A Simulator-based Autoencoder approach for Focal-Plane Wavefront Sensing:

principle, vortex phase diversity, perspectives for on-sky test

Maxime Quesnel[a,b]

Gilles Orban de Xivry[b], Olivier Absil[b], Gilles Louppe[a], Jyotirmay Paul[b]

[a]Montefiore Institute of Electrical Engineering and Computer Science

[b]Space sciences, Technologies and Astrophysics Research (STAR) Institute

University of Liège

GRD seminar at Laboratoire d'Astrophysique de Marseille

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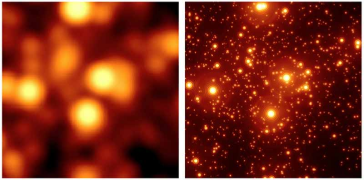
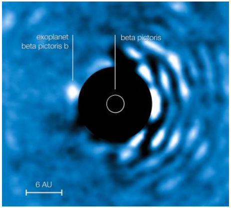
maxime.quesnel@uliege.be

Exoplanet imaging

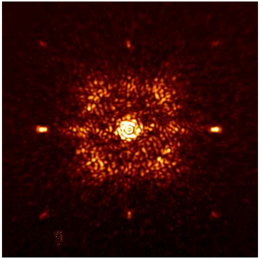
- Limitations:
  - ⋆ **small angular separations**
  - ⋆ **high contrasts**
- Instrumental solutions:
  - ⋆ **adaptive optics**
  - ⋆ **coronagraphy**
- **Quasi-static speckles** remain.



Credit: GMT

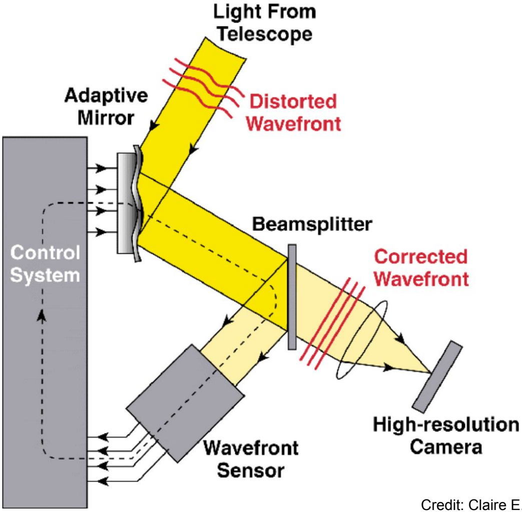


Credit: ESO



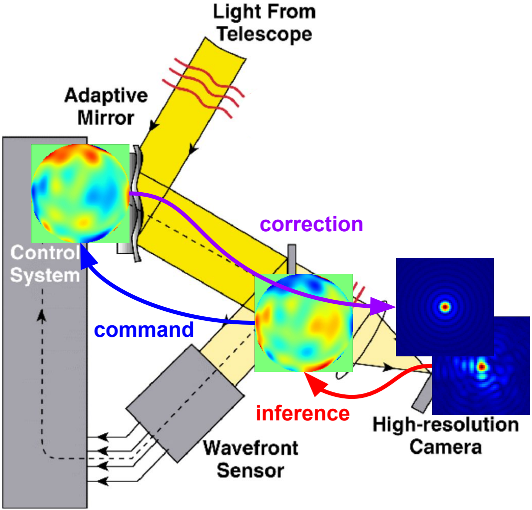
Martinez et al. 2013

Non-common path aberrations



Credit: Claire E. Max, UCSC

Focal-plane wavefront sensing



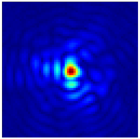
Limitation: phase sign ambiguity

$$\Theta_{pupil} = \sum_{i=0}^{N} c_i \, Z_i$$

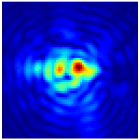
- Problem: sign ambiguity for **even** modes.

$$\mathscr{F}\{E_{pupil}(x)\} = \mathscr{F}\{E^*_{pupil}(-x)\}$$

- Solution: phase diversity.

