

## Phase encoding with random binary phase plates for photon-limited imaging

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### INTRODUCTION & AIM

Photon-limited imaging inherently faces the challenge of quantum shot noise, where the variance nears the mean, leading to degradation in image quality, particularly at extremely low total photon counts below 1000 or so [1].

This necessitates advanced computational methods for reconstruction, often involving regularization techniques to incorporate prior knowledge and prevent "fitting the noise". The proposed use of random binary phase plates aims to leverage "wavefront diversity" to stabilize image reconstruction by improving spatial-frequency mixing. This is conceptually distinct from contrast enhancing phase plates, such as Zernike or vortex designs, which impose fixed symmetries [2].

Zernike phase plates, for instance, operate by selectively altering the phase and amplitude of un-diffracted background light to make transparent objects visible. However, their fixed nature might limit their robustness in highly photon-deprived environments where adaptability to noise characteristics is paramount.

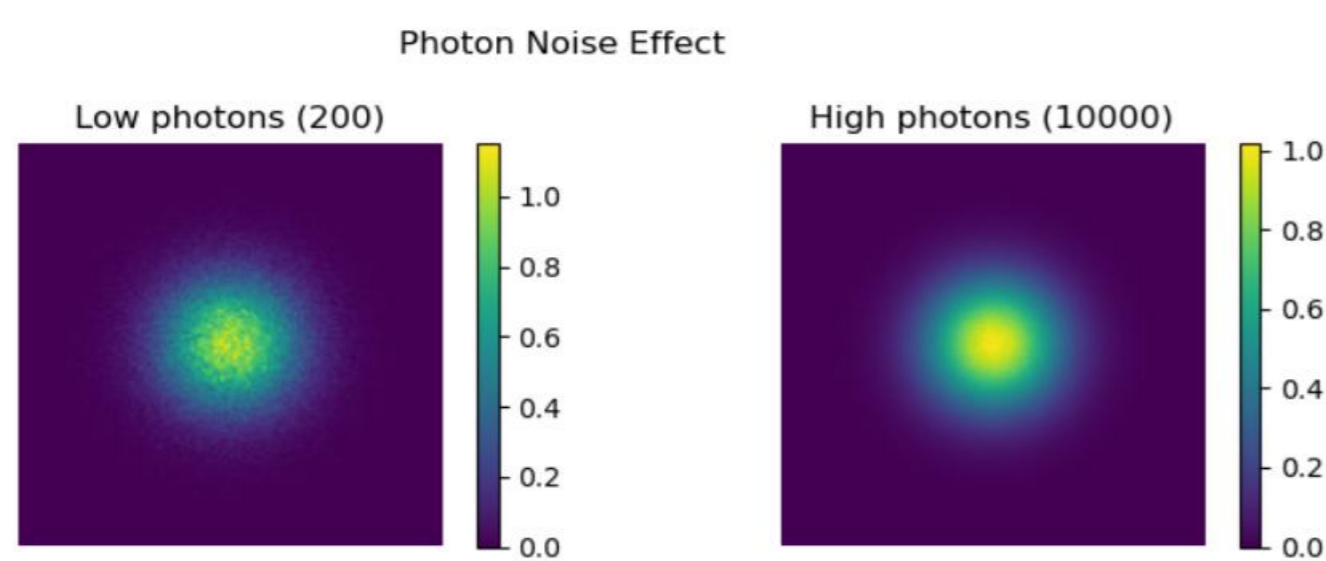


Fig:1\_Effect of noise.

