Planet signal extraction from direct imaging using common spatial pattern filtering

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Paper 10400-56

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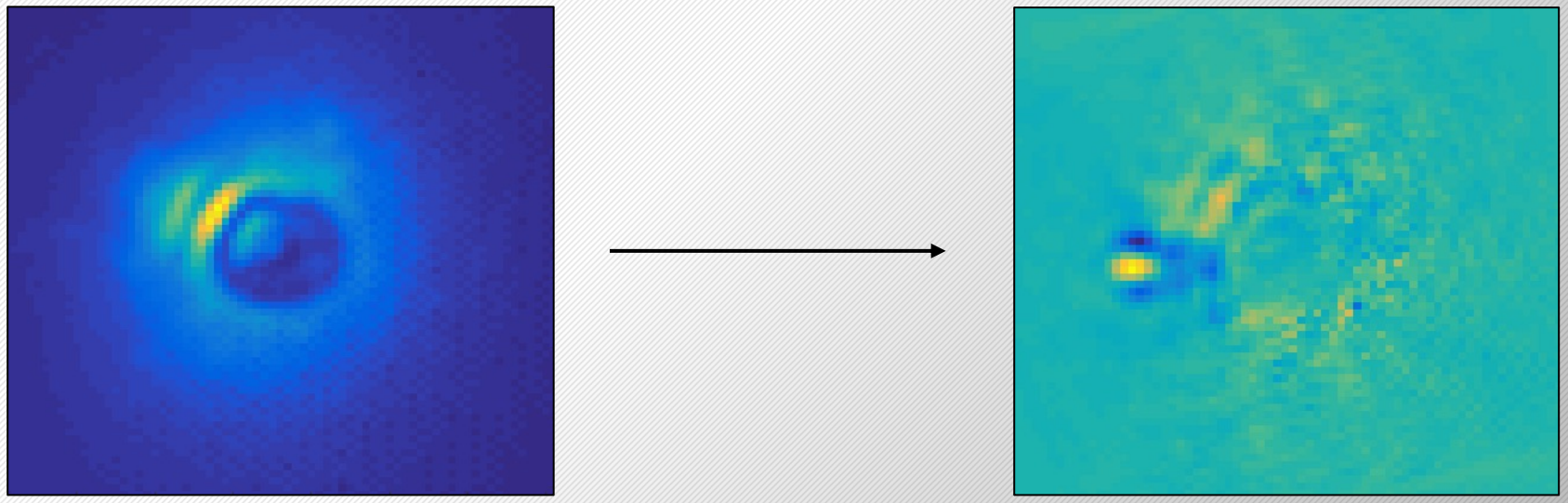
Direct Imaging Standards

- Exoplanet imaging is difficult:
  - Faint signal
  - Significant noise
- The Current Standard: Principal Component Analysis (PCA)(Wold, 1987)



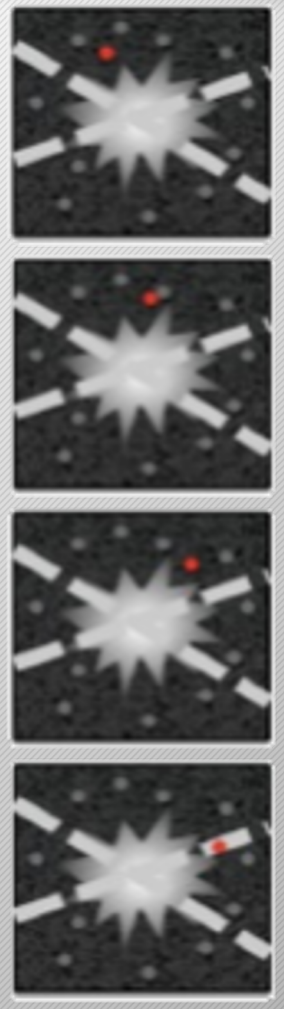
β Pic, GPIES Nov 2015

PCA and Common Spatial Patterns(Wang,2005)

- Angular Differential Imaging(Marois, 2006)

