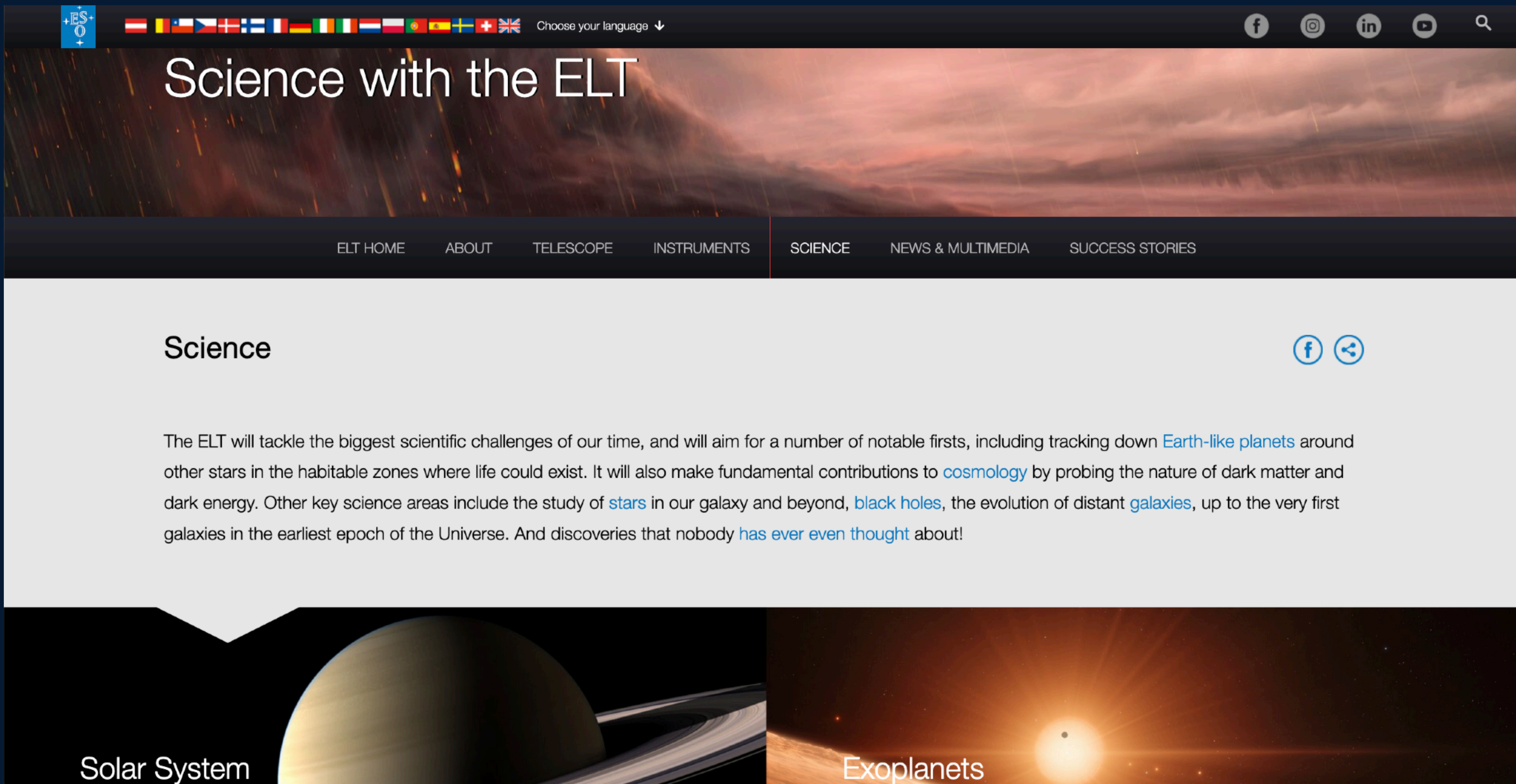
Estimating differential pistons for the Extremely Large Telescope using deep learning

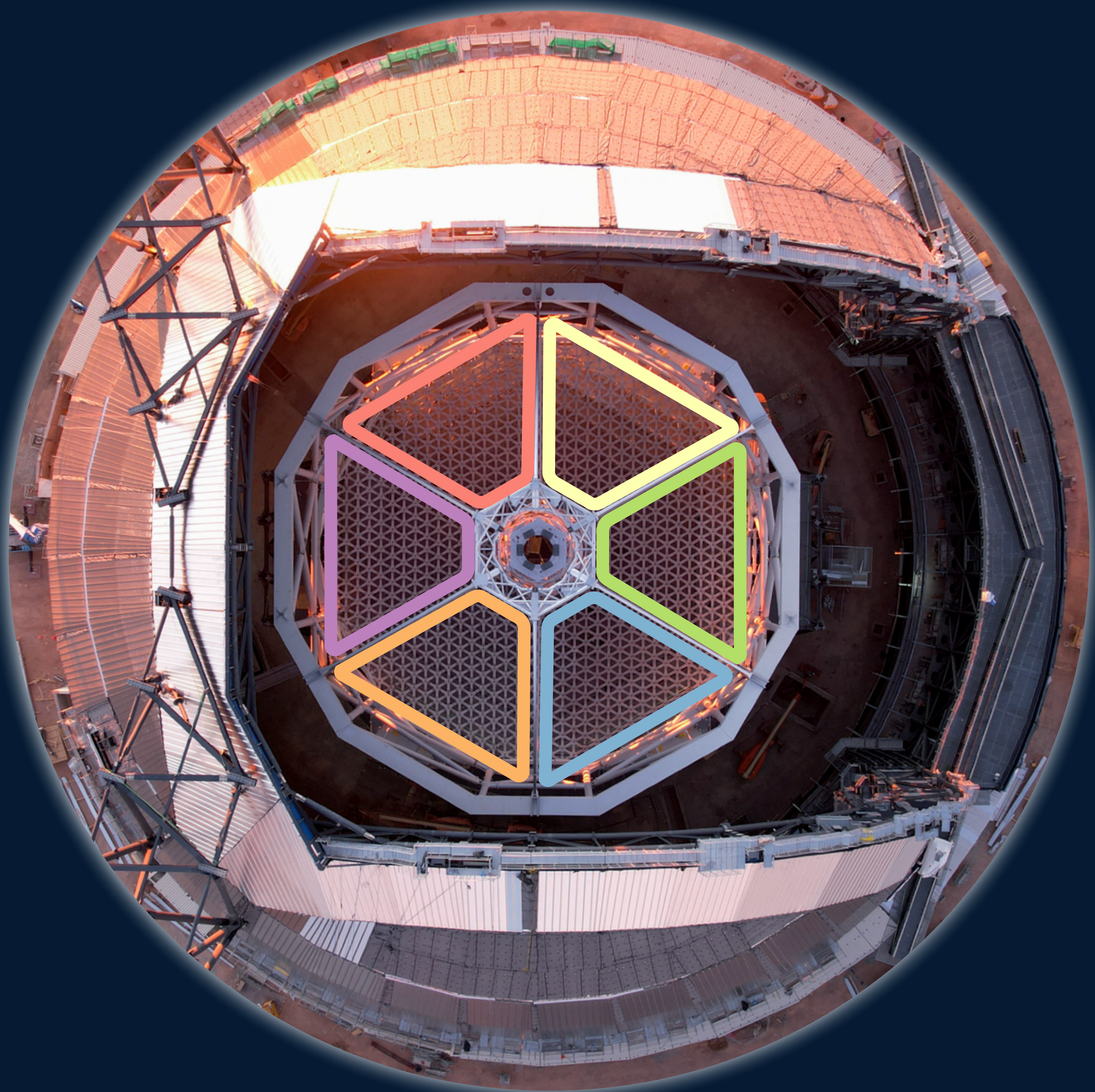
... or how to make a Residual Network measure petaling from focal plane images

