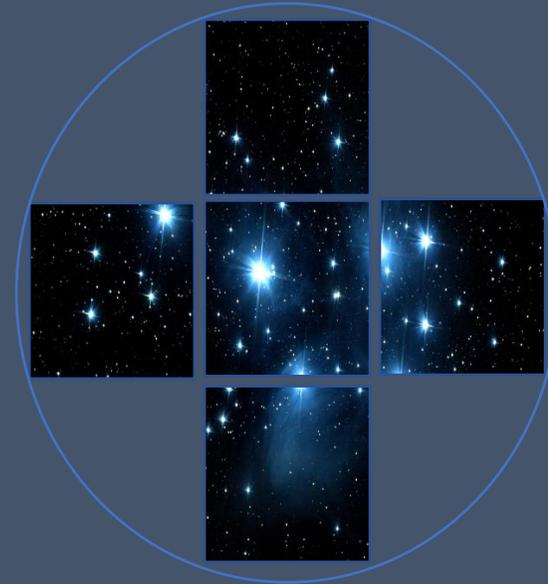
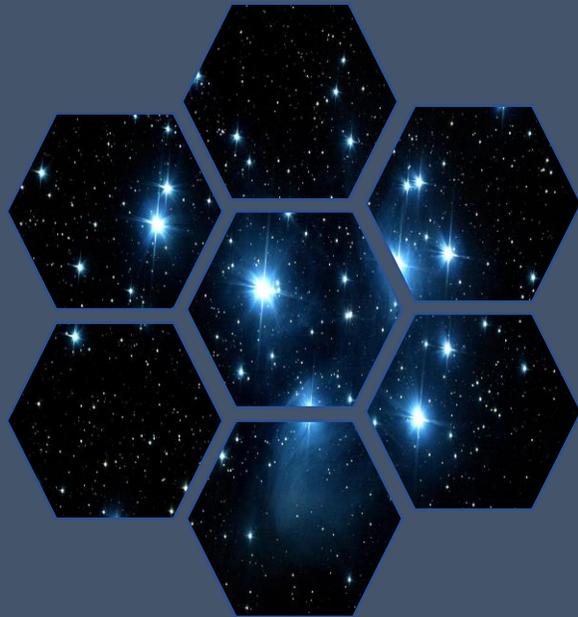
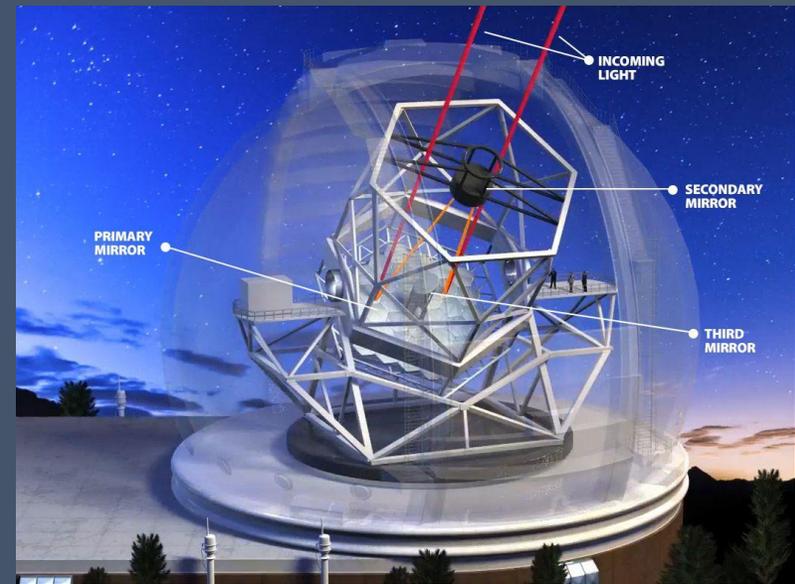


Segmented pupil phasing with deep learning

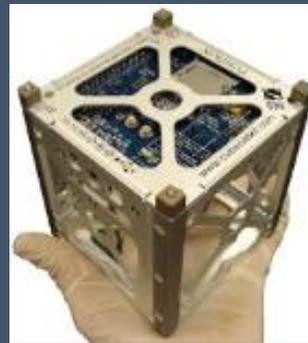
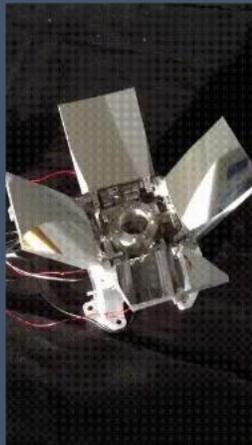


Context: Segmentation errors

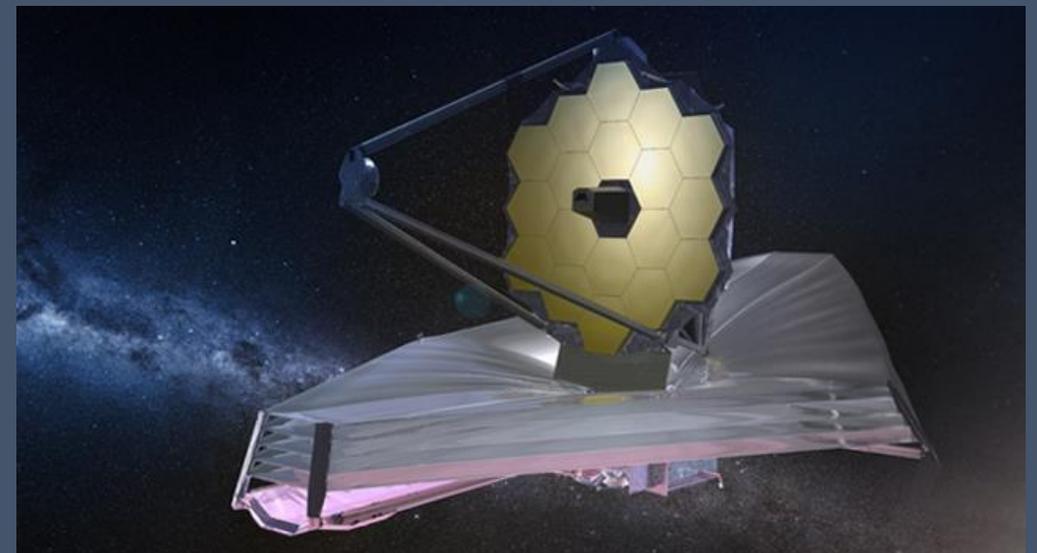
- For astronomy or Earth observation, challenge of high angular resolution
- Segmented pupil : Angular resolution > Platform



