The visual qualities of attenuation and phase reconstructions performed by both of mixed-scale dense network and contrast transfer function become worse as noise level increases from 24dB (PPSNR) to 6dB. And the visual quality of reconstructions performed by contrast transfer function is similar to what mixed-scale dense network does.

#### 5.5.2.5 Conclusion

For single density case, the robustness of attenuation and phase projection reconstructions towards noise depends on the image we are dealing with. When shapes in original projection images have less overlaps, the reconstructions can overcome the disturbance made by noise for some degree, especially for the mixed-scale dense network. Otherwise, the reconstructions become more and more difficult when noise level increases or there is more overlap between shapes in images. We can see there is more overlapping in the worst case than in the best case.

### 5.5.3 Diverse densities

#### 5.5.3.1 Testing Error of Trained Network for Noisy Phase Contrast Images as Input

| Trained Network Applied | Noise Level & Index | Average NMSE | Average MSE | Average SSIM | Average PSNR |
|---|---|---|---|---|---|
| I | 6dB Attenuation | 0.27297965 | 7.87442326e-06 | 0.99817192 | 57.39607595 |
| J | 12dB Attenuation | 0.23571901 | 2.42667943e-06 | 0.99882133 | 60.76368307 |
| K | 24dB Attenuation | 0.19890280 | 3.79288196e-06 | 0.99936463 | 60.60328413 |
| I | 6dB Phase | 0.33534382 | 1.98648603 | 0.30483966 | 50.66973861 |
| J | 12dB Phase | 0.32262287 | 2.02388010 | 0.29032299 | 51.32813504 |
| K | 24dB Phase | 0.31067529 | 1.88051331 | 0.13751980 | 51.64779834 |

Table 5.11: Testing Error of Trained Network for Noisy Phase Contrast Images as Input

Comparing with neural network based reconstruction on non-noisy diverse densities case as recorded in Table 5.6, the reconstruction quality drops as shown by nearly all evaluation metrics except for the average NMSE of phase reconstruction. Actually the average NMSE of attenuation is influenced by noise added more clearly than the phase. Even if the average NMSE of both attenuation and phase increases as noise level increases, a strange thing is that the average NMSEs of phase for the noisy case are a little bit lower than for the non-noisy case as recorded in Table 5.6. This is due to the increase in the number of training epochs for the noisy case training for some extent, but the decrease of the NMSE of phase reconstruction as noise is gradually added is quite small in comparison with the decrease of NMSE of attenuation reconstruction. Therefore, there is some kind of robustness of mixed-scale dense network towards noise for the diverse densities case.

Comparing with Table 5.9, i.e. the single density and noisy case, the quality of attenuation and phase projection reconstruction performed by mixed-scale dense network from diverse densities noisy phase contrast images becomes worse. The inverse problem becomes more complicated with diverse densities, there are more ratios between phase and attenuation that depends on the region, it causes more difficulties for mixed-scale dense network to learn data mapping relationship between phase contrast images and original projection images.

The reconstructions performed by mixed-scale dense network mainly become better when noise level decreases from 6dB (PPSNR) to 24dB (PPSNR) in terms of nearly all the evaluation metrics, but the improvement made when decreasing the noise level is quite limited.

#### 5.5.3.2 Testing Error of Contrast Transfer Function Method on Same Testing Datasets

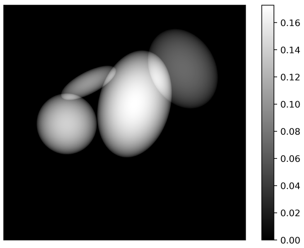
| Noise Level & Index | Average NMSE | Average MSE | Average SSIM | Average PSNR |
|---|---|---|---|---|
| 6dB Attenuation | 8.96505757 | 0.00477201 | 0.59532163 | 31.12309427 |
| 12dB Attenuation | 4.77428605 | 0.00164740 | 0.76434833 | 35.27844915 |
| 24dB Attenuation | 1.92983567 | 0.00066310 | 0.92117089 | 40.14312221 |
| 6dB Phase | 1.32625865 | 39.88925205 | 0.07787613 | 37.69500454 |
| 12dB Phase | 1.20959460 | 37.95771506 | 0.11964321 | 38.17530462 |
| 24dB Phase | 1.16528138 | 37.38681544 | 0.23015646 | 38.38724322 |