By Pierre Janin-Potiron
(postdoc @ IPAG)

WITH GREAT POWER COMES GREAT INSTRUMENTAL RESPONSIBILITY



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

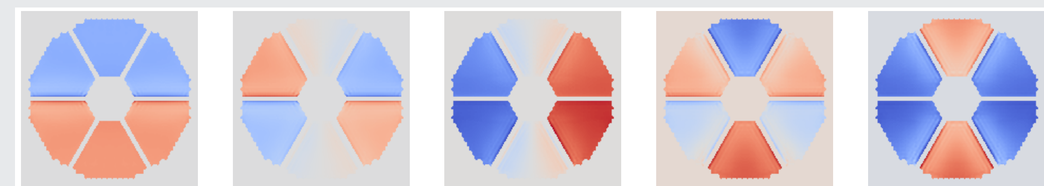
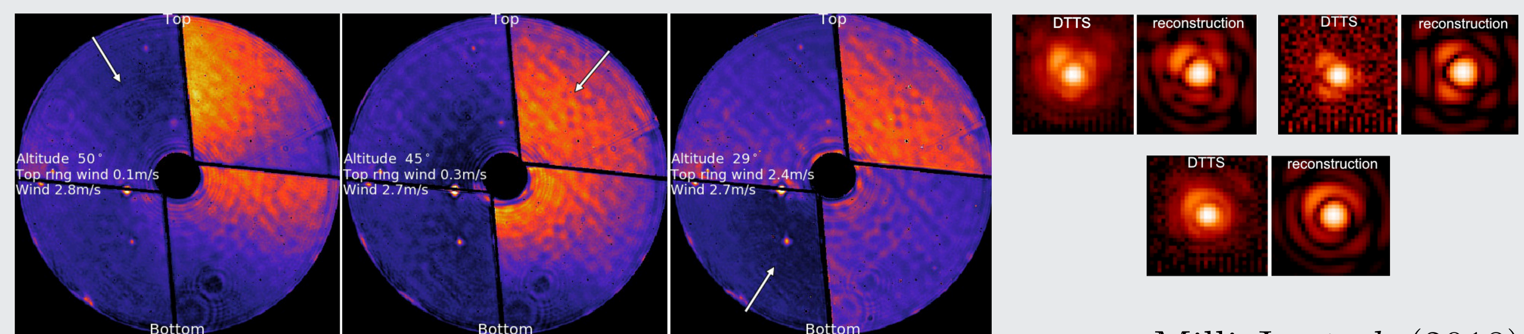


Fig. 2. Last eigenvectors of the interaction matrix: they are dominated by petal modes.

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

LOW WIND EFFECT

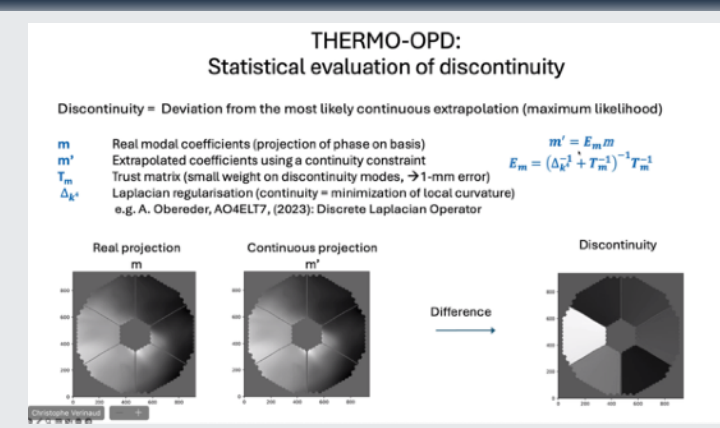
When the wind does not blow fast enough.



Milli J. *et al.* (2018)