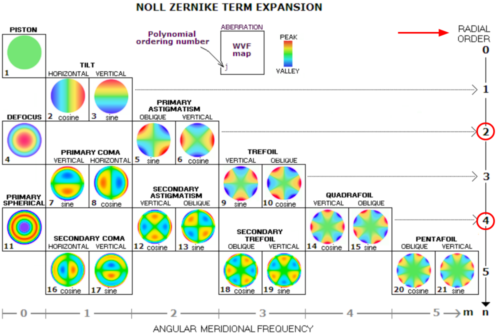


in-focus PSF



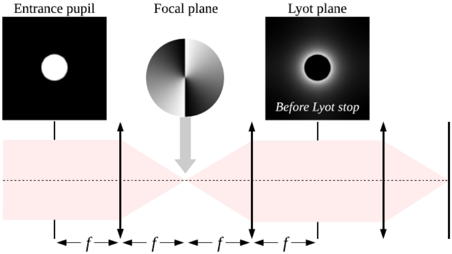
out-of-focus PSF

→ Decomposition of Θ_{pupil} into **Zernike modes**

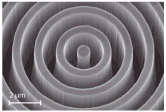


Credit: www.telescope-optics.net

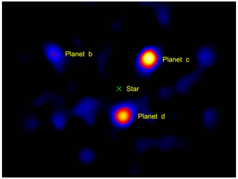
Vortex coronagraphs



Huby et al. 2015



Delacroix et al. 2013



NASA/JPL-Caltech/Palomar Observatory

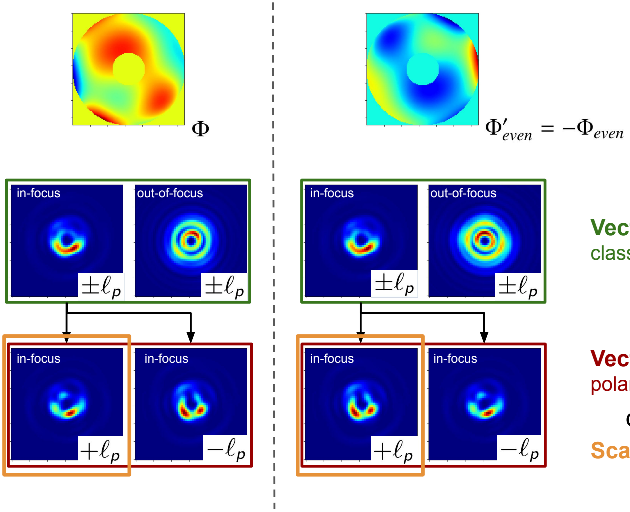
Vector Vortex coronagraph (VVC):
(Mawet et al. 2005)

- Conjugated phase ramps $e^{i \pm \ell_p \theta}$.
- Split circular polarization states and use two in-focus PSFs.

Scalar Vortex coronagraph (SVC):
(Ruane et al. 2019)

- Same phase ramp $e^{i \ell_p \theta}$ for both circular polarization states.
- Use one in-focus PSF.

Vortex phase diversity



Concept introduced by Riaud et al. 2012

Vector VC
classical phase diversity

Vector VC
polarization separation

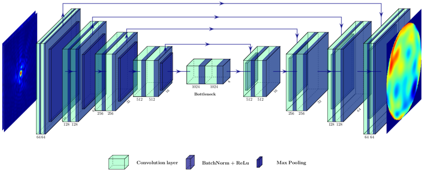
or

Scalar VC

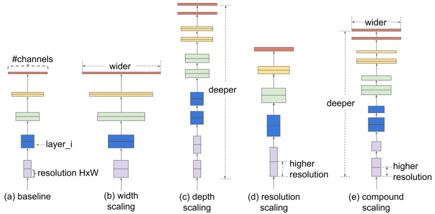
Deep Convolutional Neural Networks

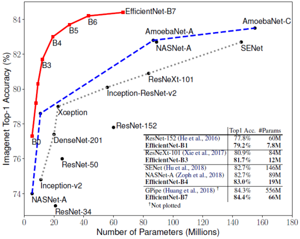
→ Motivation: fast predictions, higher performance, better robustness.

U-Net (Ronneberger et al. 2015):

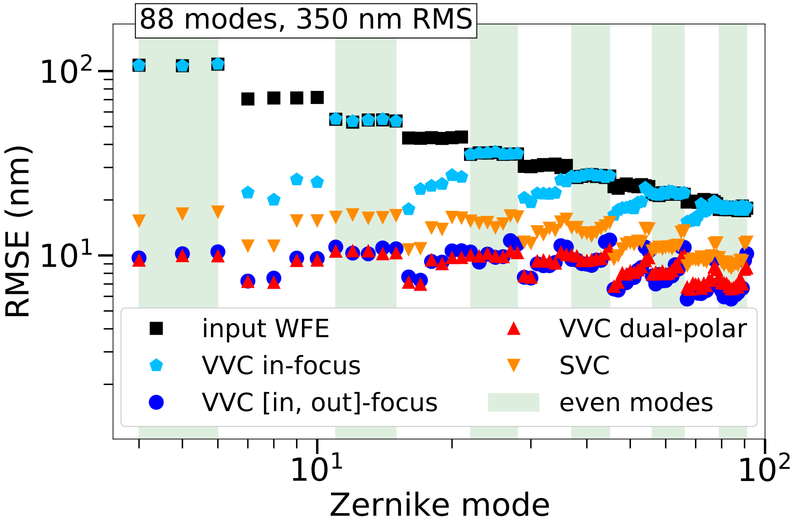


EfficientNet (Tan et al. 2019):