Table 5.12: Testing Error of Contrast Transfer Function Method on Same Testing Datasets for Noisy Phase Contrast Images as Input

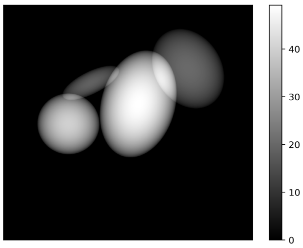
Comparing with CTF based reconstruction on non-noisy diverse densities case as recorded in Table 5.7, the reconstruction quality as shown by all the evaluation metrics drops when noise is added. And the average NMSE of attenuation is influenced by noise added more clearly than phase, this is quite in line with the reconstruction performed by mixed-scale dense network, but the NMSE of attenuation projection reconstructions are larger than that of phase projection.

The reconstructions performed by contrast transfer function become better when noise level decreases from 6dB (PPSNR) to 24dB (PPSNR) in terms of all the evaluation metrics, but they are worse than the ones obtained with mixed-scale dense network for each noise level.

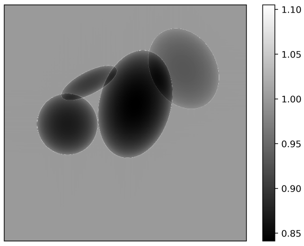
#### 5.5.3.3 Best Case of Diverse Density Noise Model Phase Retrieval