THERMO-MECHANICAL EFFECTS

When physics finds every possible way to mess with you

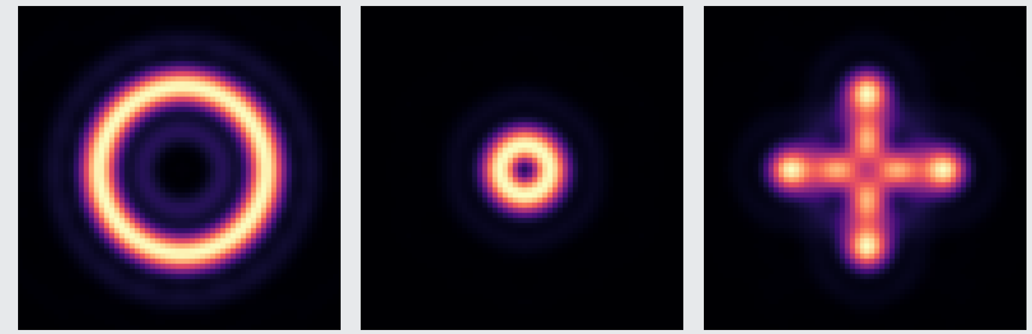


ESO

DIFFERENTIAL PISTON IS ALREADY MANAGEABLE WITH CONVENTIONAL TECHNIQUES

ADAPTATION OF THE CONTROL LOOP

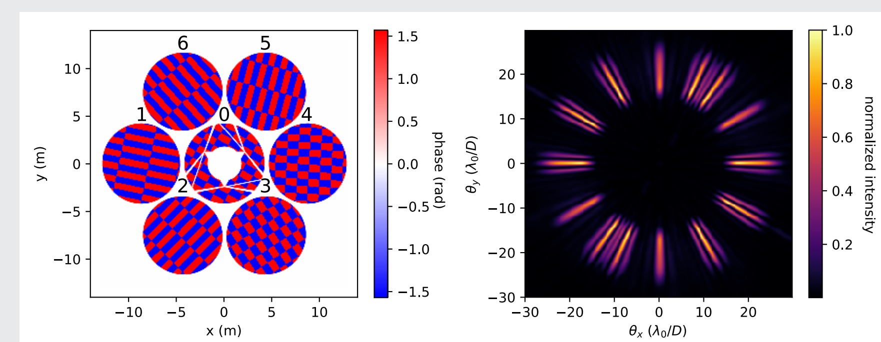
Tune the sensitivity to petal modes



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