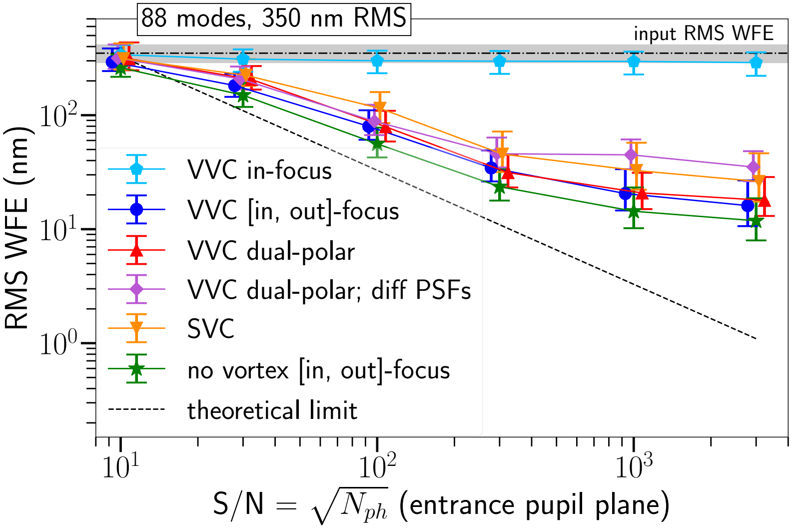




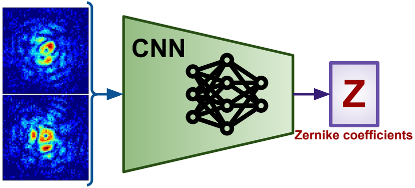
Zernike modes reconstruction



Phase retrieval performance



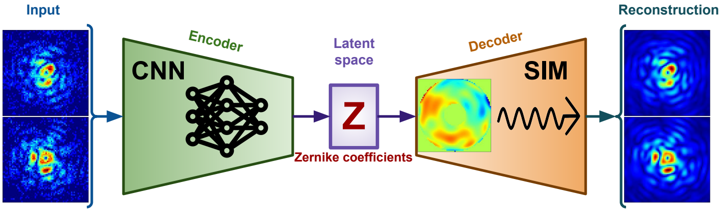
Simulator-based Autoencoder (SimAE)



CNN loss function (supervised):

$$\mathcal{L}_{CNN}(z, \widehat{z}(x;\phi)) = \sqrt{\frac{1}{N}\sum_{i}^{N}(z_i - \widehat{z}_i(x;\phi))^2)}$$

Simulator-based Autoencoder (SimAE)



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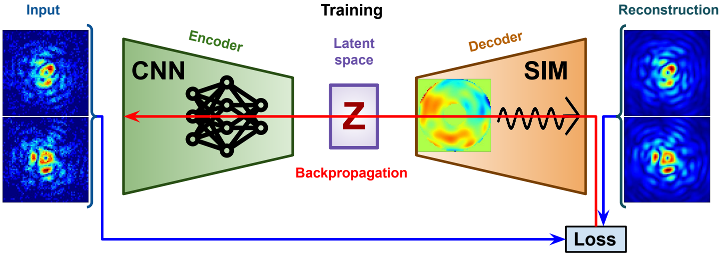


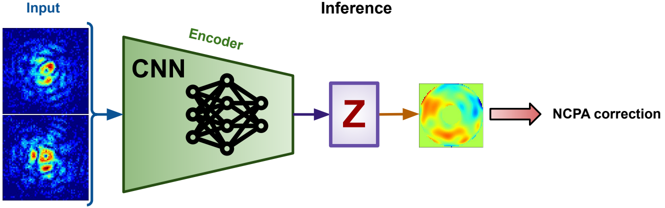
CNN loss function (supervised):

$$\mathcal{L}_{CNN}(z, \hat{z}(x;\phi)) = \sqrt{\frac{1}{N}\sum_{i}^{N}(z_i - \hat{z}_i(x;\phi))^2))}$$