### METHOD

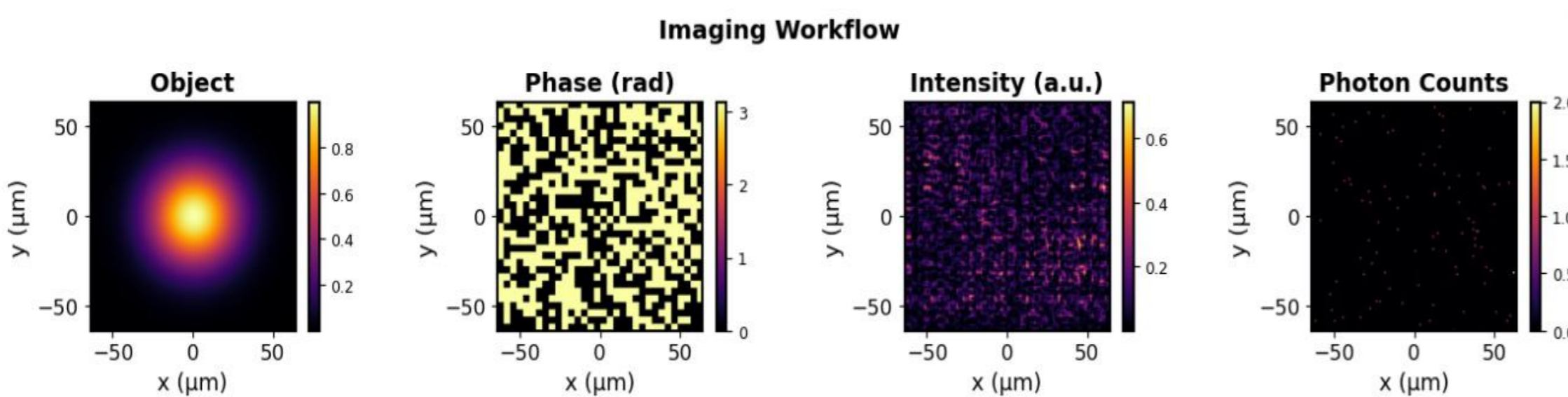


Fig:2a



Fig:2b\_2a and 2b\_Stages of forward model propagation

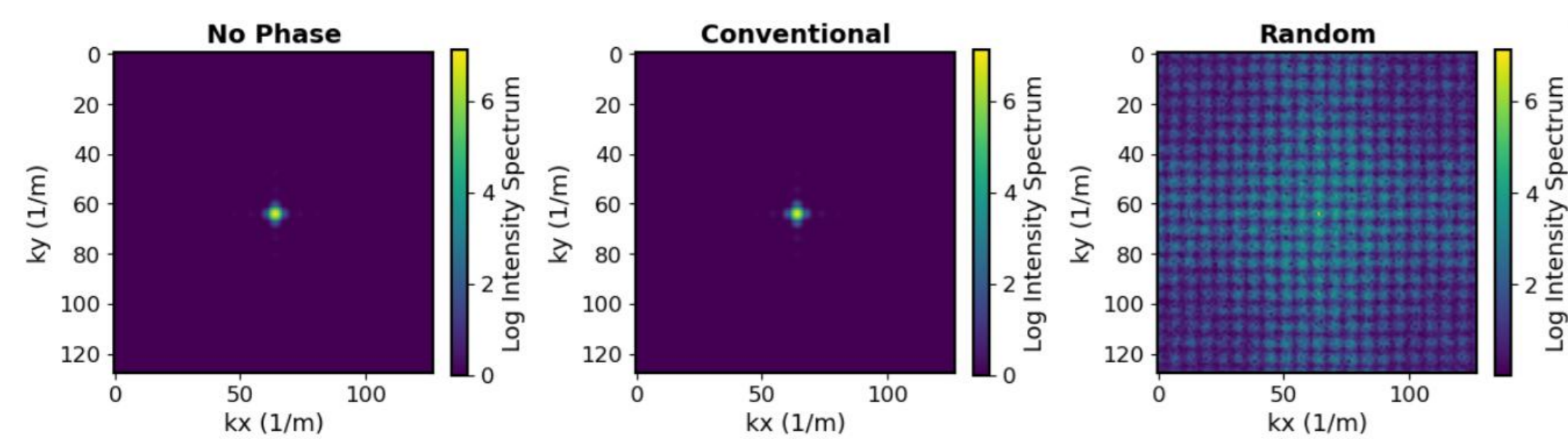


Fig:3a\_Intensity modulation after applying angular spectrum propagation for three cases of phase distribution.