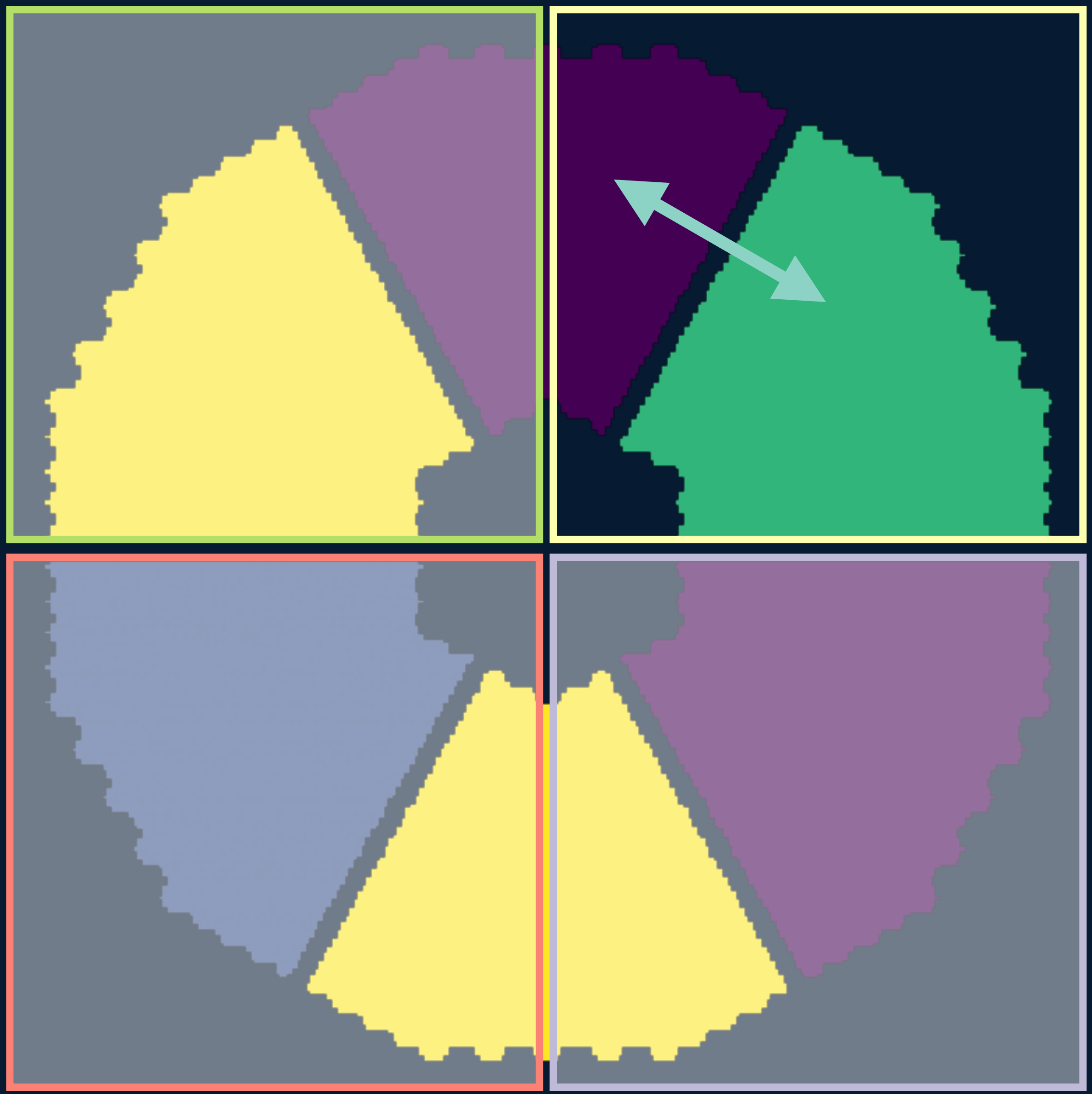
Mapping features to piston estimates

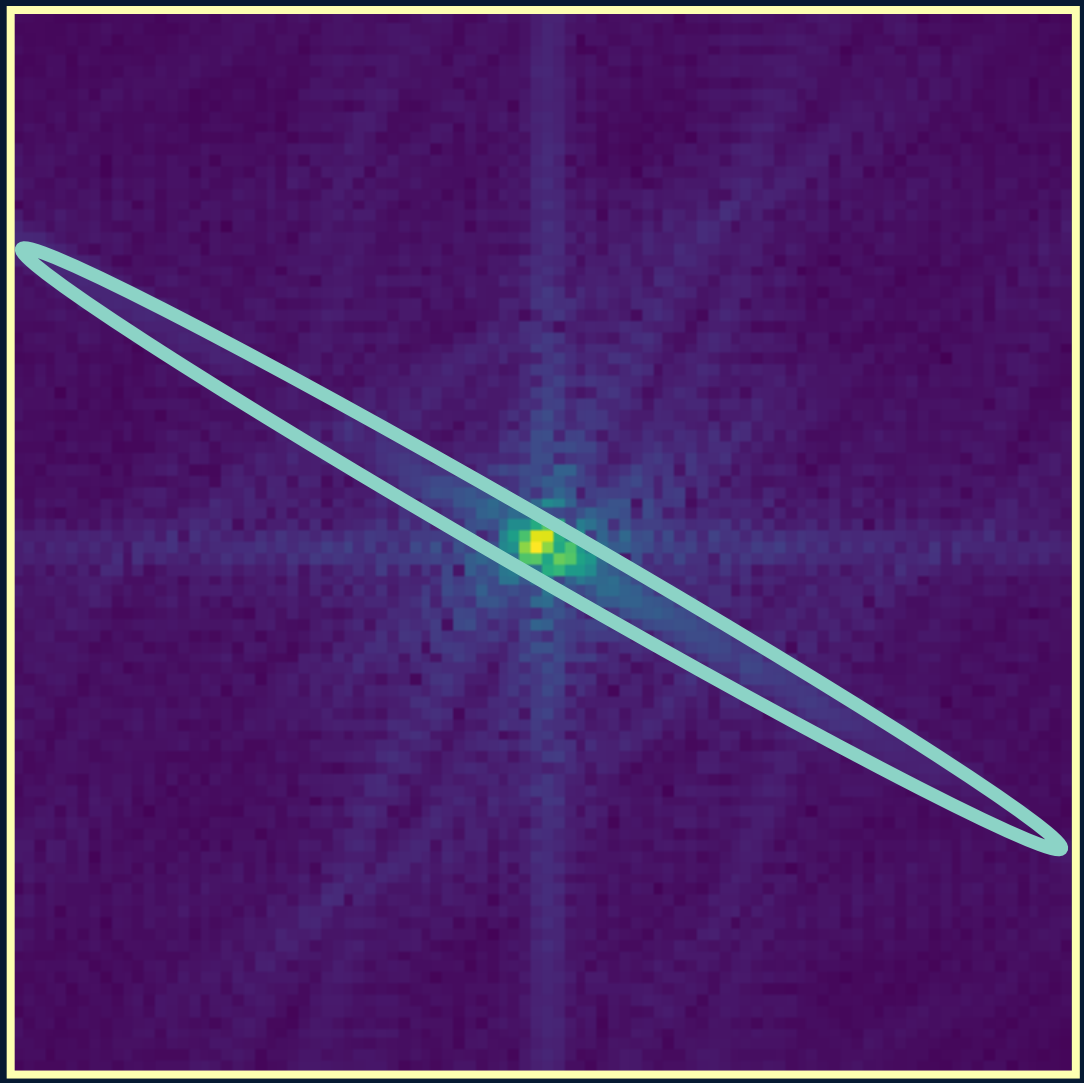
OUTPUT LAYER

```
==========================================================================================
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

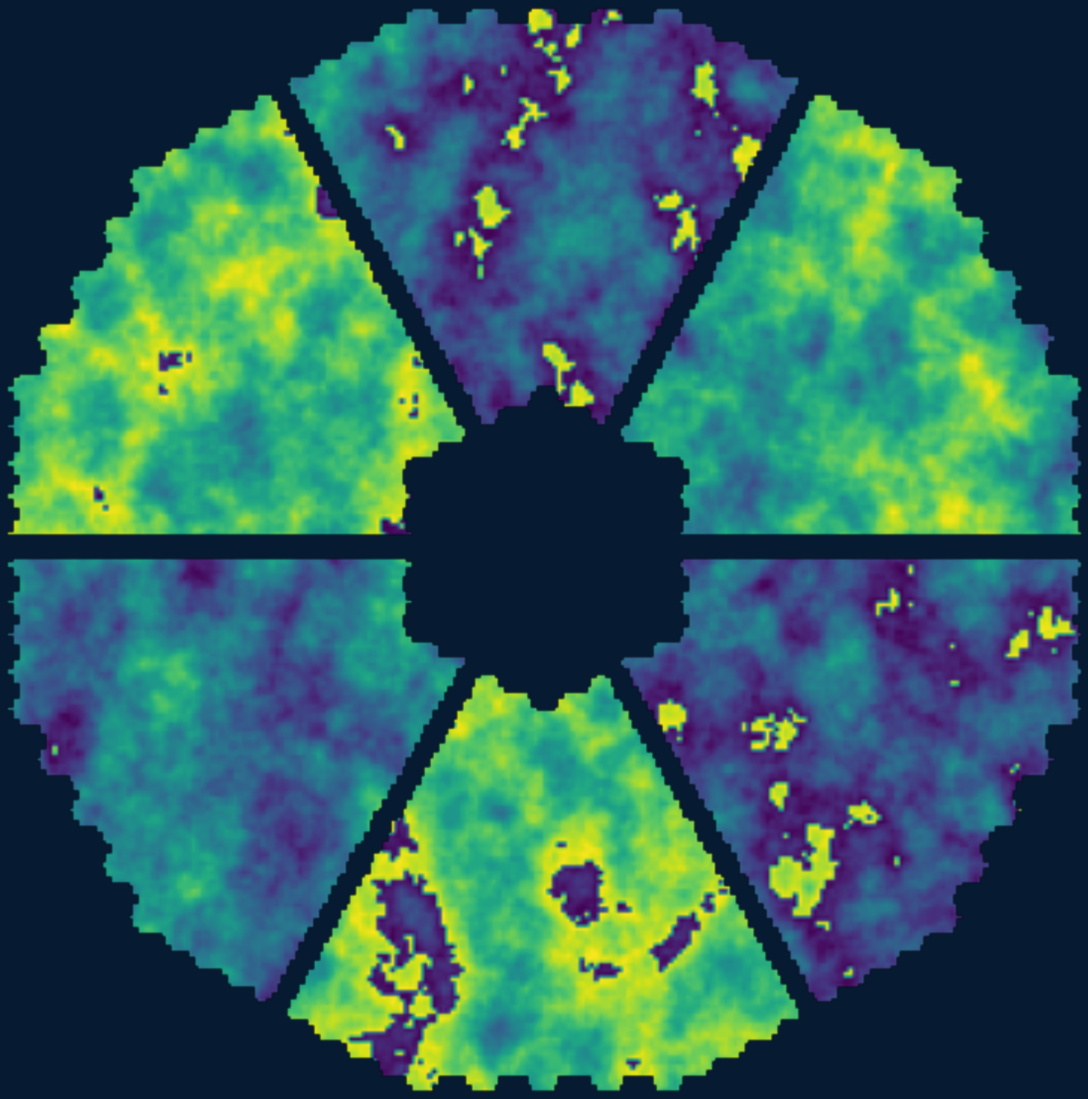
