A physics-based deep learning approach for focal-plane wavefront sensing

Maxime Quesnel[a,b]

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

[a]Montefiore Institute of Electrical Engineering and Computer Science

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

University of Liège

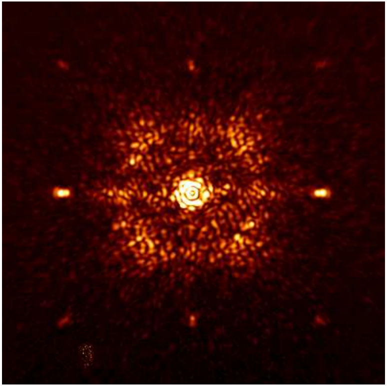
ESA/ESO SciOps workshop

18 May 2022

maxime.quesnel@uliege.be

Exoplanet imaging: Limitation

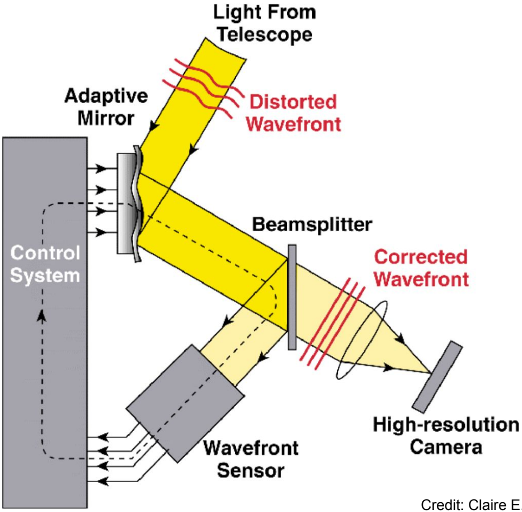
The problem: **SPECKLES**



Martinez et al. 2013

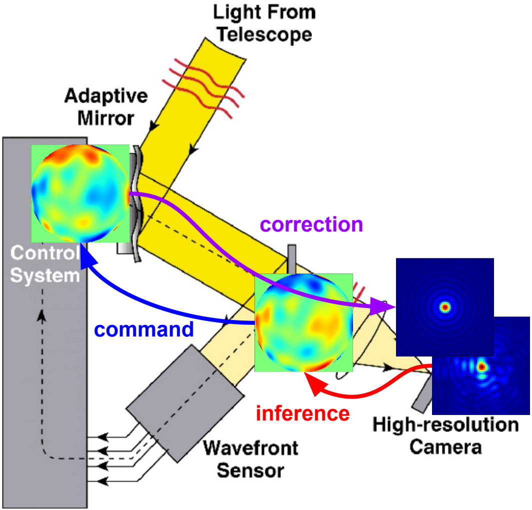
Especially the **quasi-static** ones

Non-common path aberrations



Credit: Claire E. Max, UCSC

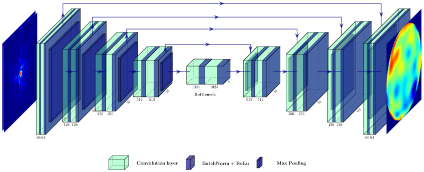
Focal-plane wavefront sensing: Principle



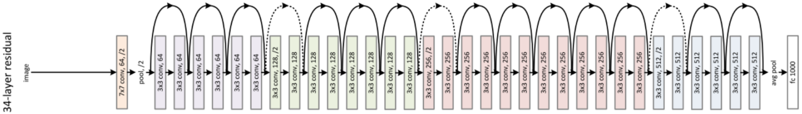
Deep Convolutional Neural Networks

- Motivation: fast predictions, higher performance, better robustness.
- Deep convolutional neural networks: U-Net, ResNet, EfficientNet.
- Applied on (post-coronagraphic) simulated data and in-lab data.

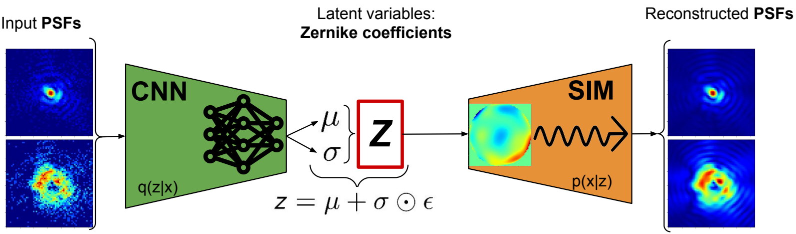
U-Net:



ResNet:



Simulator-based autoencoder: Unsupervised learning



Loss function: ELBO

Reconstruction term:

$$\boxed{\alpha \, \mathbb{E}_{q(z|x;\phi)}[log(p(x|z))]}$$

$$p(x|z) := Pois(\lambda)$$

K-L divergence term:

$$\boxed{-\beta \, KL(q(z|x;\phi)||p(z))}$$

$$q(z|x) := \mathcal{N}(\mu, \sigma^2)$$

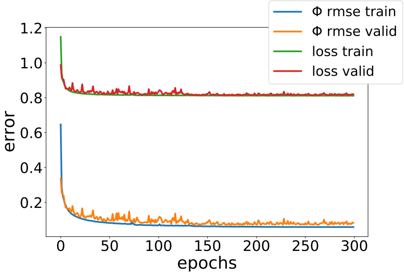
$$p(z) := \mathcal{N}(0, 1)$$

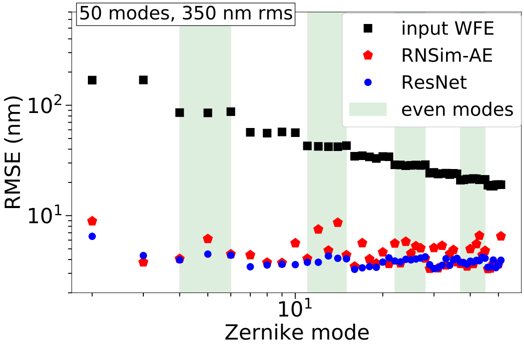
Sim-VAE: Performance

- Simple simulator:

$$\mathbf{PSF}(\mathbf{x},\mathbf{y}) = |\mathscr{F}[A(x,y)e^{i\boldsymbol{\theta}(\mathbf{x},\mathbf{y})}]|^2$$

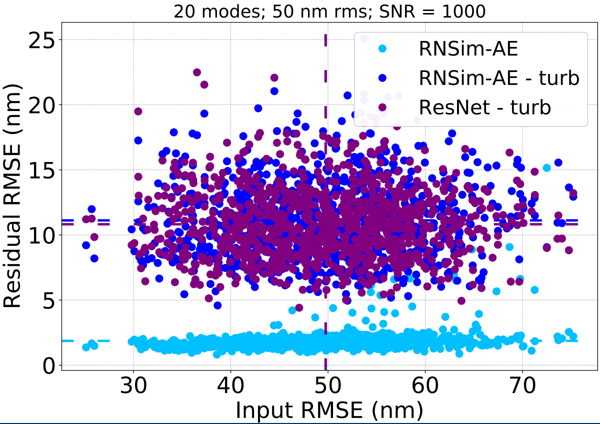
- K-L divergence term factor: $\beta = 0$
- Learning rate $= 10^{-4}$
- SNR $= 100 \pm 20$



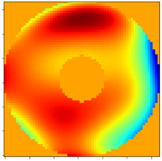


Sim-VAE: Robustness to AO residuals

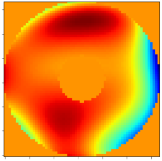
- Adding phase turbulence residuals: 50nm rms, $t = 100$ms.
- Information not included in labels (CNN) nor simulator (AE).
- WFS telemetry: could add AO residuals into simulator.



Predicted phase:



True phase:

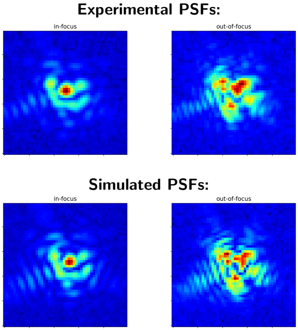


Application to real data: SCExAO instrument

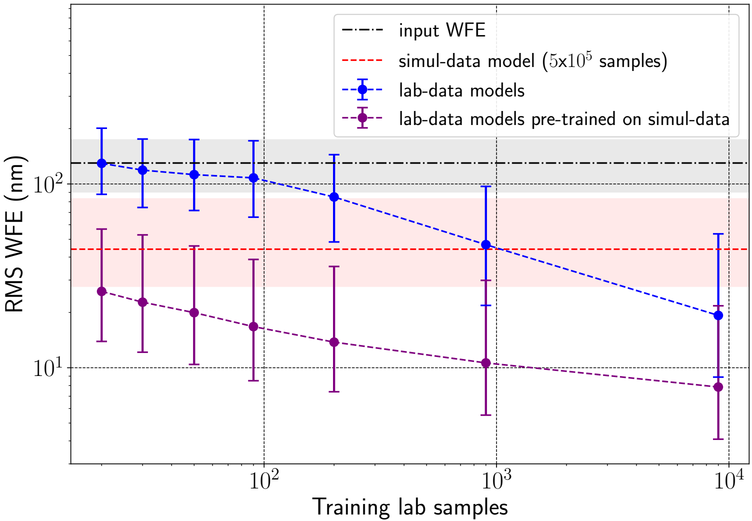
SCExAO Subaru Coronagraphic Extreme Adaptive Optics

Credits: NAOJ

- SCExAO: science and technology development.
- Labelled datasets + control of the instrument.
- Simulations close enough to in-lab PSFs.
- SimVAE: **Morphine** package (Poppy + JAX).
  github.com/benjaminpope/morphine

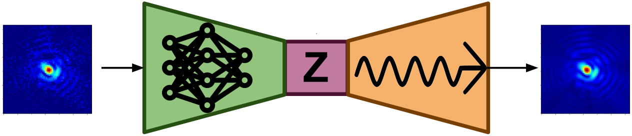


Transfer learning with SCExAO data

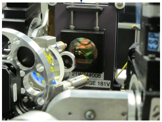


Conclusions

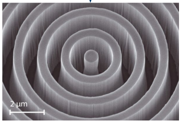
Physics-based learning for focal-plane wavefront sensing



Improving the VAE



Application to real data



Phase diversity