Keck Telescope



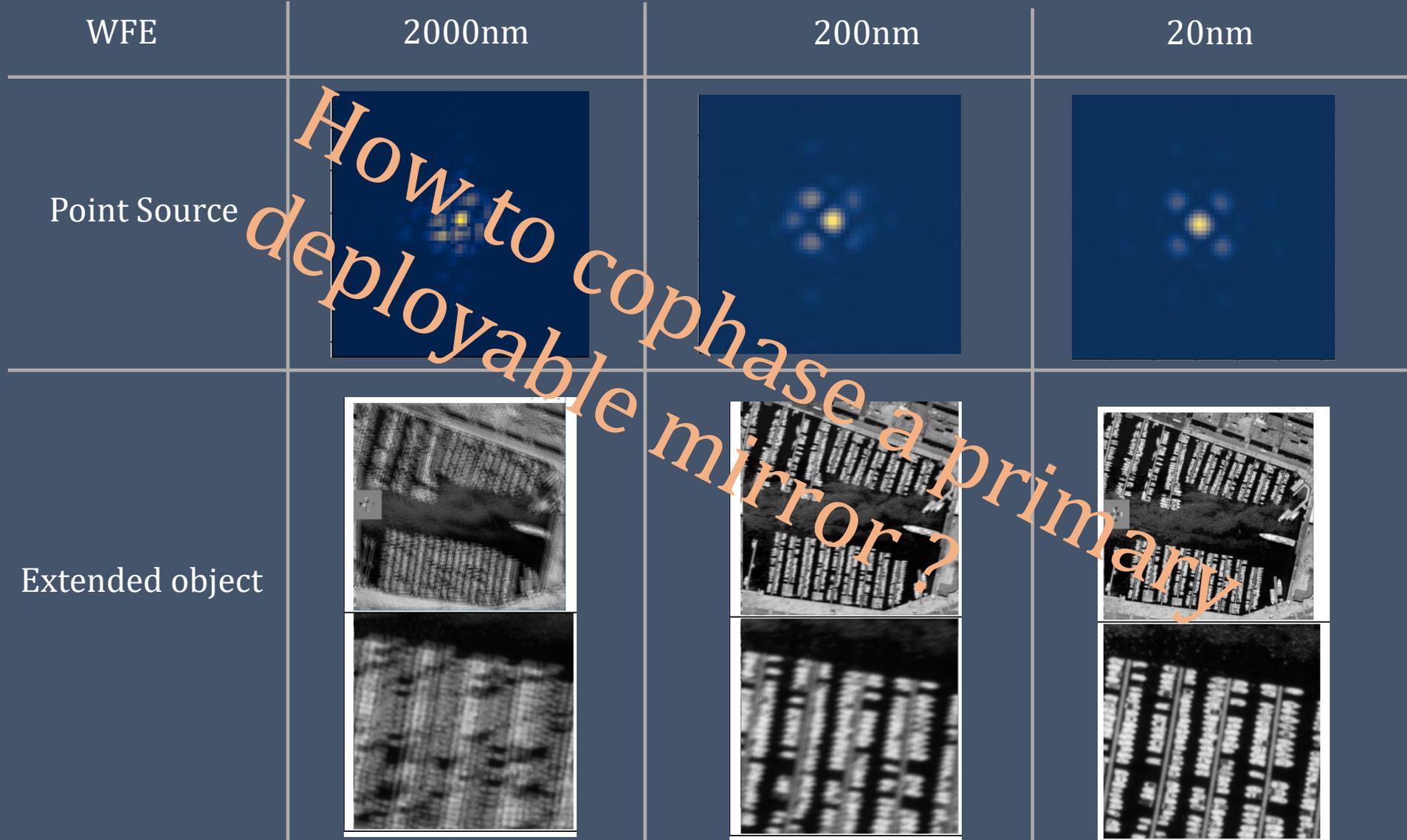
- Segmented pupil requires a perfect mirrors alignment



James Webb Space Telescope

Segmented pupil image formation

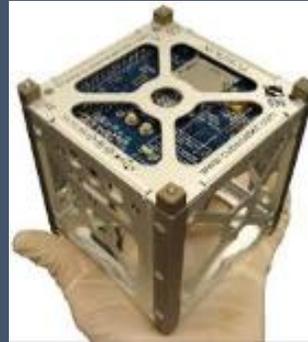
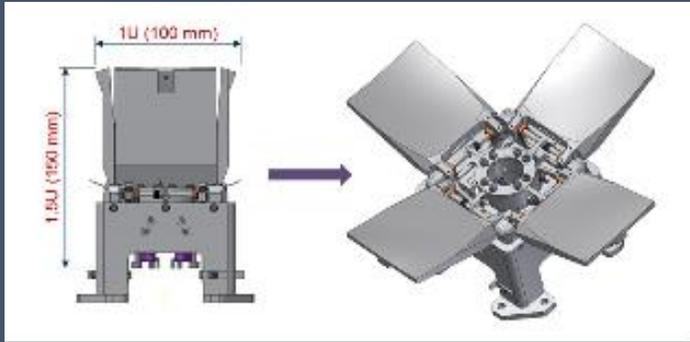
Observation in the visible



How to cophase a primary
deployable mirror?

Methods

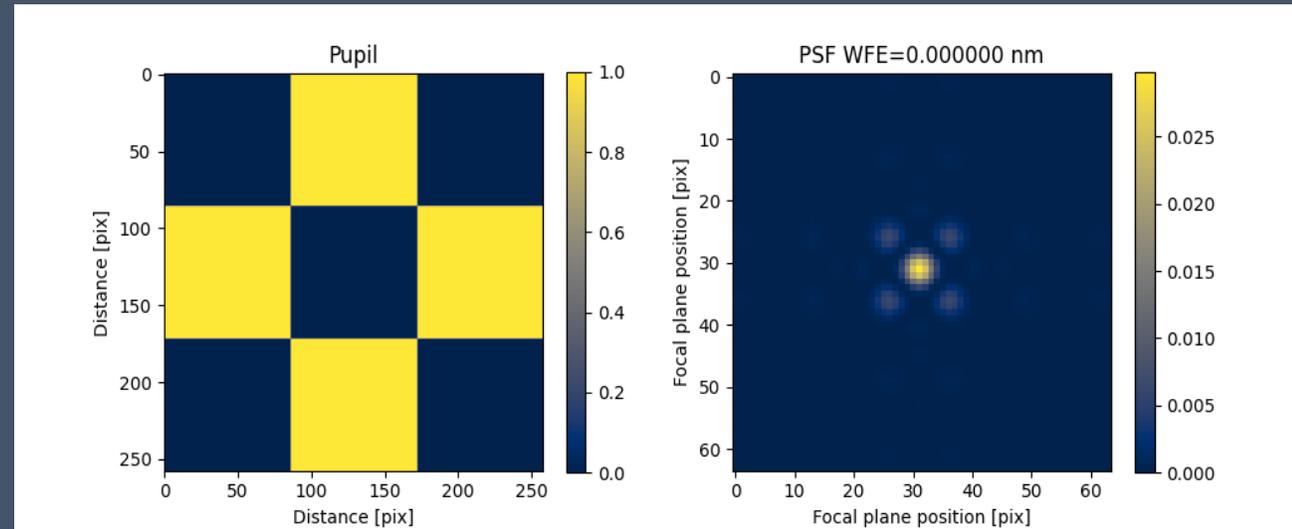
Deployable telescope at LEO for earth observation



- Computing burden
- No additional optics -> FPWFS
- $PSF = \left| FT \left(A e^{\frac{2i\pi OPD}{\lambda}} \right) \right|^2$
- Thermal gradient sensitivity
- PTT control

DEEP LEARNING

- Non linear problem solvers
- Computing burden: Training off-line
- 2D image compatibility
- Widely used for WFS ⁽¹⁾⁽²⁾⁽³⁾
 1. Point source
 - Understand the NN behavior
 2. Extended scene



(1) Yohei Nishizaki, Matias Valdivia, Ryoichi Horisaki, Katsuhisa Kitaguchi, Mamoru Saito, Jun Tanida, and Esteban Vera, "Deep learning wavefront sensing," *Optics Express* 27, 240-251 (2019)

(2) Orban De Xivry, Gilles, et al. "Focal plane wavefront sensing using machine learning: performance of convolutional neural networks compared to fundamental limits." *Monthly Notices of the Royal Astronomical Society* 505.4 (2021): 5702-5713.