The pupil is divided into four quarters to break symmetry (and because the 2x2 SH-WFS is a thing).

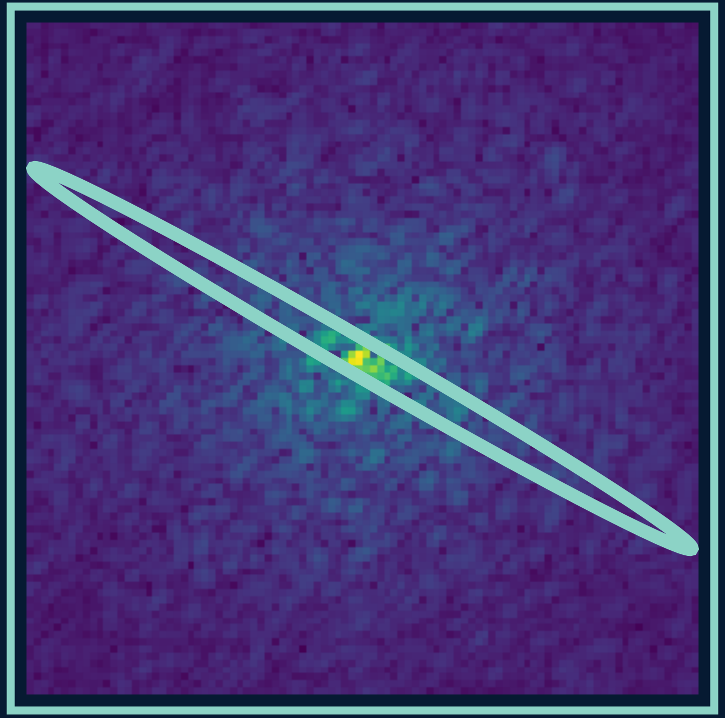


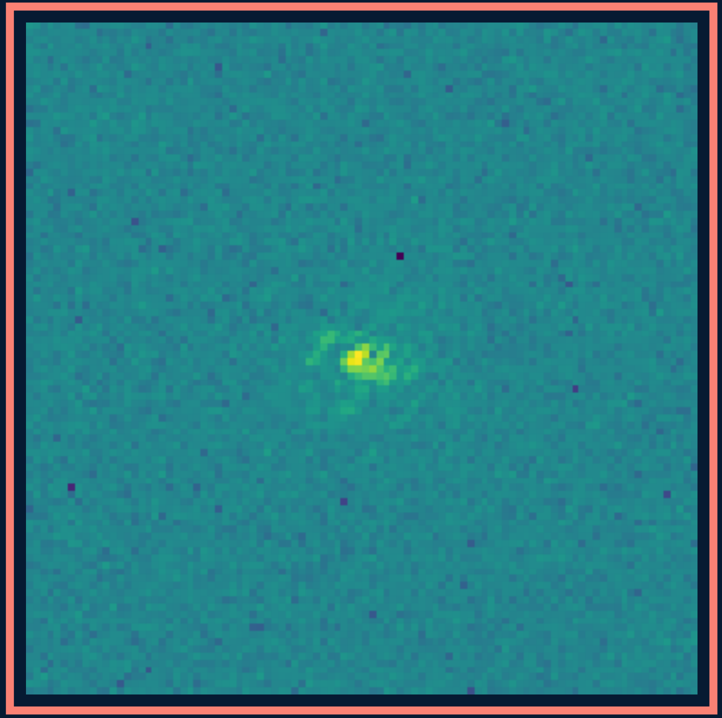


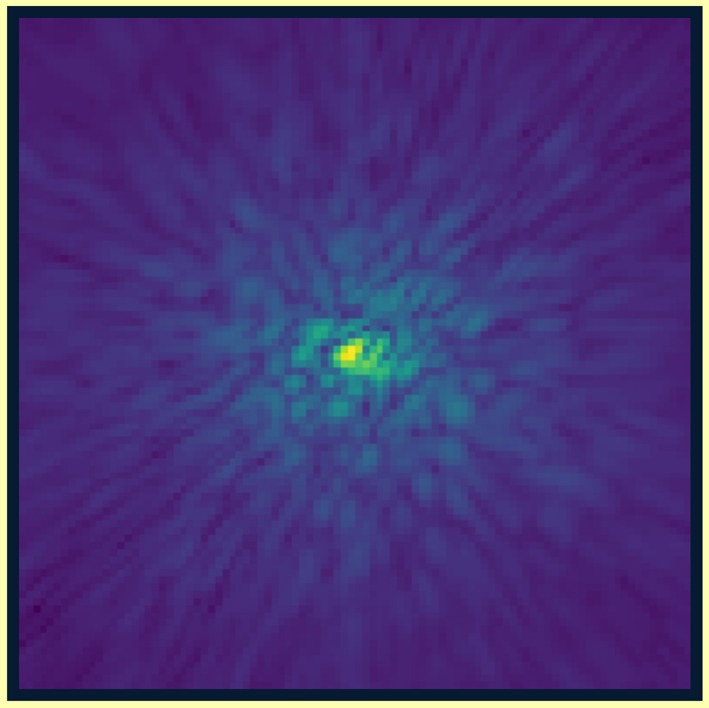
The differential piston diffraction pattern exhibits a preferred direction.

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