- PCA: $\underset{w}{argmax} \|Xw\|^2 \;\; s.t. \|w\| = 1$
  - Subtracting a least-squares approximation of an image from the image itself
  - Karhunen-Loève Image Processing (KLIP)(Soummer, 2012)

- CSP: $\underset{w}{argmax} \frac{\|X_1 w\|^2}{\|X_2 w\|^2} \;\; s.t. \|w\| = 1$

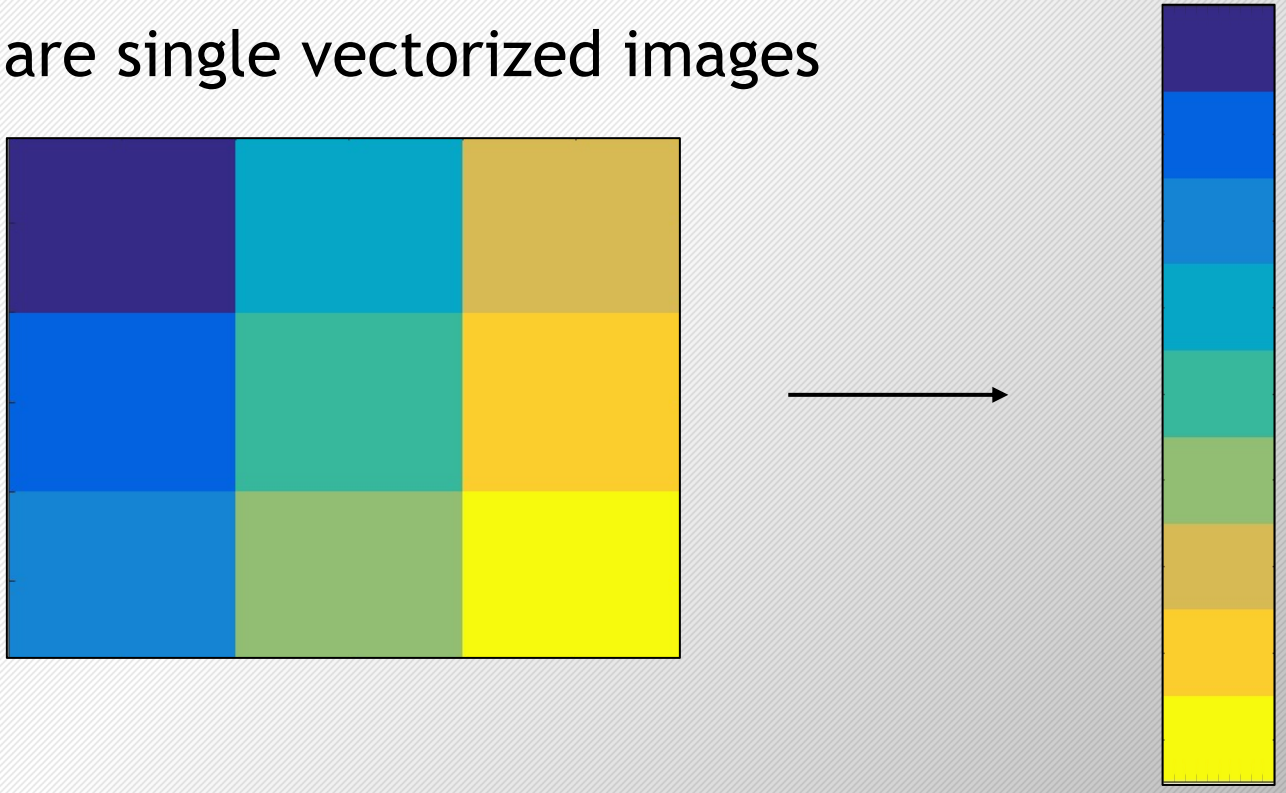


Jessica Donaldson
astrobites, 2013

Problem Definition

- Let X_1 be all the images from one observing sequence
- Let X_2 be the same data, derotated

- Columns of X_n are single vectorized images



Solving $\underset{w}{argmax} \frac{\|X_1 w\|^2}{\|X_2 w\|^2} \quad s.t. \|w\| = 1$