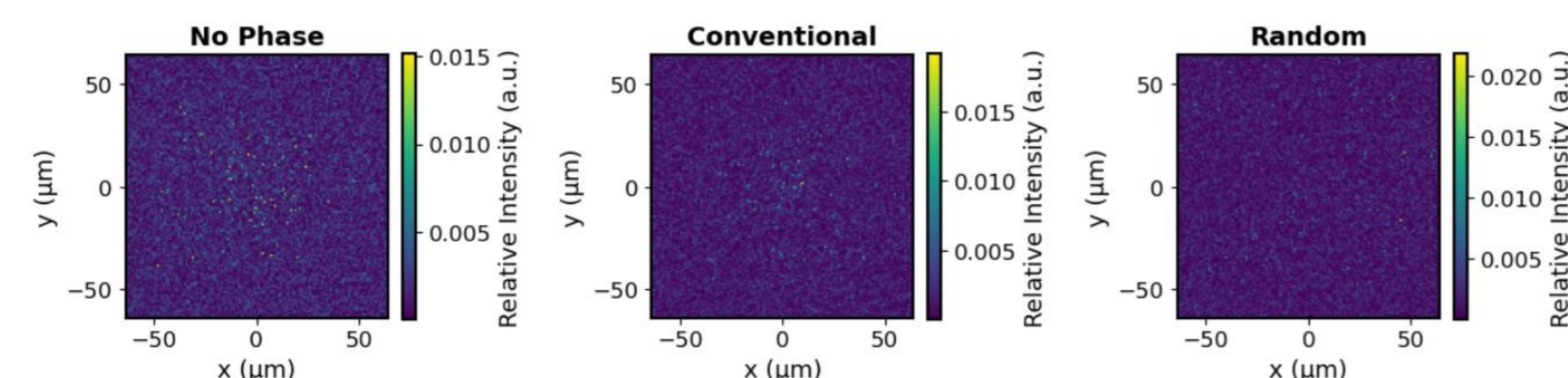


Fig:3b\_After reconstruction (regularized inverse filter).