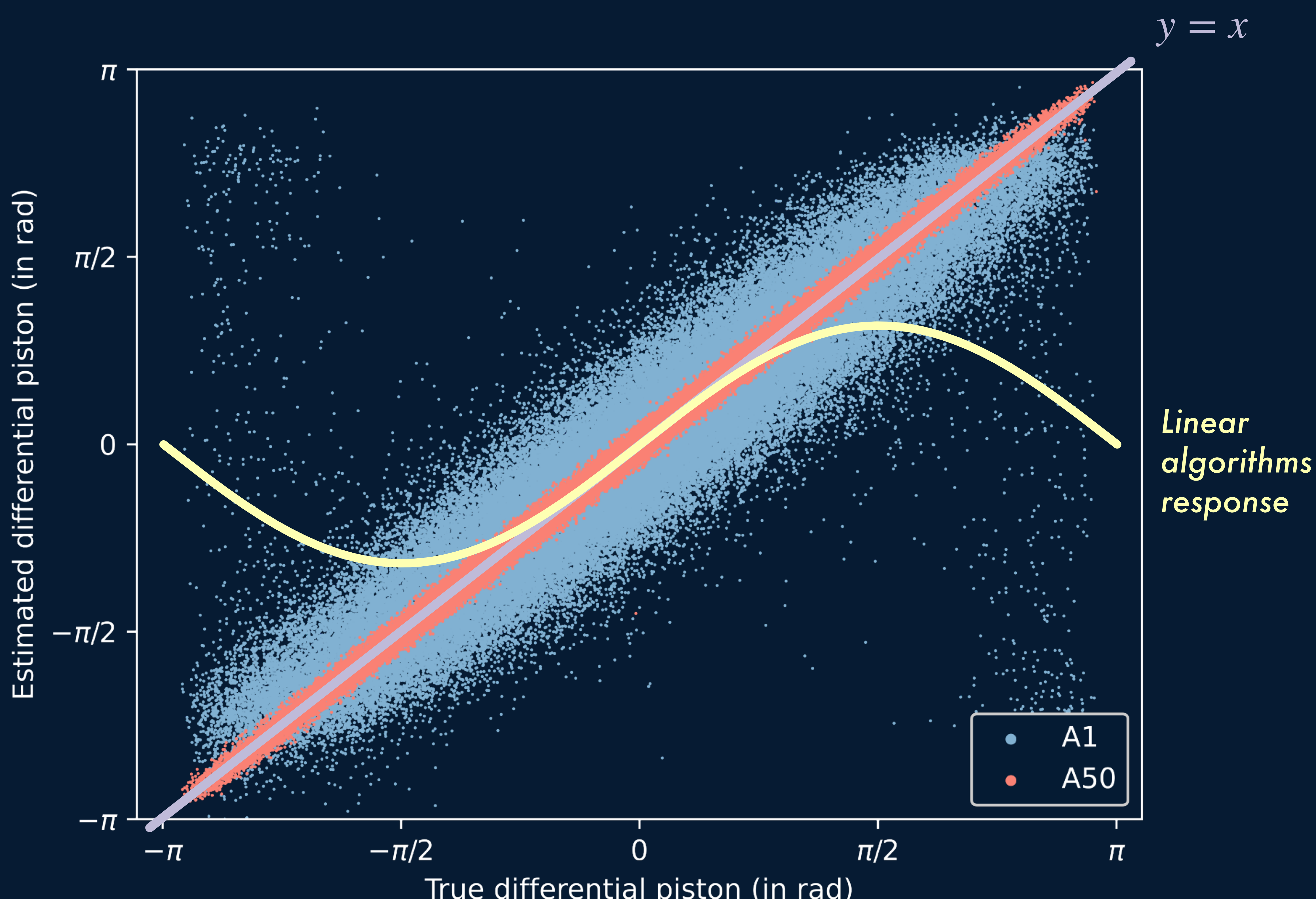






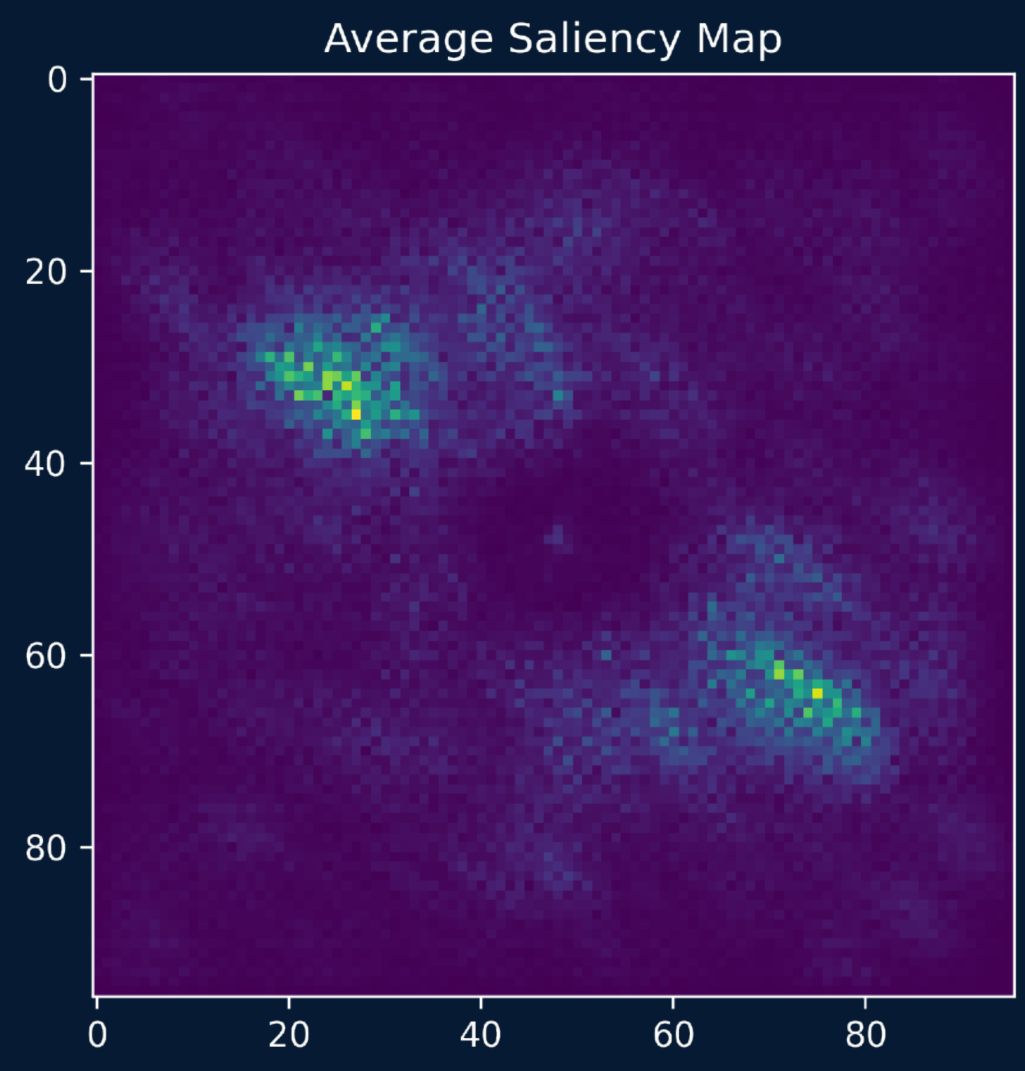
Residual turbulence speckles, detector noise, and chromatic blur all overlap with the differential piston signal.

AND THE NETWORK PERFORMS PRETTY WELL



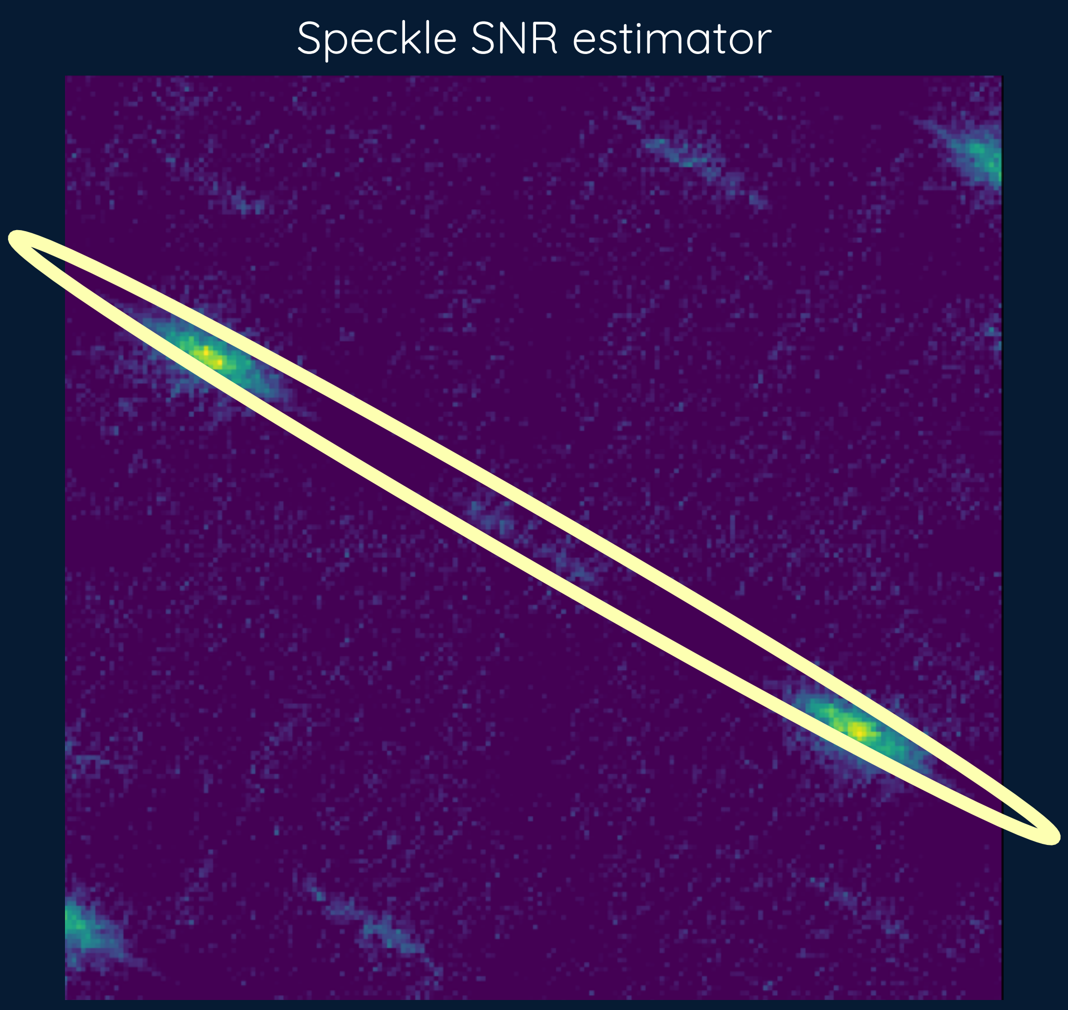
Full details in Janin-Potiron P. *et al. (2025)*