1. Image–Image Covariance Matrices

$$S_n = \frac{X_n {X_n}^T}{p-1}$$

2. Composite Covariance Eigenvalue Decomposition

$$S = S_1 + S_2 = U_0 \Sigma {U_0}^T$$

3. Whitening Matrix

$$P = \Sigma^{-1/2} {U_0}^T.$$

4. Whitened, Normalized Data

$$\overline{S_n} = P S_n P^T$$

Solving $\underset{w}{argmax} \frac{\|X_1 w\|^2}{\|X_2 w\|^2} \quad s.t. \|w\| = 1$

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$$\overline{S_1} + \overline{S_2} = \mathrm{I}$$

Solving $\underset{w}{argmax} \frac{\|X_1 w\|^2}{\|X_2 w\|^2} \; s.t. \|w\| = 1$

Reformulation

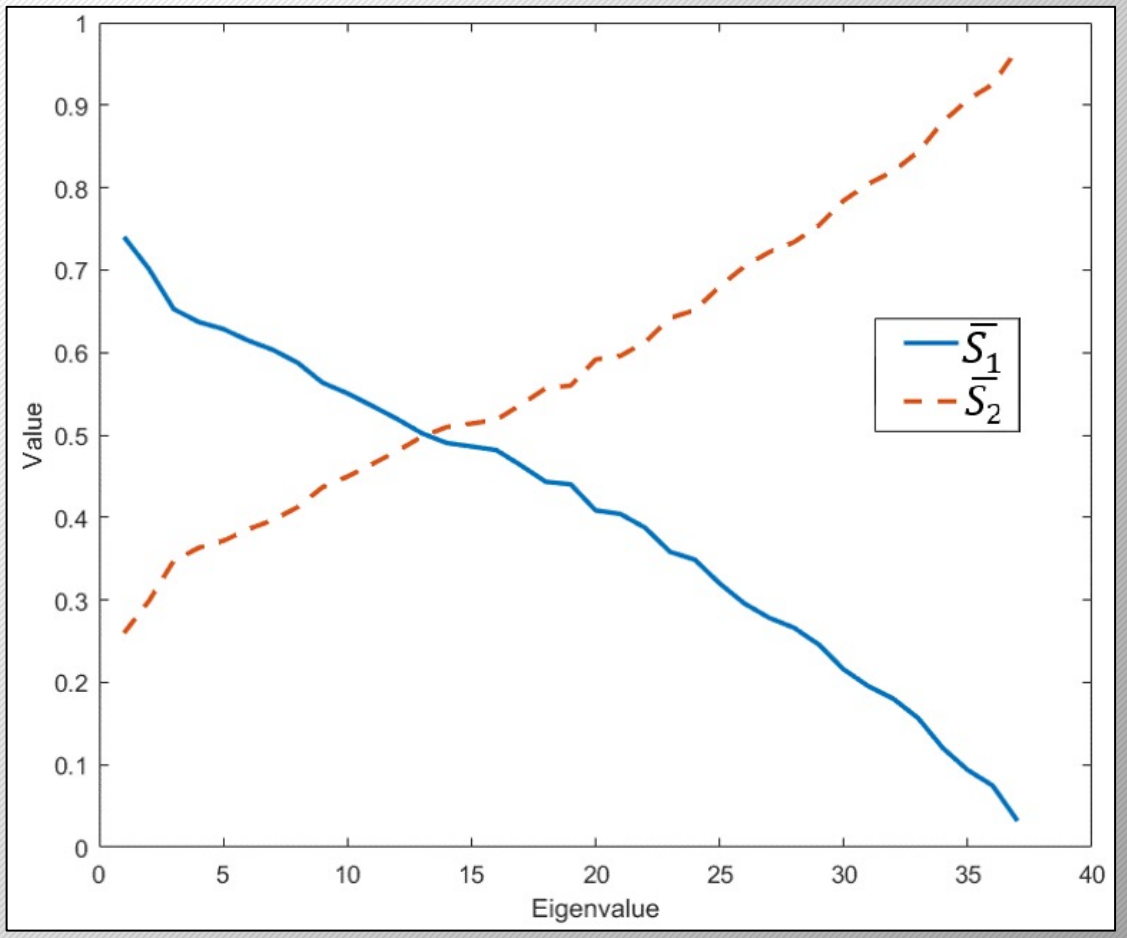
$$\underset{w}{argmax} \|\overline{X_1} w\|^2 \;\; s.t. \|(\overline{S_1} + \overline{S_2})w\| \; = 1$$