SimAE loss function (unsupervised) → Poisson distributions:

$$\mathcal{L}_{SimAE}(x;\phi) = -\mathbb{E}_{x\sim p(x)}\left[\log\left(\frac{\lambda(x;\phi)^x}{x!}\exp(-\lambda(x;\phi))\right)\right]$$

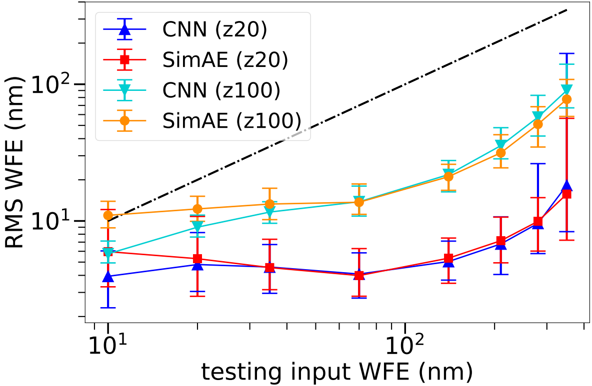
Simulator-based Autoencoder (SimAE)



SimAE: Performance

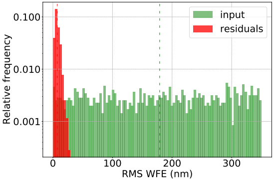
- WFE $\in$ [0, 350] nm rms
- SNR $\simeq$ 100
- 10^5 training & 10^2 test samples

Evaluated on specific WFE distributions:

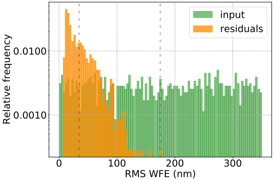


Entire WFE distribution:

20 Zernike modes:

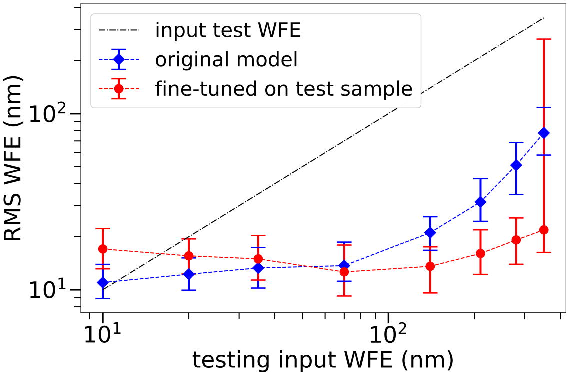


100 Zernike modes:

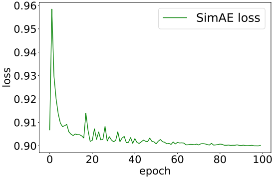


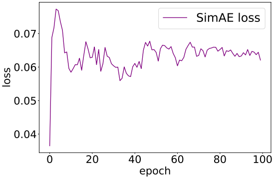
SimAE: fit on-the-fly

- Pre-trained on 10^5 samples
- Fine-tuned on 1 test sample
- Convergence time: $\sim$ 10 seconds



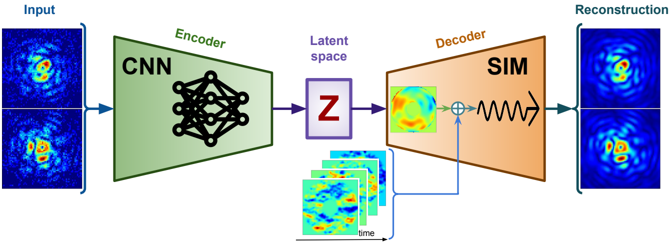
Fine-tune at 10 nm rms:





Improving the simulator

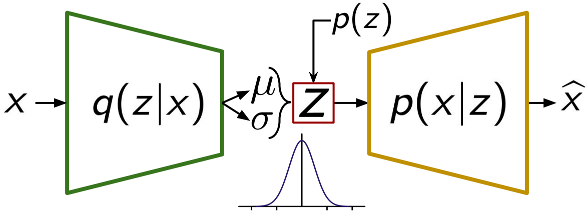
- Learnable instrumental parameters: for now Vortex rejection factor
- Including AO telemetry into the simulator:



- Use optical propagation package: HEEPS (PyTorch) or δLux (Jax)