(3) Paine, Scott W., and James R. Fienup. "Machine learning for improved image-based wavefront sensing." *Optics letters* 43.6 (2018): 1235-1238.

Summary

- Inside the black box :

- 1 Pupil – 1 Mode
- 1 Pupil – 2 Modes
- 2 Pupils – 1 Mode
- 2 Pupils – 2 Modes

- Full Pupil

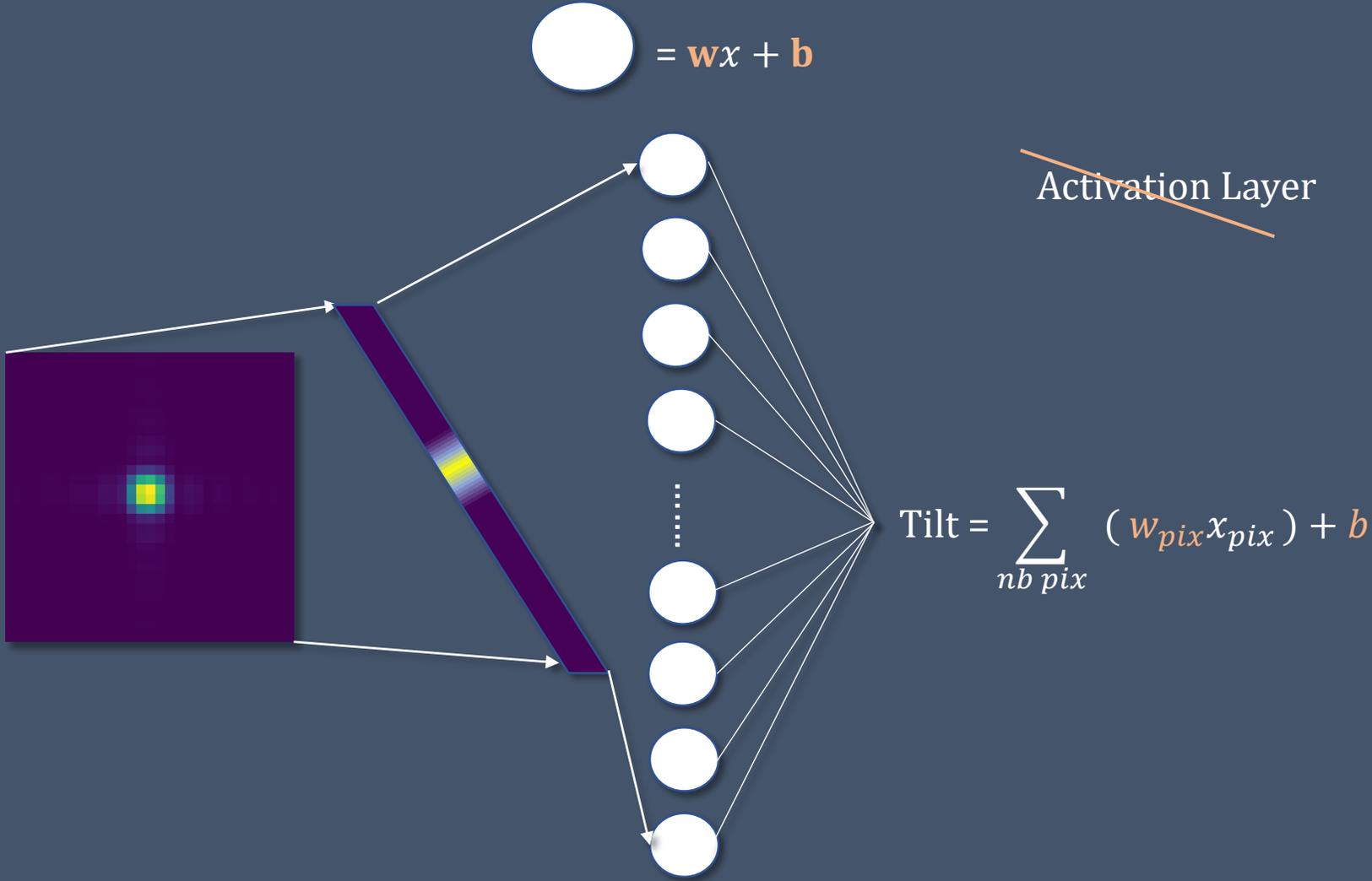
- Validation
- Noise
- Stronger aberrations



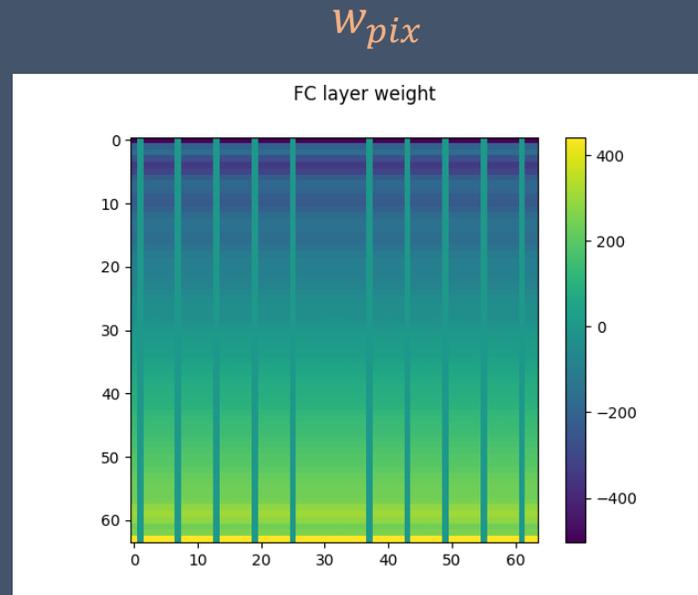
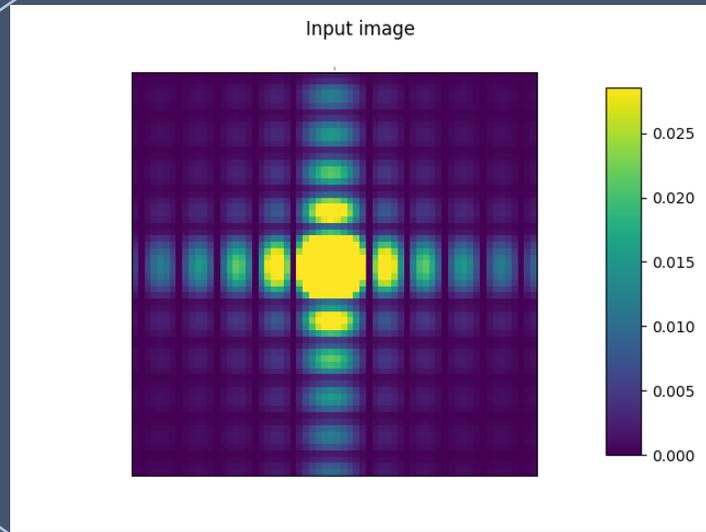
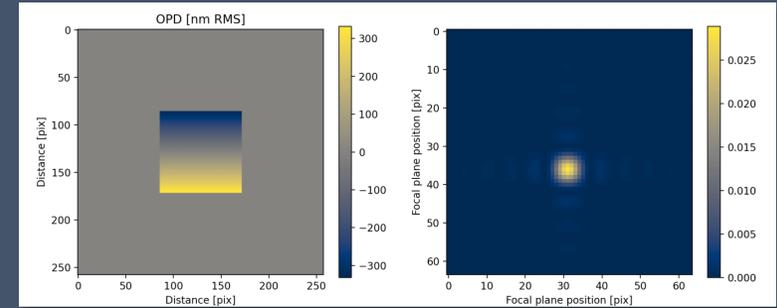
Find the smallest architecture to make the NN interpretable