Solution

$$L(w, \lambda) = w^T \overline{X_1}^T \overline{X_1} w - \lambda[w^T(\overline{S_1} + \overline{S_2})w - 1]$$

$$\dots$$

$$\bar{S}_1 w = \lambda w$$



Extracting the Planet Signal

$$\bar{S}_n = U\Sigma U^T$$

$$Z = U^T P X_1$$

Z_k is final k rows from Z

Signal for a given target image t is $({Z_k}^T Z_k)t$

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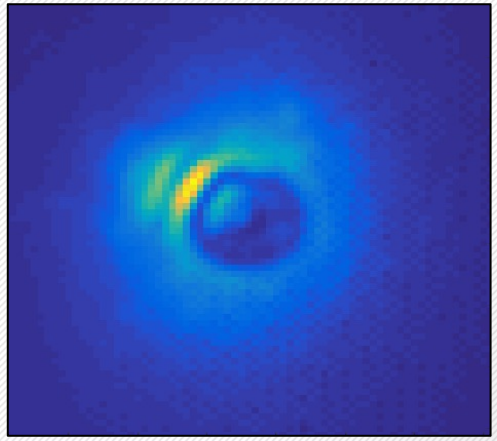
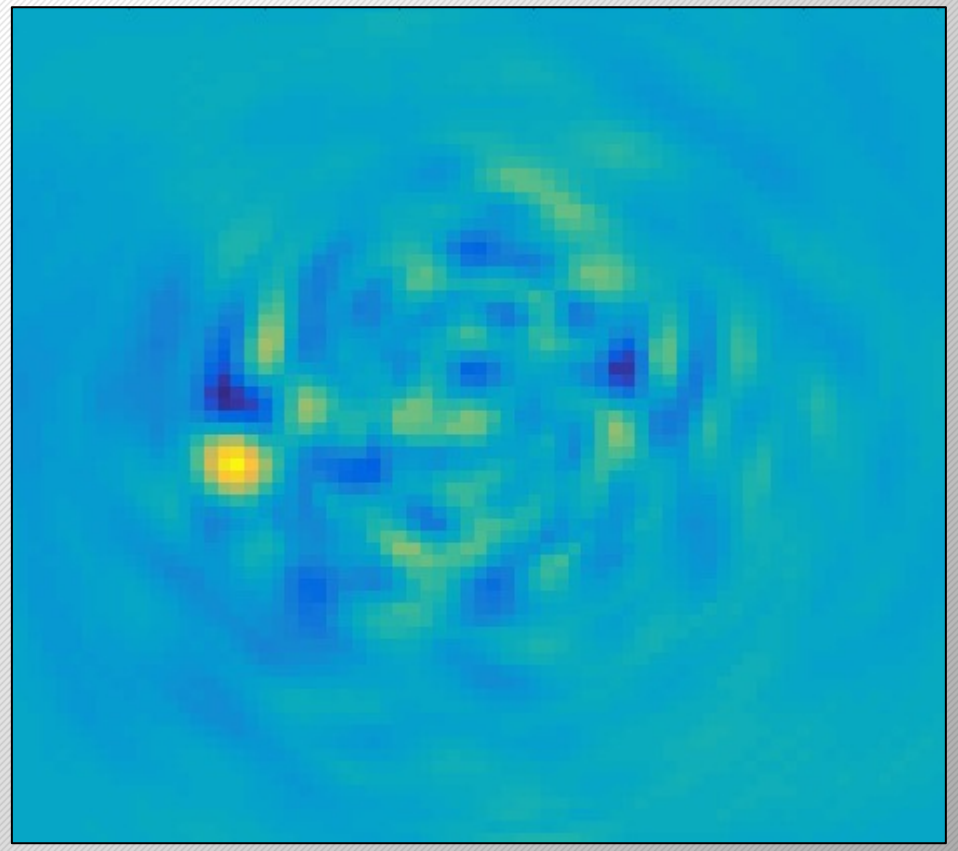
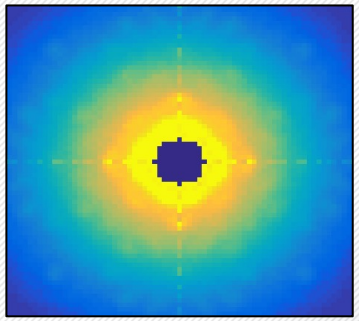