Variational inference

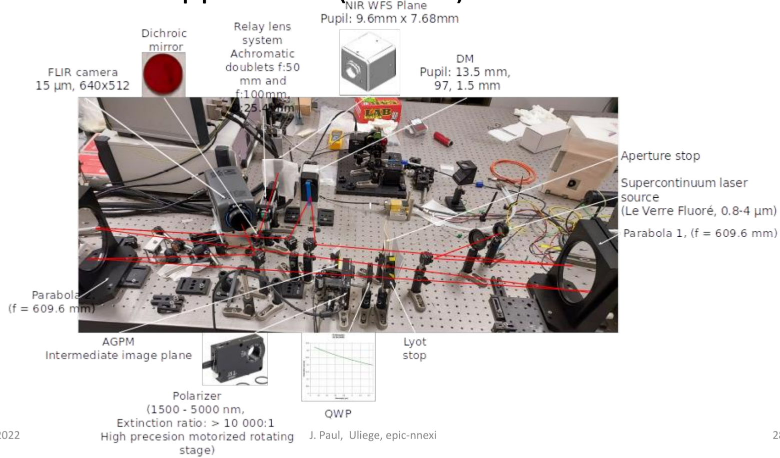
- Add Posterior $q(z|x)$ and Prior distributions $p(z)$:



- KL divergence loss term: $-\beta\, KL(q(z|x;\phi)||p(z))$
  $\rightarrow$ training now stable
- Evaluation metric: $\mathbb{E}_{p(x)}[\log\, q(z|x)]$
- How do we pick the best z?

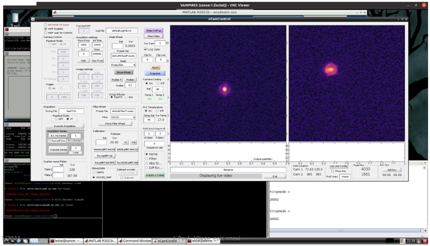
VODCA bench

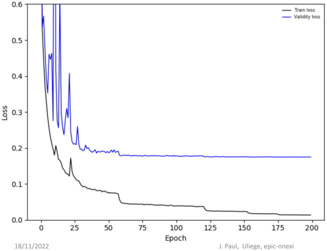
Vortex Optical Demonstrator for Coronagraphic Application (VODCA) test bench

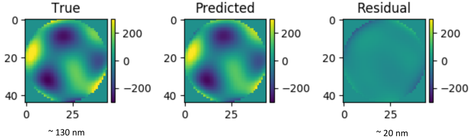


Credits: Jyotirmay Paul

Subaru/SCExAO instrument





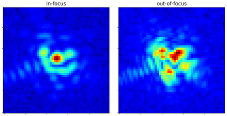


Credits: Subaru/SCExAO and Jyotirmay Paul

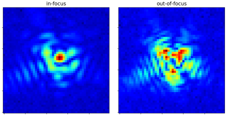
Transfer learning with SCExAO data

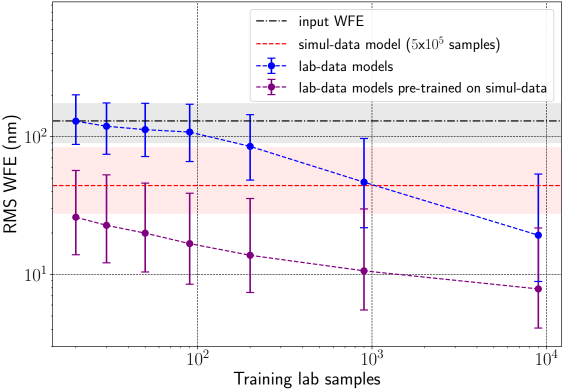
SCExAO Subaru Coronagraphic Extreme Adaptive Optics

Experimental PSFs:



Simulated PSFs:

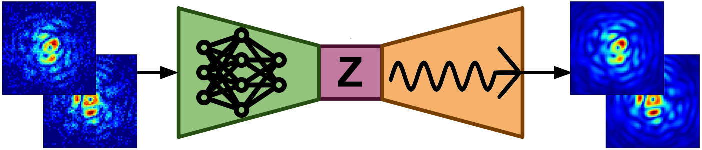


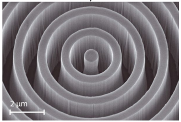


maxime.quesnel@uliege.be
University of Liège

Conclusions

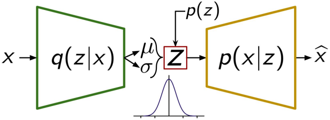
Simulator-based autoencoder for focal-plane wavefront sensing





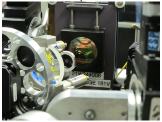
Vortex Phase diversity

Quesnel et al. 2022
(A&A, accepted)



Improving the autoencoder

- Variational approach
- Complete simulator



Application to real data

- Subaru/SCExAO
- ULiège/VODCA bench