### RESULTS & DISCUSSION

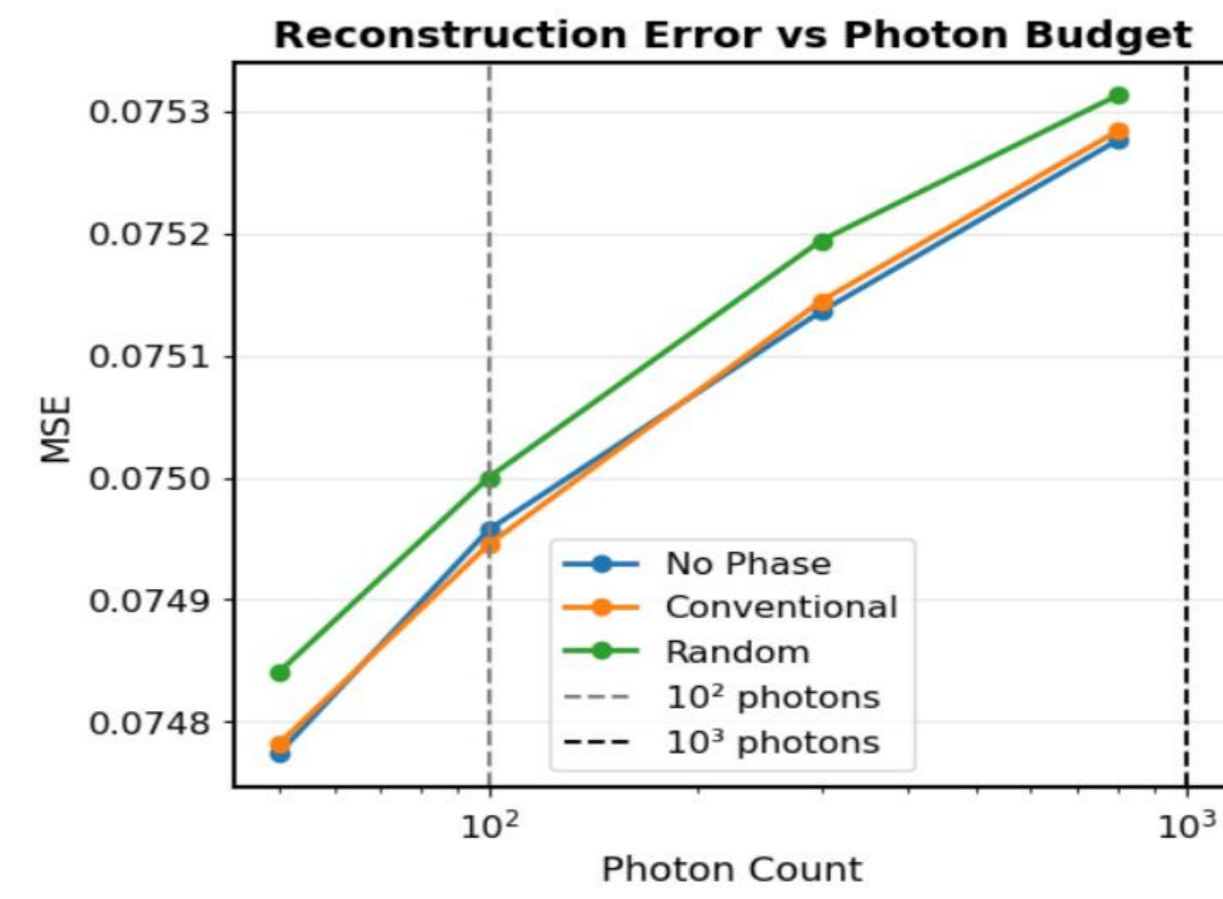


Fig:4a\_Reconstruction error for 3 phase distributions under varying photon budgets.

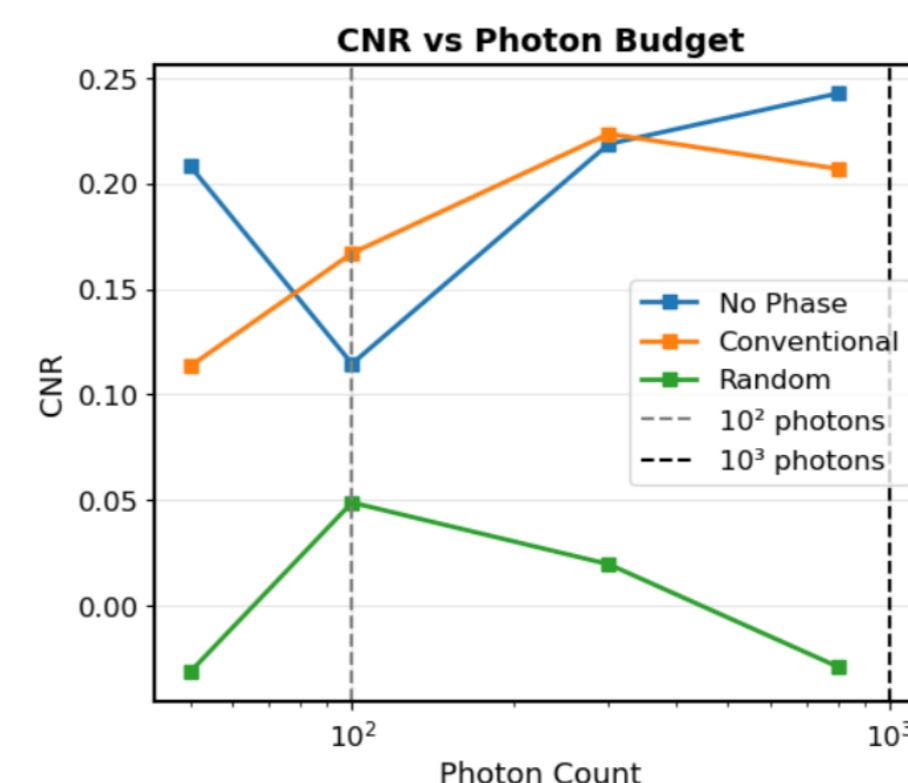


Fig:4b\_Contrast to noise ratio for 3 phase distributions under varying photon budgets.