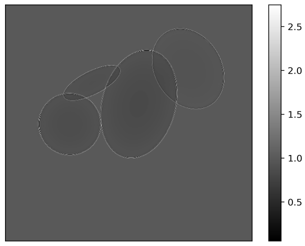

(a) Attenuation Projection



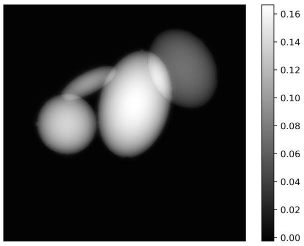

(b) Phase Projection



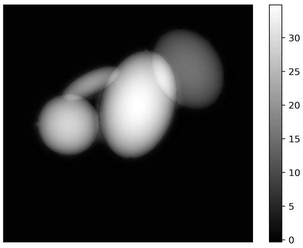

(c) Non-noisy Phase Contrast Image for Shortest Distance



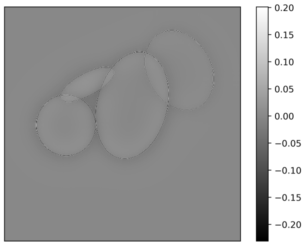

(d) Non-noisy Phase Contrast Image for Longest Distance



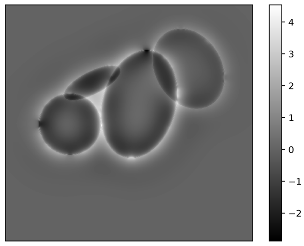

(e) Attenuation Retrieval Based on Non-noisy Phase Contrast Images



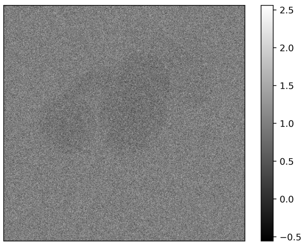

(f) Phase Retrieval Based on Non-noisy Phase Contrast Images



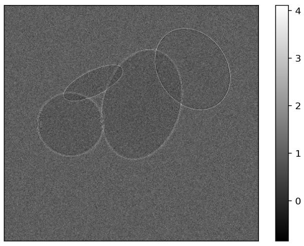

(g) Corresponding Attenuation Retrieval by CTF



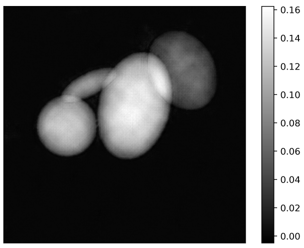

(h) Corresponding Phase Retrieval by CTF



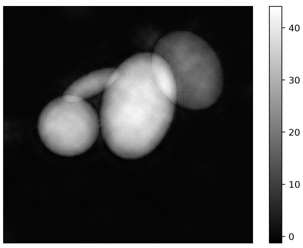

(i) 6dB Noise Level Phase Contrast Image for Shortest Distance



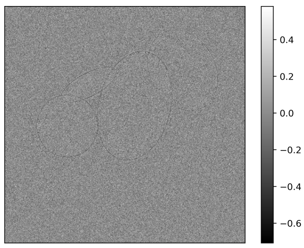

(j) 6dB Noise Level Phase Contrast Image for Longest Distance



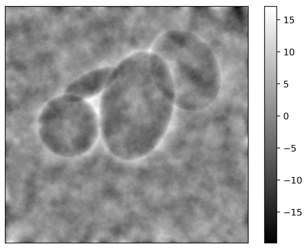

(k) 6dB Attenuation Retrieval



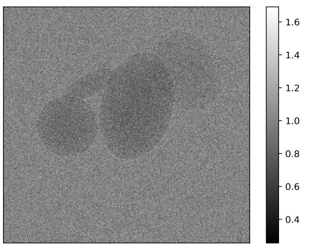

(l) 6dB Phase Retrieval



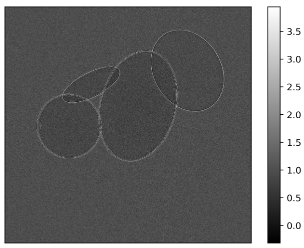

(m) CTF Attenuation Retrieval



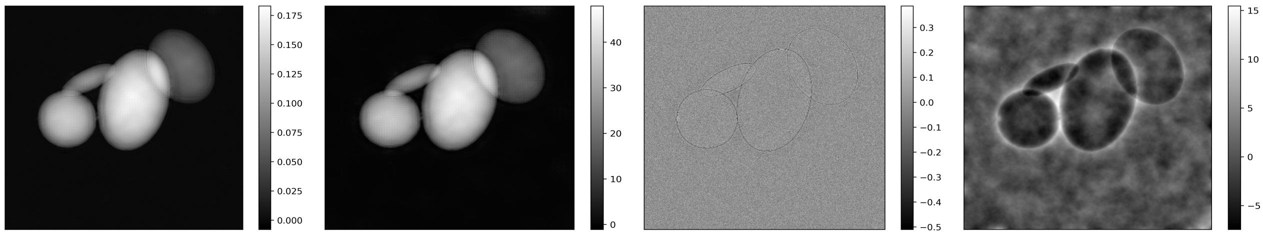

(n) CTF Phase Retrieval



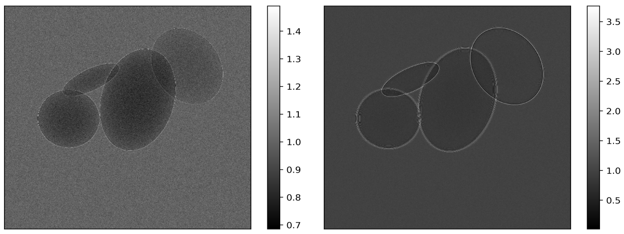

(o) 12dB Noise Level Phase Contrast Image for Shortest Distance



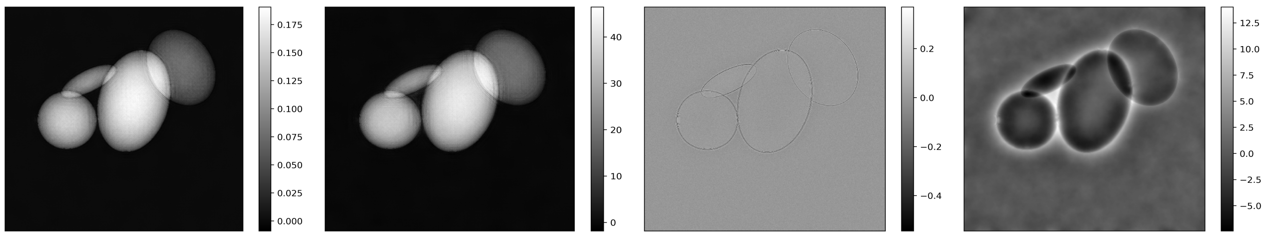

(p) 12dB Noise Level Phase Contrast Image for Longest Distance



(q) 12dB Attenuation Retrieval (r) 12dB Phase Retrieval (s) CTF Attenuation Retrieval (t) CTF Phase Retrieval



(u) 24dB Noise Level Phase Contrast Image for Shortest Distance (v) 24dB Noise Level Phase Contrast Image for Longest Distance