Single fully connected layer



1 PUPIL – 1 TIP



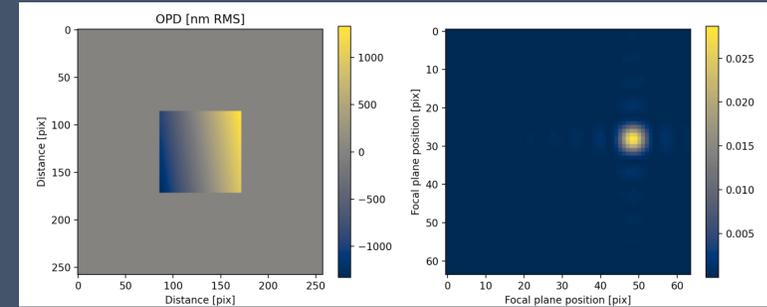
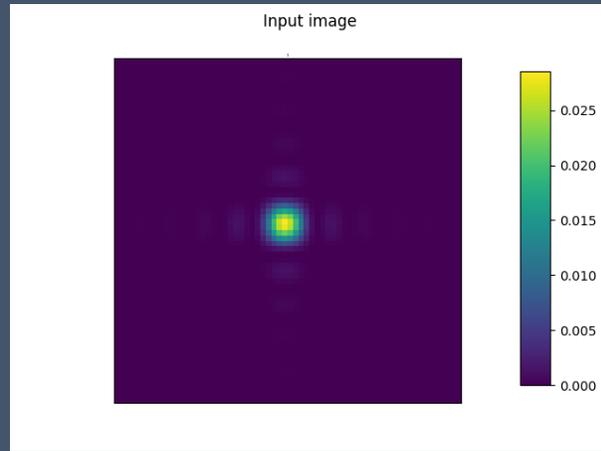
Biais = - 3.75

~ COG

$$COG = \int xf(x)dx$$

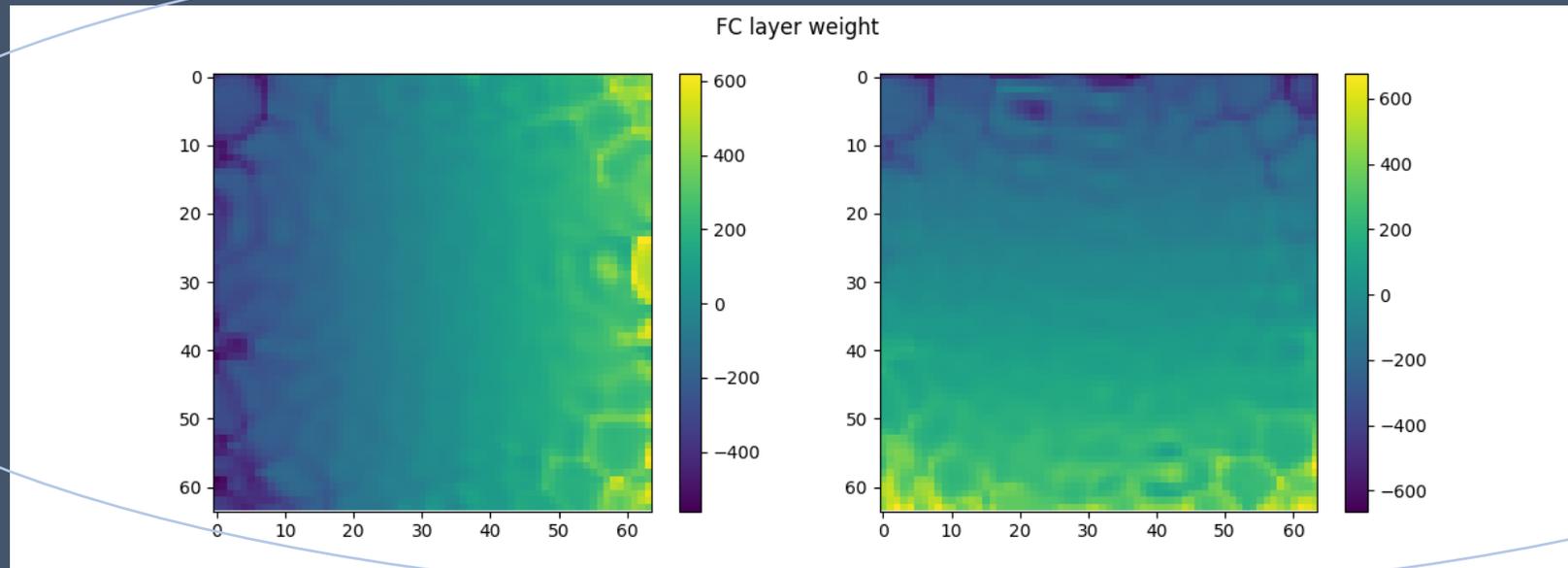
$$\text{Tilt} = \sum_{nb\ pix} (w_{pix}x_{pix}) + b$$