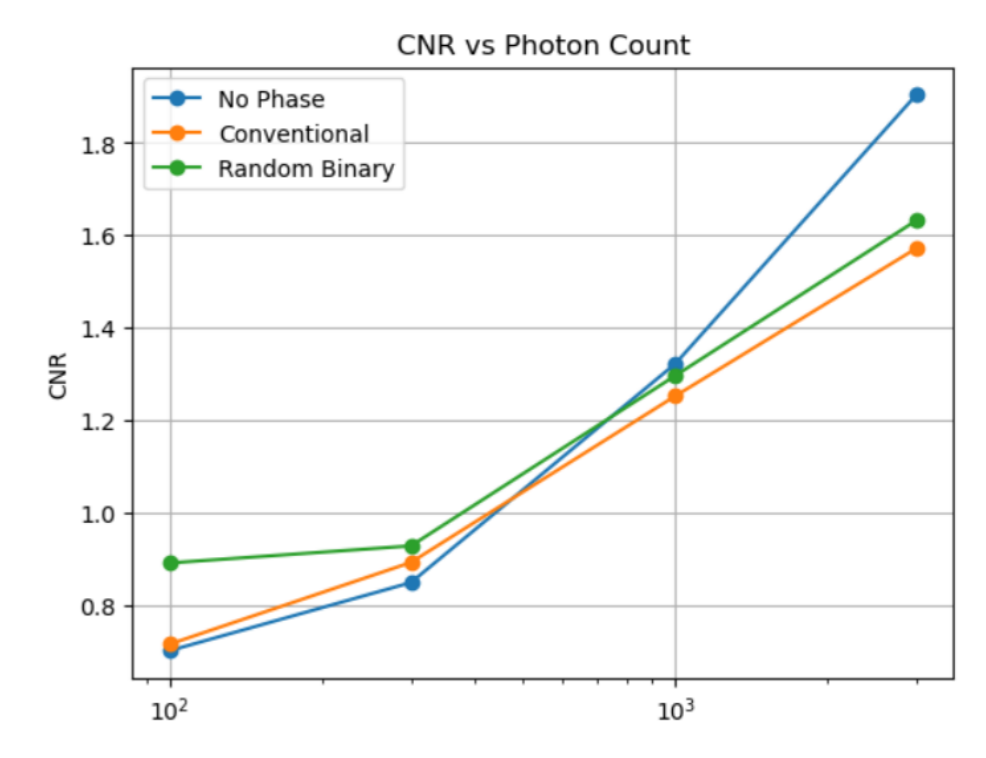


Fig:4c\_Contrast to noise ratio for 3 phase distributions under varying photon budgets without applying angular spectrum propagation.

In Fig:4a reconstruction mean square error across photon counts (50–800) shows that **random binary phase encoding improves robustness in the photon-limited regime**, achieving lower MSE than no-phase and conventional designs below  $\sim 10^3$  photons. This **indicates enhanced recoverability through redistribution of spatial information**, stabilizing reconstruction under strong shot noise.

In contrast, **CNR evaluated without angular spectrum propagation**[Fig:4c] suggests an apparent **advantage for the random phase plate**. However, this arises from a basic forward model where phase variations are not properly accounted to intensity, leading to artificially elevated local contrast due to high-frequency fluctuations rather than true image improvement.

**With physically consistent propagation and choice of inverse filtering** in [Fig:4b], CNR trends differ. **Conventional phase plates often yield comparable or higher CNR by preserving localized contrast**, while random encoding spreads energy across spatial frequencies, reducing local contrast despite improved overall reconstruction.

Overall, random phase encoding enhances performance via spatial-frequency mixing rather than contrast amplification. The discrepancy in CNR highlights the need for accurate forward modelling and indicates that global metrics like MSE provide a more reliable measure of performance in photon-limited imaging, with CNR serving as a secondary, context-dependent metric.

### CONCLUSION

Random binary phase encoding enhances spatial-frequency mixing and improves reconstruction robustness under photon-limited conditions, with performance depending on combination of evaluation metric and reconstruction model. Hence binary phase plate is suitable to increase wavefront diversity rather than region specific contrast enhancement as in the case of Zernike/vortex phase plates.

### FUTURE WORK / REFERENCES

- Incorporate **advanced reconstruction methods** (e.g., iterative.)
- Analysing **task-specific metrics** beyond MSE and CNR, possibly predicting experimental errors through a pattern identification map from these metrics.
- Study **robustness under system aberrations and detector noise models**.

1. Sych, D. V. (2025). Quantum Single-Pixel Imaging via Compressive Sampling at the Single-Photon Level. *Lobachevskii Journal of Mathematics*, 46(6), 2659–2664. <https://doi.org/10.1134/s199508022507878>.
2. Li, Y., Wang, Y., Zhou, L., He, Y., He, W., Gu, G., & Chen, Q. (2024). Real-time ultra-sensitive anisotropic edge enhanced imaging based on frequency upconversion. *Optics & Laser Technology*, 176, 110988. <https://doi.org/10.1016/j.optlastec.2024.110988>.
3. Yoav Shechtman, Yonina C. Eldar, Oren Cohen, et al. Phase Retrieval with Application to Optical Imaging. [arXiv:1402.7350](https://arxiv.org/abs/1402.7350) [cs.IT]