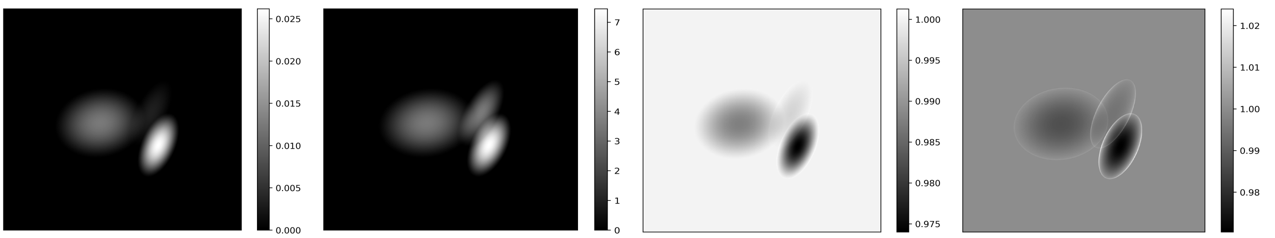


(w) 24dB Attenuation Retrieval (x) 24dB Phase Retrieval (y) CTF Attenuation Retrieval (z) CTF Phase Retrieval

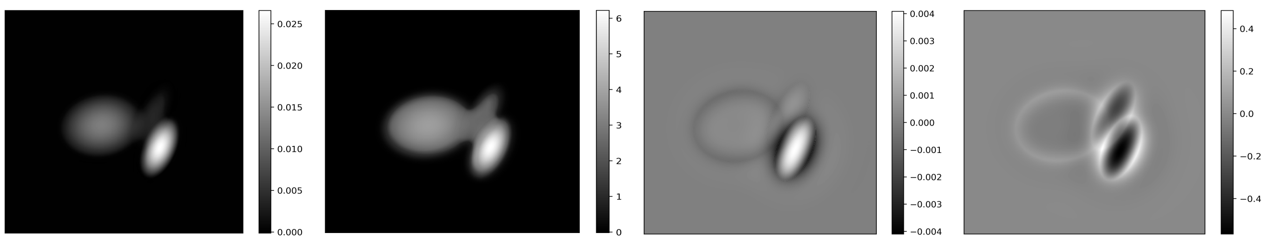
Figure 5.7: Best Case of Diverse Density Noise Model Reconstruction Performance and Corresponding CTF Performance In Comparison

The visual qualities of attenuation and phase reconstructions performed by mixed-scale dense network slightly increase as noise level decreases from 6dB to 24dB. And the visual quality of reconstructions performed by contrast transfer function becomes better when noise level decreases from 6dB (PPSNR) to 24dB (PPSNR), but all these reconstructions behave worse than the ones obtained with mixed-scale dense network for each noise level if we take the original projection as reference without considering any image enhancement effect.

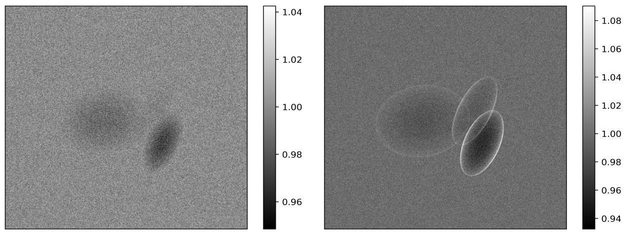
#### 5.5.3.4 Worst Case of Diverse Density Noise Model Phase Retrieval



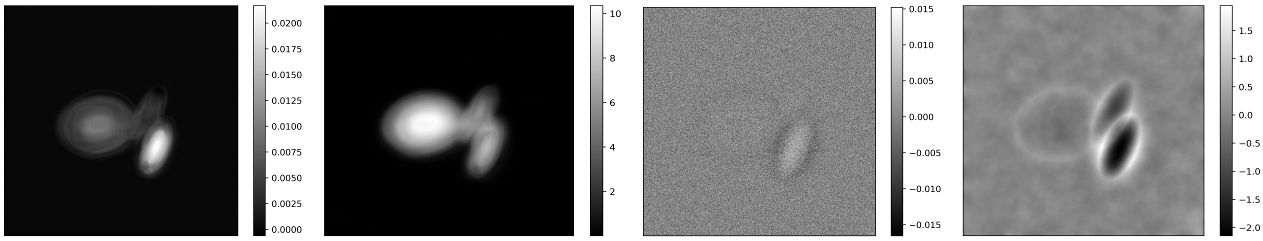
(a) Attenuation Projection (b) Phase Projection (c) Non-noisy Phase Contrast Image for Shortest Distance (d) Non-noisy Phase Contrast Image for Longest Distance