1 PUPIL - TIP/TILT



W_{TIP}

W_{TILT}

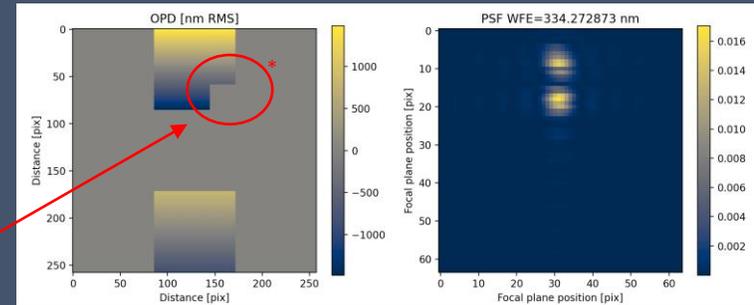


$$Bias_{TIP} = 0.47$$

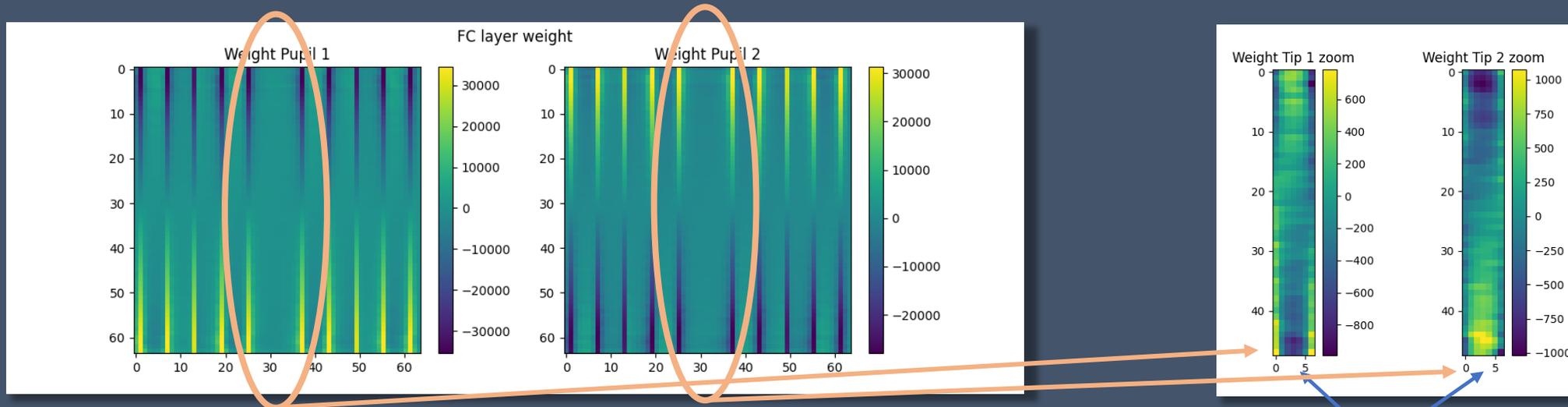
$$Bias_{TILT} = 2.02$$

~ COG

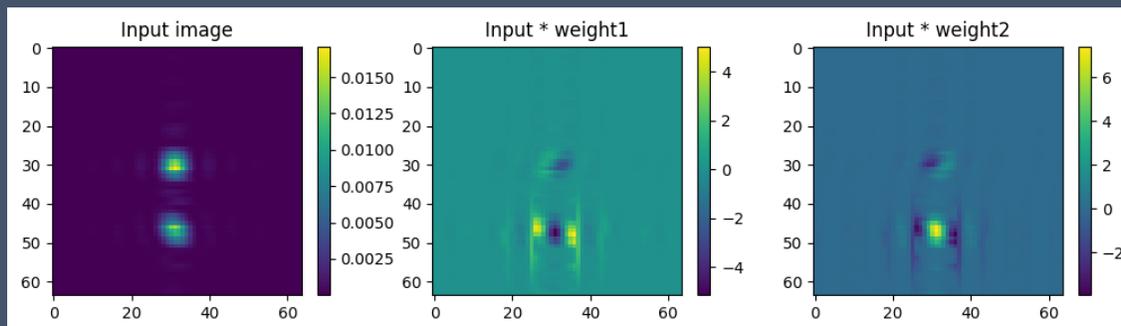
2 PUPILS - TILT



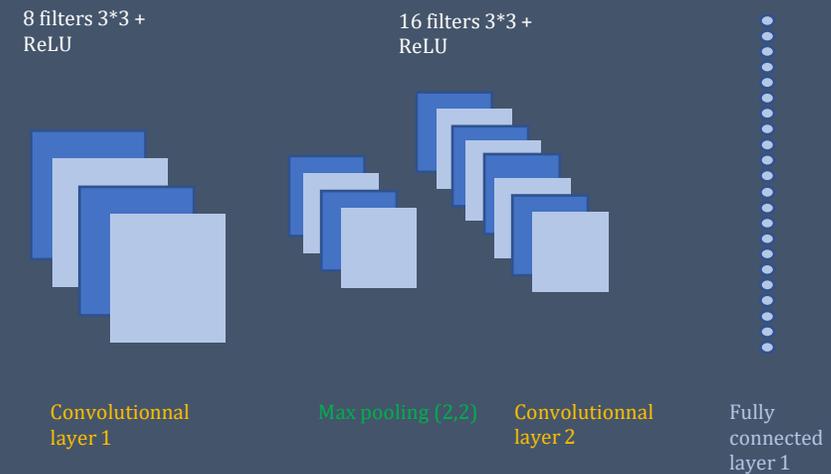
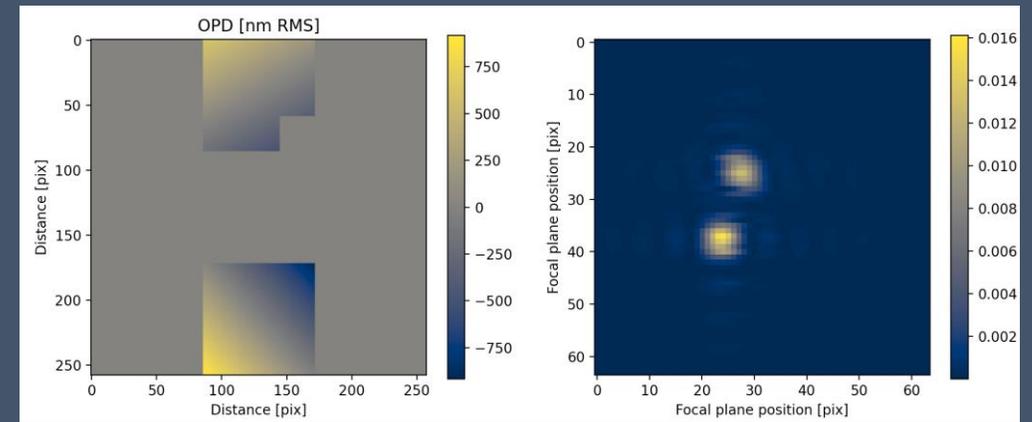
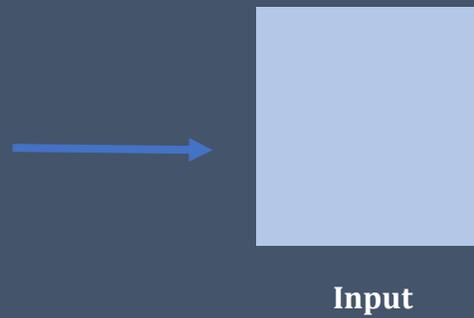
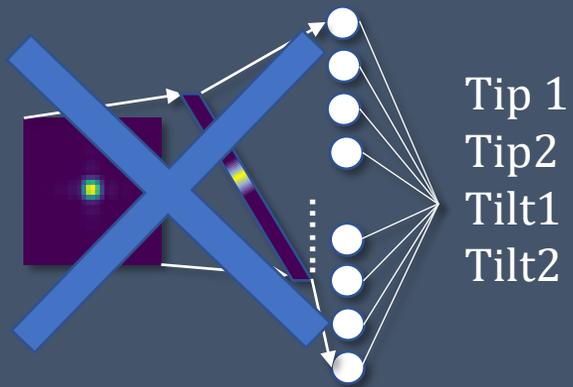
Introduce pupil asymmetry