THE LEARNINGS ARE EXPLAINABLE



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

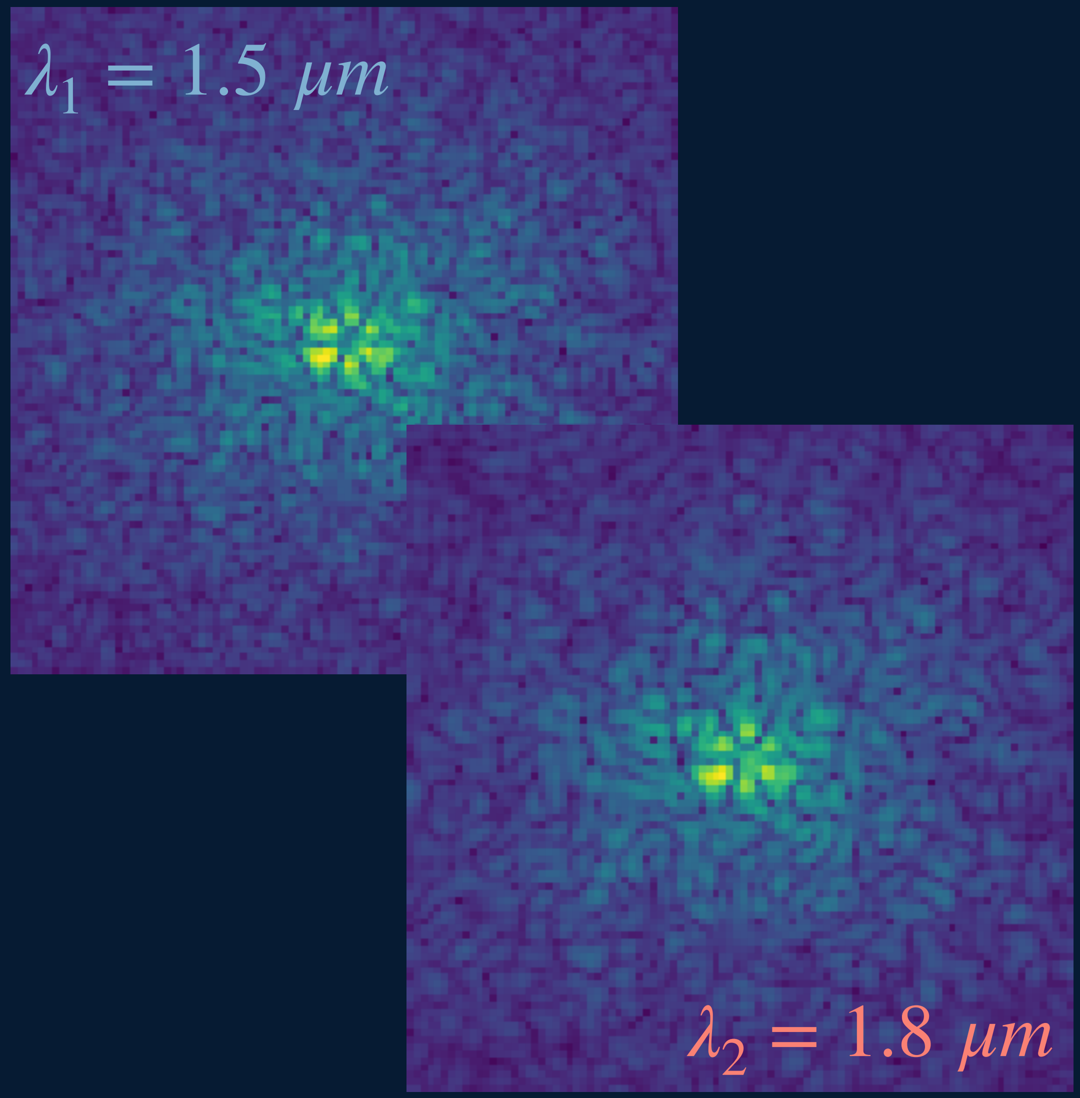
Symonyan et al. 2014



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

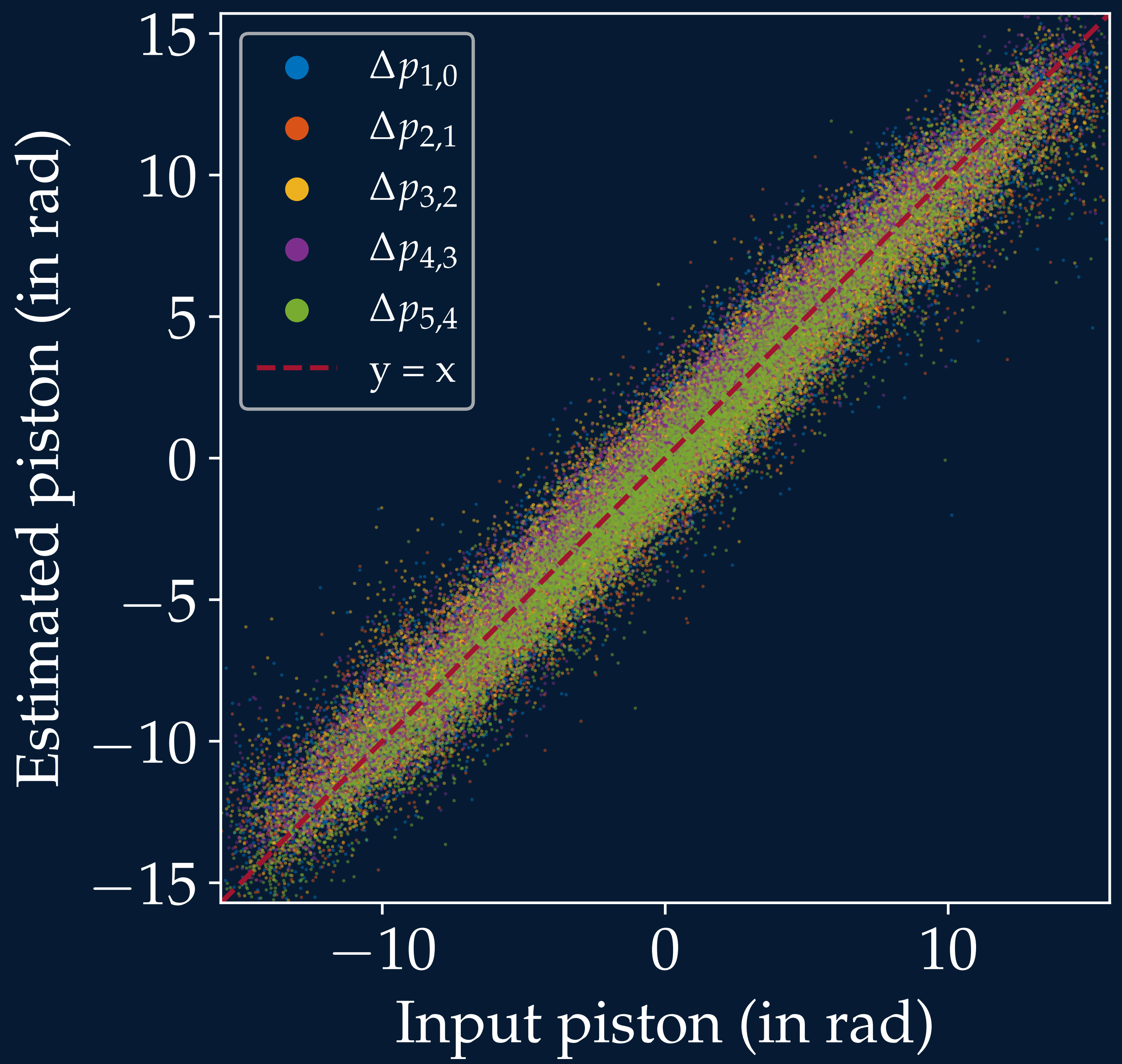
Janin-Potiron et al. 2024

CAN WE RECOVER ALL SIX PISTONS FROM TWO COLORED DEFOCUSED IMAGES?