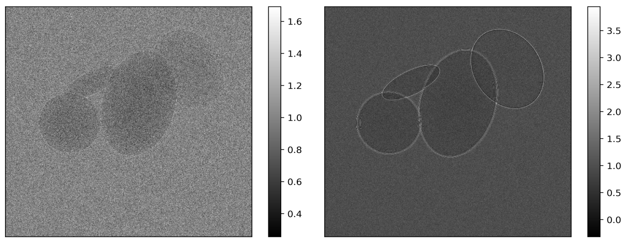
(e) Attenuation Retrieval Based on Non-noisy Phase Contrast Images (f) Phase Retrieval Based on Non-noisy Phase Contrast Images (g) Corresponding Attenuation Retrieval by CTF (h) Corresponding Phase Retrieval by CTF



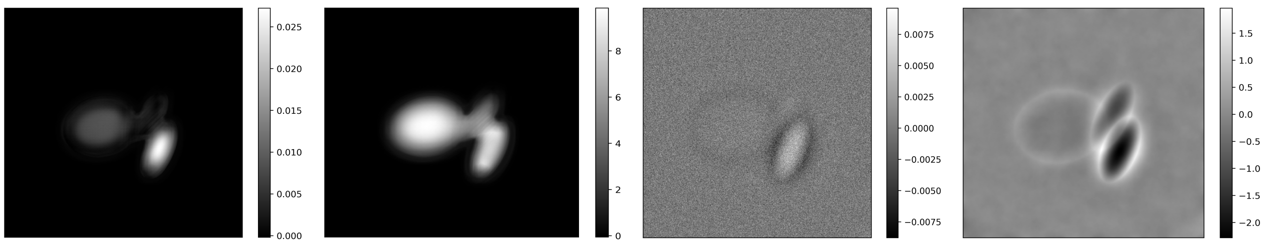
(i) 6dB Noise Level Phase Contrast Image for Shortest Distance (j) 6dB Noise Level Phase Contrast Image for Longest Distance



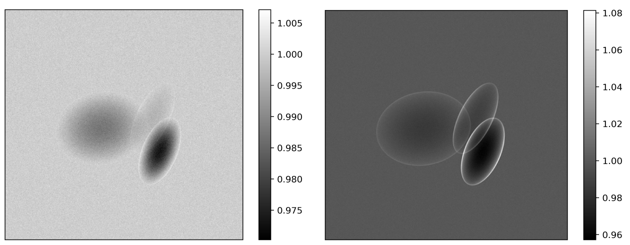
(k) 6dB Attenuation Retrieval (l) 6dB Phase Retrieval (m) CTF Attenuation Retrieval (n) CTF Phase Retrieval



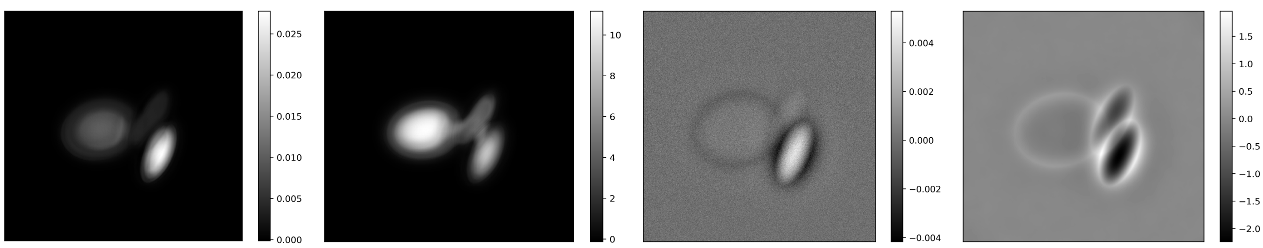
(o) 12dB Noise Level Phase Contrast Image for Shortest Distance (p) 12dB Noise Level Phase Contrast Image for Longest Distance



(q) 12dB Attenuation Retrieval (r) 12dB Phase Retrieval (s) CTF Attenuation Retrieval (t) CTF Phase Retrieval



(u) 24dB Noise Level Phase Contrast Image for Shortest Distance (v) 24dB Noise Level Phase Contrast Image for Longest Distance



(w) 24dB Attenuation Retrieval (x) 24dB Phase Retrieval (y) CTF Attenuation Retrieval (z) CTF Phase Retrieval