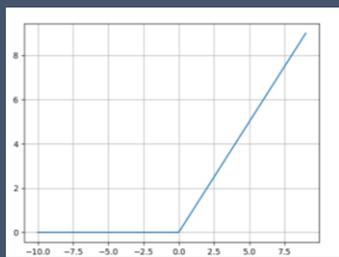
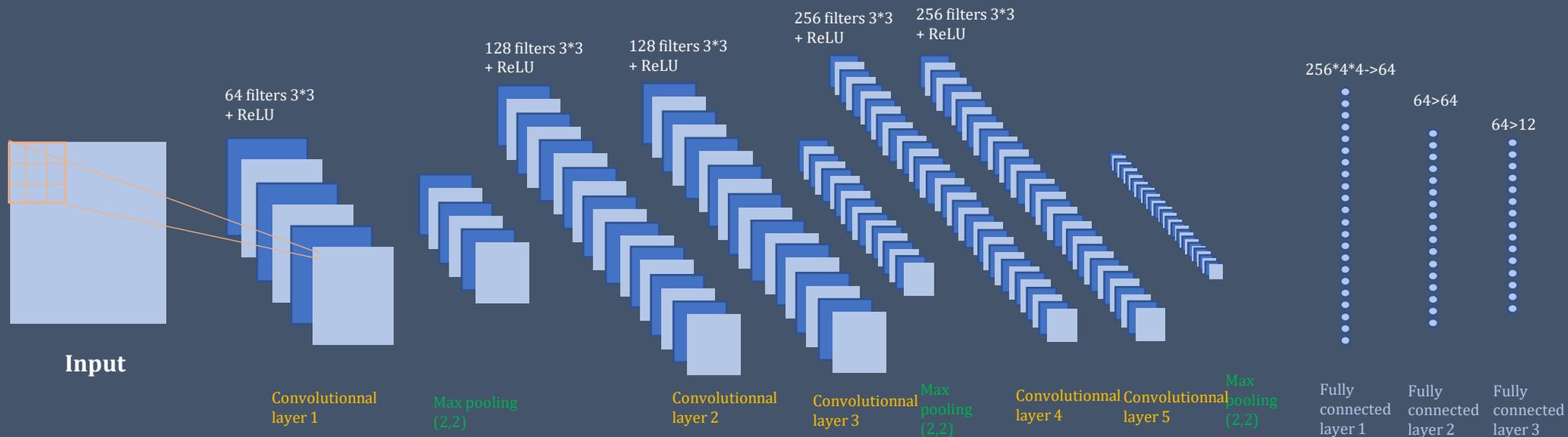
Still the COG ramp !



2 PUPILS - TIP/TILT



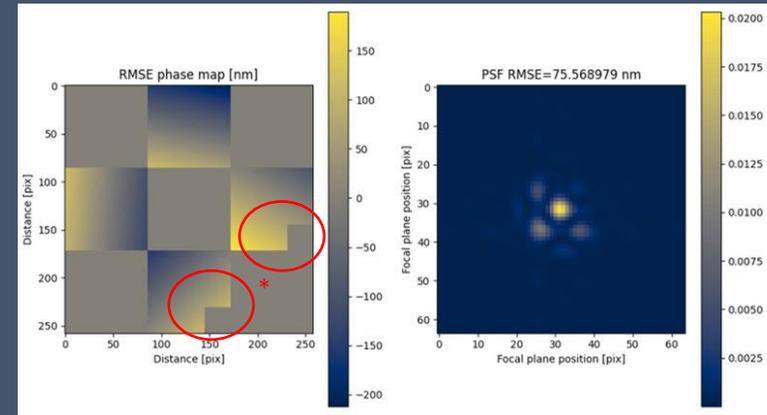
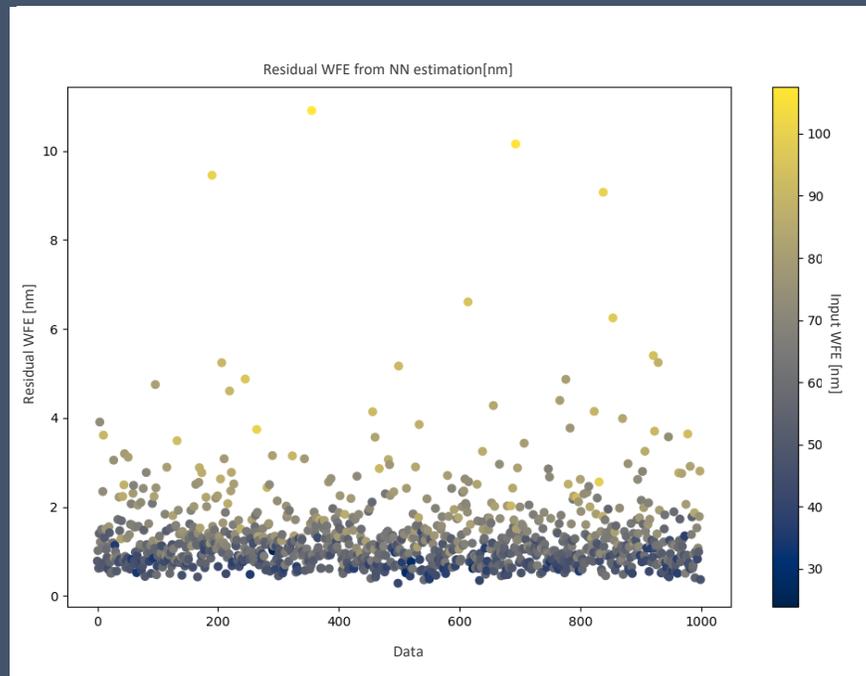
Full pupil- 12 coefficients



ReLU

Full pupil – 12 Coefficients

Low input WFE

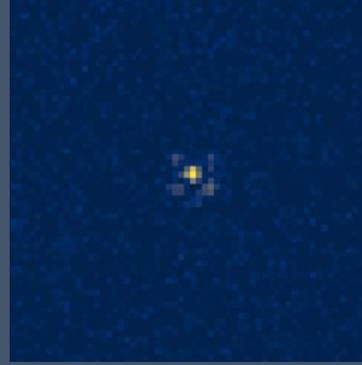


- Acceptable impact on the image
- Futur design compatible

What now :

