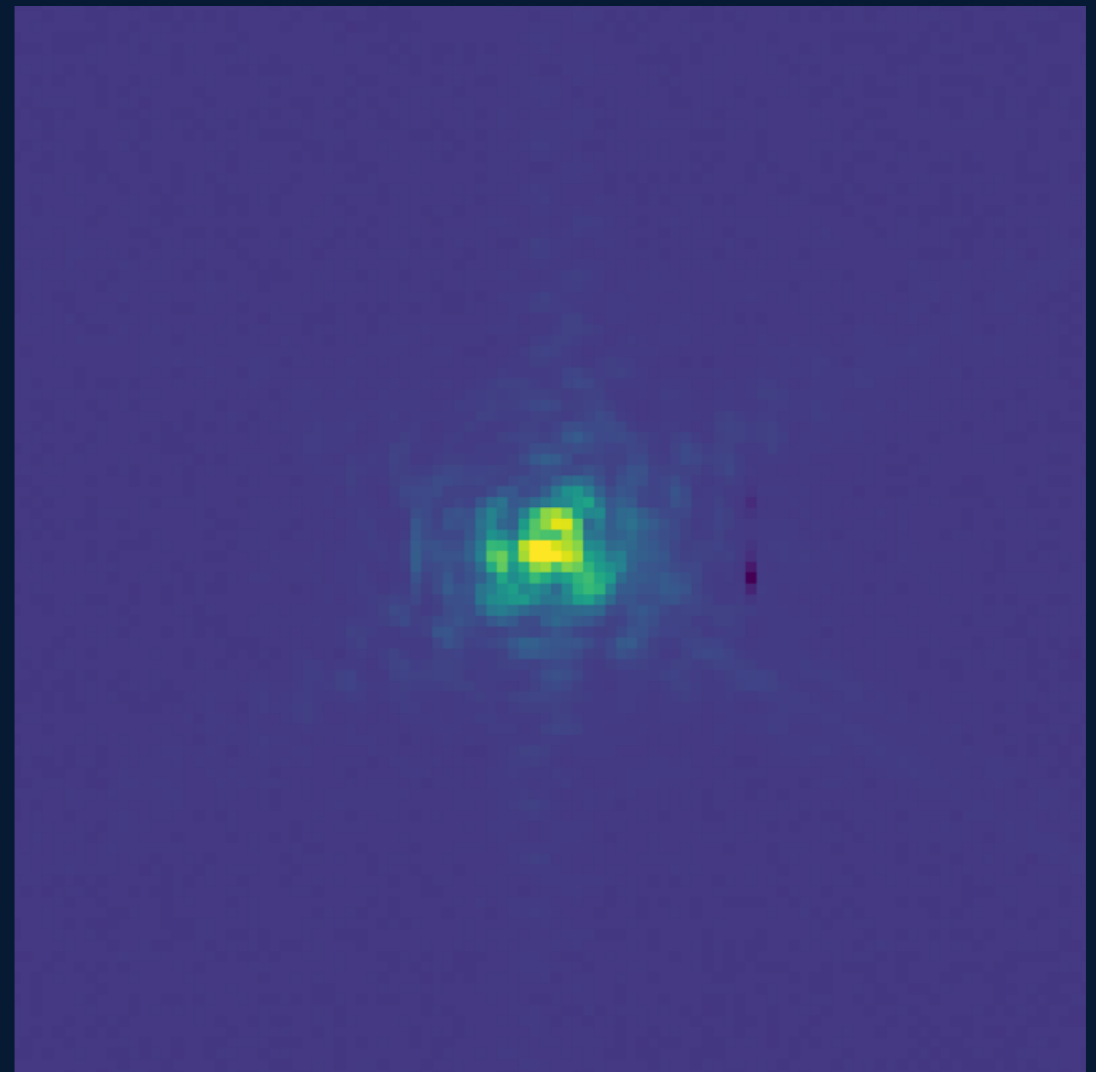
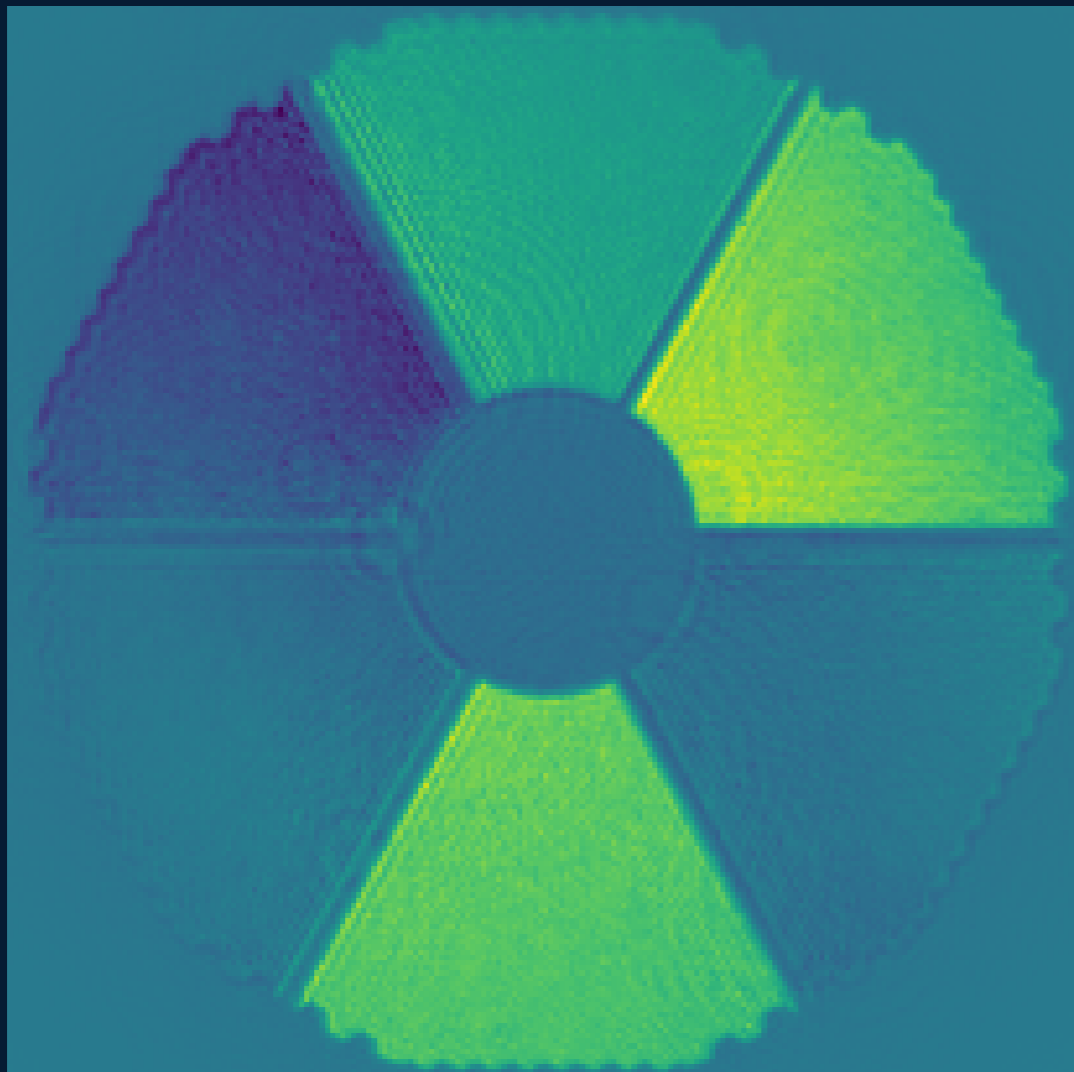
*A defocus is added to the image to break the symmetry and two wavelengths are considered*

**YES ! AND WE GAIN INCREASED CAPTURE RANGE  
WITHOUT EXTRA EFFORT.**



*This represents 5 times the original capture range.*

# WE HOPE TO VALIDATE THE MODEL ON LAB AND SKY DATA SOON



*A R&D optical bench at IPAG can be used to produce PSFs from an ELT-like pupil with petaling.*

# THANK YOU



THE FRENCH AEROSPACE LAB



GRENOBLE ALPES RECHERCHE

INFRASTRUCTURE DE CALCUL INTENSIF ET DE DONNÉES