Figure 5.8: Worst Case of Diverse Density Noise Model Reconstruction Performance and Corresponding CTF Performance In Comparison

The visual qualities of attenuation and phase reconstructions performed by both mixed-scale dense network and contrast transfer function become worse as noise level increases from 24dB (PPSNR) to 6dB. However, this effect related to the augmentation of the noise level is more obvious on mixed-scale dense network based phase projection reconstruction. The visual quality of contrast transfer function based phase reconstruction is quite robust towards gradually increased noise level because contrast transfer function has image enhancement effect especially for object contour, so that we can distinguish each shape from the overlapping objects. However, mixed-scale dense network has not the same property.

#### 5.5.3.5 Conclusion

For diverse densities case, the robustness of attenuation and phase projection reconstructions towards noise also depends on the image we are dealing with. When shapes in original projection images have less overlaps, the reconstructions can overcome the disturbance made by noise for some degree, especially for the mixed-scale dense network. We can see there is more overlapping in the worst case than in the best case. This is in line with single density case,

### 5.5.4 Conclusion

Basically we have three factors to be considered for analysis, they are the number of densities involved, the noise level and the shapes overlapping degree.

Increase on each of them would triggers more difficulty for mixed-scale dense neural network to learn data distribution mapping between phase contrast images and projection images whatever attenuation or phase projection, the reconstruction would become more and more complicated and error would increase definitely. The neural network behaves worse as the inverse problem becomes more complicated as shown by experiments above.

The mixed-scale dense network based phase reconstruction has some kind of robustness towards gradually augmented noise in the more complicated diverse densities case, this is a good property as expected. Its efficiency to solve the shape overlapping issue is still quite limited, this is its drawback compared with contrast transfer function based phase reconstruction because contrast transfer function can extract the contour information from phase contrast images. Generally speaking, network reconstructions are closer to original projections numerically and visually compared to contrast transfer function method, but it depends on our visual requirements on phase reconstruction results if we have.

## 5.6 Experiment of Exploration on De-blurring Capacity of Neural Network in Phase Retrieval

### 5.6.1 Overview on Exploration on De-blurring Capacity of Neural Network in Phase Retrieval

| Trained Network | Gaussian blurring | Noise Level(PPSNR) | Number of Density(s) involved | Shape(s) involved |
|---|---|---|---|---|
| L | Yes | No noise added | 1 | ellipsoid and paraboloid |
| M | Yes | 12dB | 1 | ellipsoid and paraboloid |

Table 5.13: Overview on Experiment of Exploration on De-blurring Capacity of Neural Network in Phase Retrieval

### 5.6.2 Testing Error of Trained Network for Gaussian Blurring Phase Contrast Images as Input

| Appplied Network | Artifacts Added & Index | Average NMSE | Average MSE | Average SSIM | Average PSNR |
|---|---|---|---|---|---|
| L | Gaussian Blur Attenuation | 0.02218 | 7.95199e-10 | 0.99999 | 95.60235 |
| M | Gaussian Blur & 12dB Attenuation | 0.0434 | 4.0303e-09 | 0.9999 | 88.7439 |
| L | Gaussian Blur Phase | 0.02218 | 0.00171 | 0.96073 | 80.40771 |
| M | Gaussian Blur & 12dB Phase | 0.0434 | 0.0087 | 0.9339 | 73.5493 |

Table 5.14: Testing Error of Trained Network for Gaussian Blurring Phase Contrast Images as Input

It is shown in Table 5.14 that the noise added causes some difficulties to mixed-scale dense network based reconstruction from phase contrast images blurred by a Gaussian kernel. Is is in line with the conclusion of the last part.

Comparing with Table 5.4, i.e. the simplistic single density case, the reconstruction from Gaussian blurred phase contrast images performs even a bit better than the simplistic case in terms of almost all evaluation metrics. It is due to more training epochs for some degree in Gaussian blurring case, and in section 5.5, all the experiments have 206 training epochs that is the largest among all the experiments done, their performance is worse than the simplistic case due to noise. Therefore, it can be justified that the mixed-scale dense network has capability to overcome the Gaussian blurring.

Comparing with Table 5.9, i.e. the single density noise case, the reconstructions from phase contrast images of 12dB noise level performs much worse than the reconstructions from Gaussian blurred phase contrast images of same noise level. This is because Gaussian blurring is acting as the noise filter.