- Noise
- Stronger aberrations
- Others aberrations

Noise



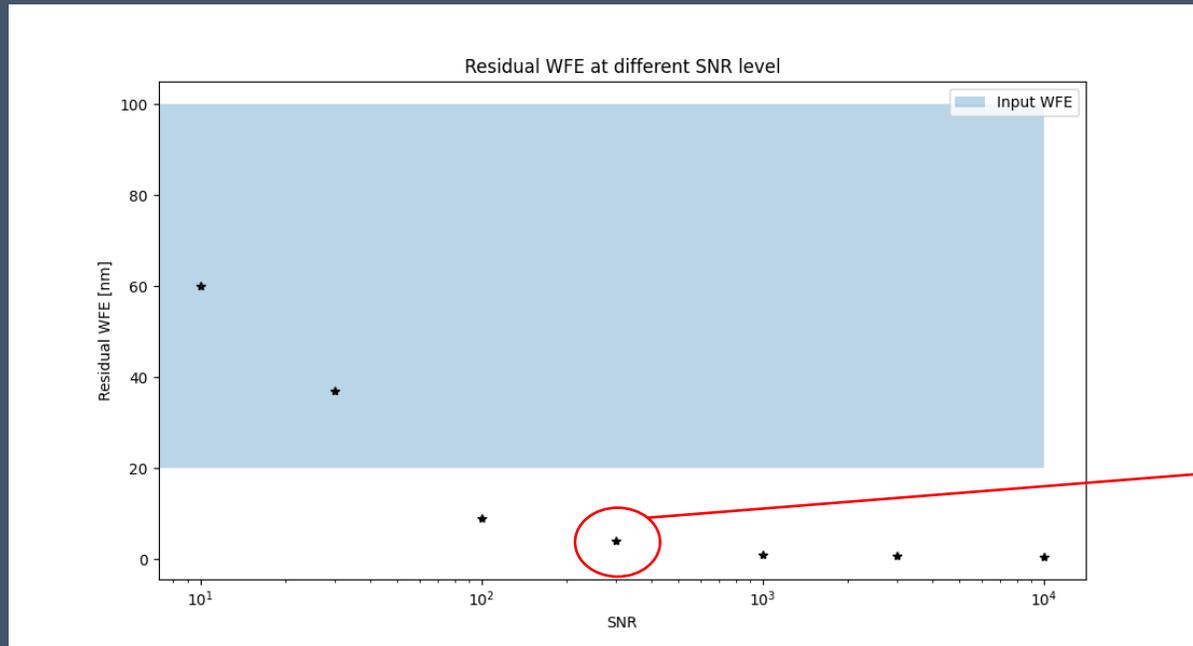
SNR = 30



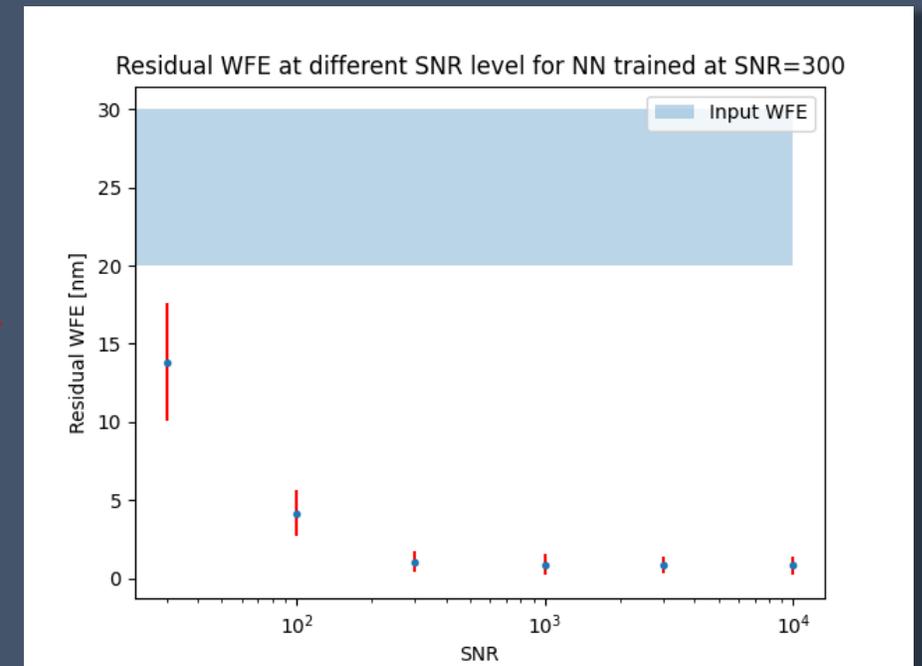
SNR = 300



SNR = 3000

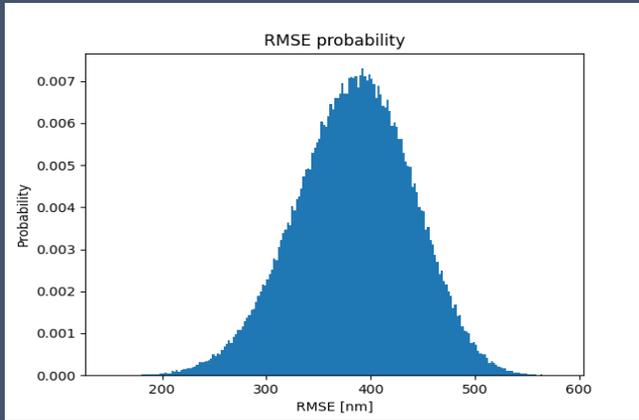


- Trained on a given SNR ratio
- Evaluated on a different SNR



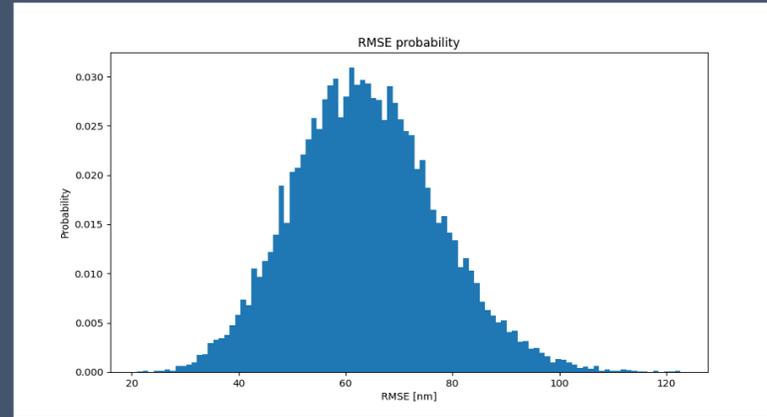
Stronger aberrations

NN 1



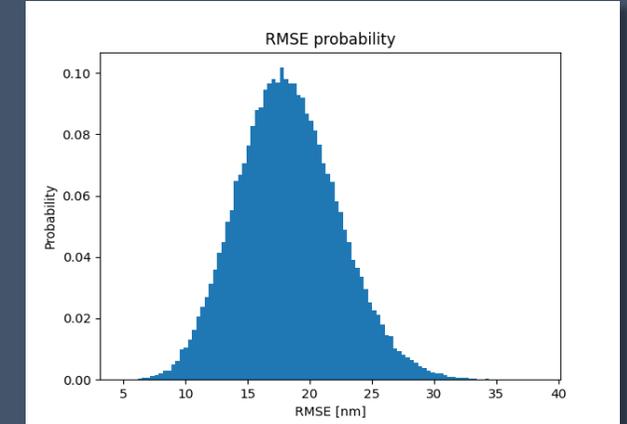
Mid -High aberrations

NN 2

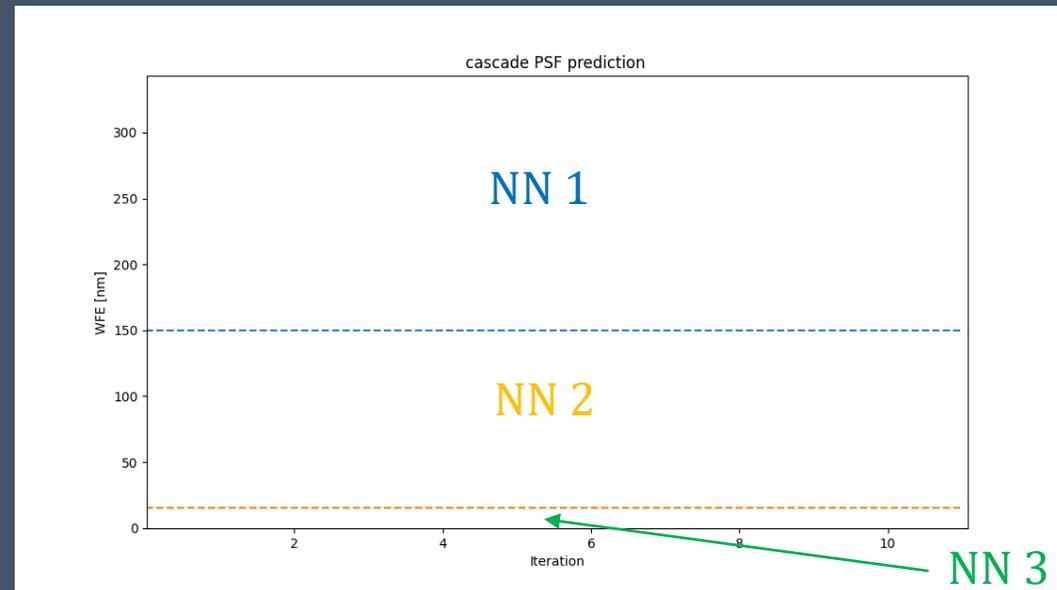


Low aberrations

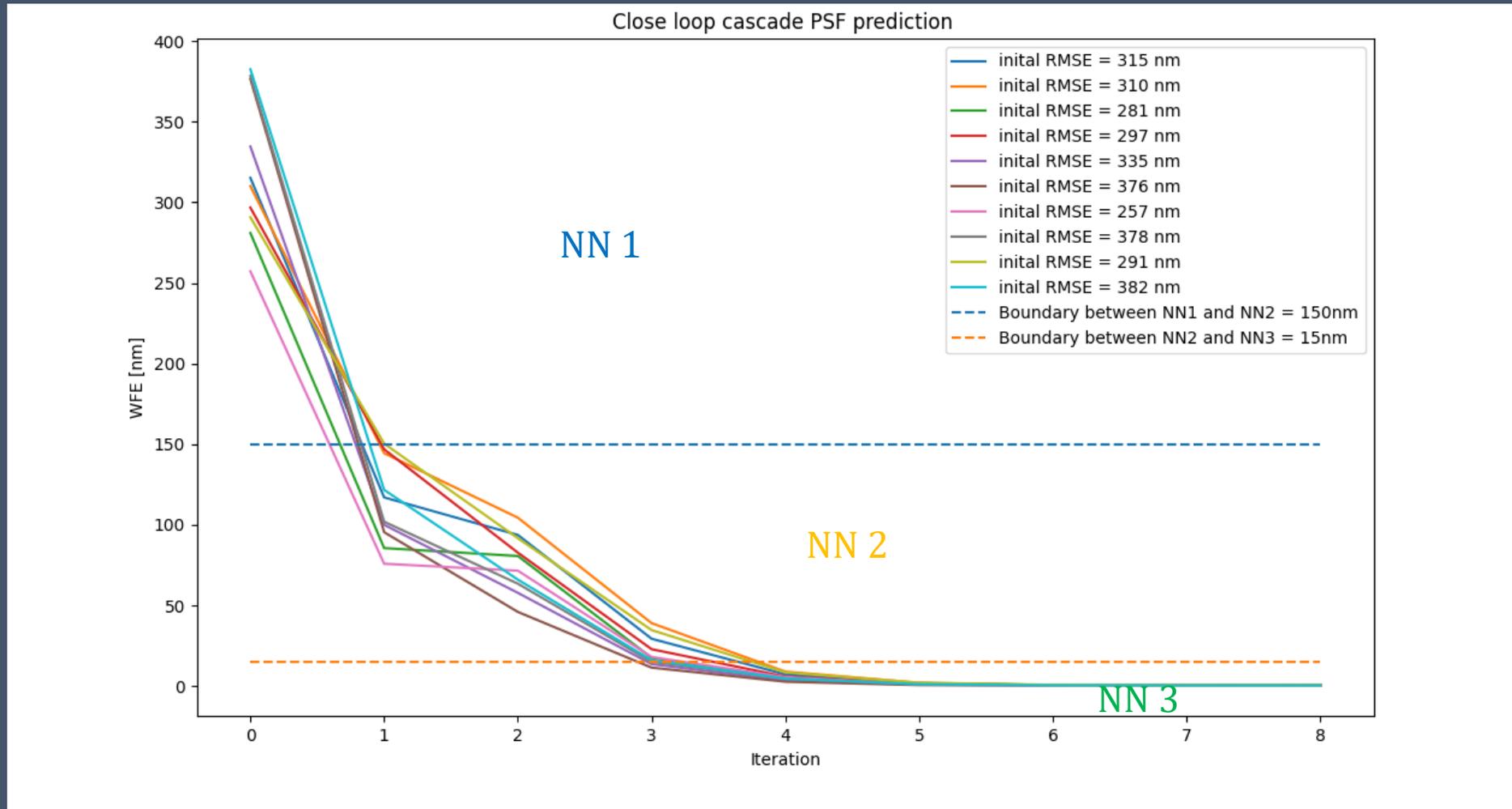
NN 3



Very low aberrations

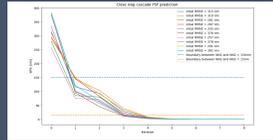


Current solution : cascade

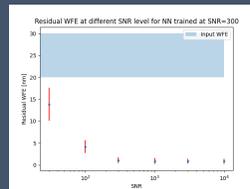


Conclusion

- NN able to measure aberrations from single image



- Robust to noise



- Improvement from state of the art method

	Residual WFE [nm]	Time [s]	Relies on a model ?
NN	1.2	0.018	Yes
Image Sharpening	0.085	3.75	No

& Further work

- Study the extended scene
- Point source :
 - Higher order aberrations
 - Search for a more generalized NN (deeper architecture)