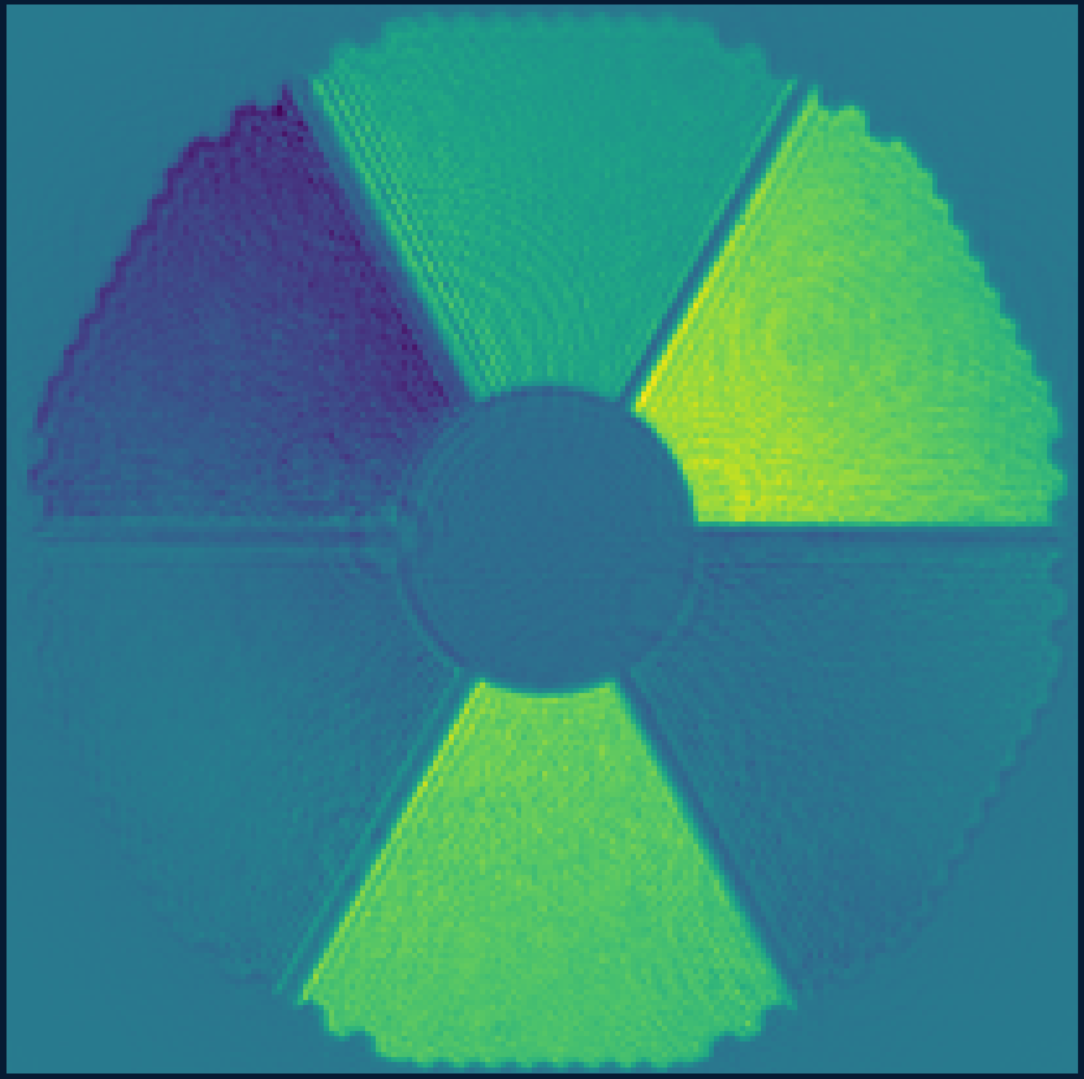
A defocus is added to the image to break the symmetry and two wavelengths are considered

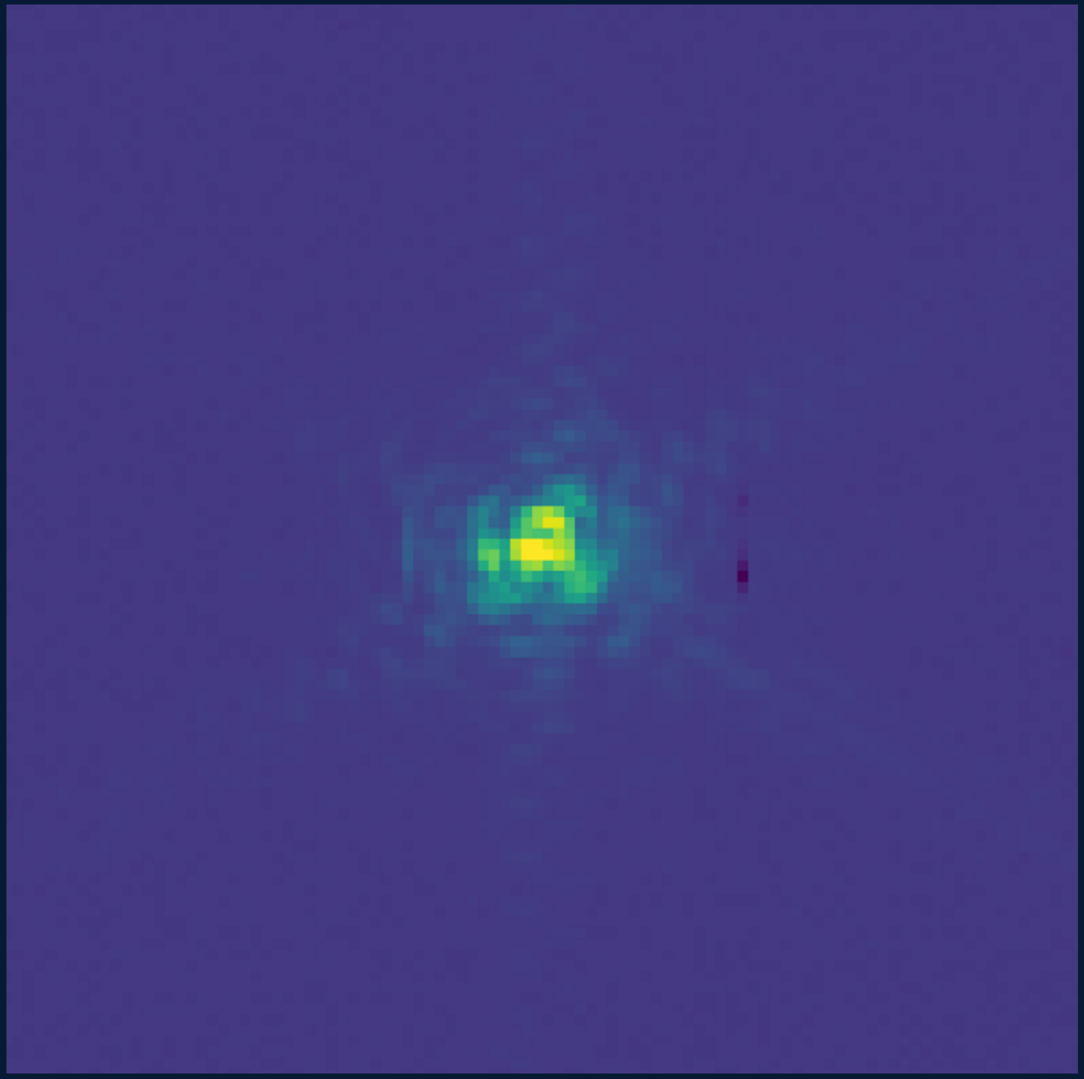
YES ! AND WE GAIN INCREASED CAPTURE RANGE WITHOUT EXTRA EFFORT.



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

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