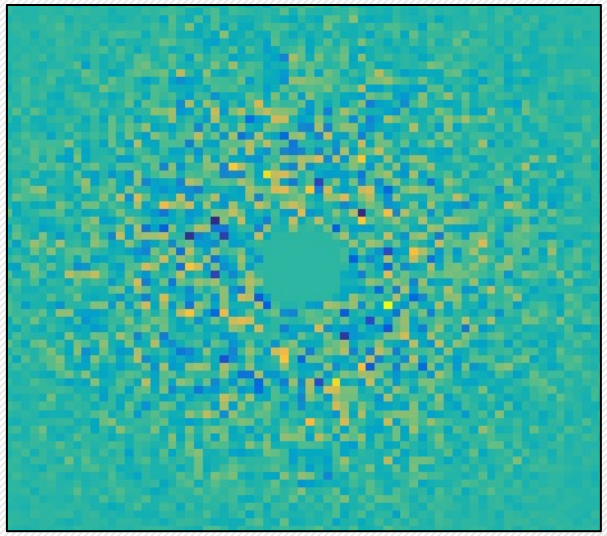
Signal for a given target image t is $({Z_k}^T Z_k)t$

Modes Overview

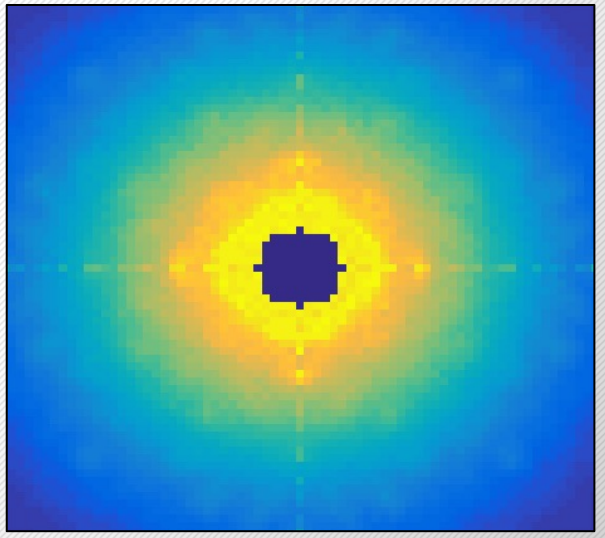
Original Image:



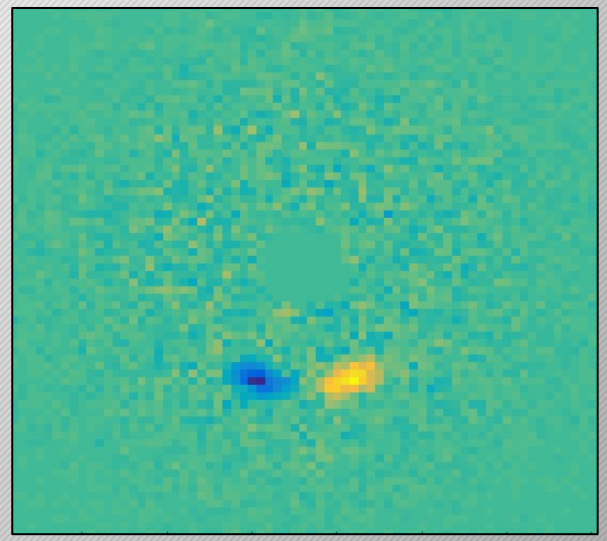
Maximum Eigenvalue



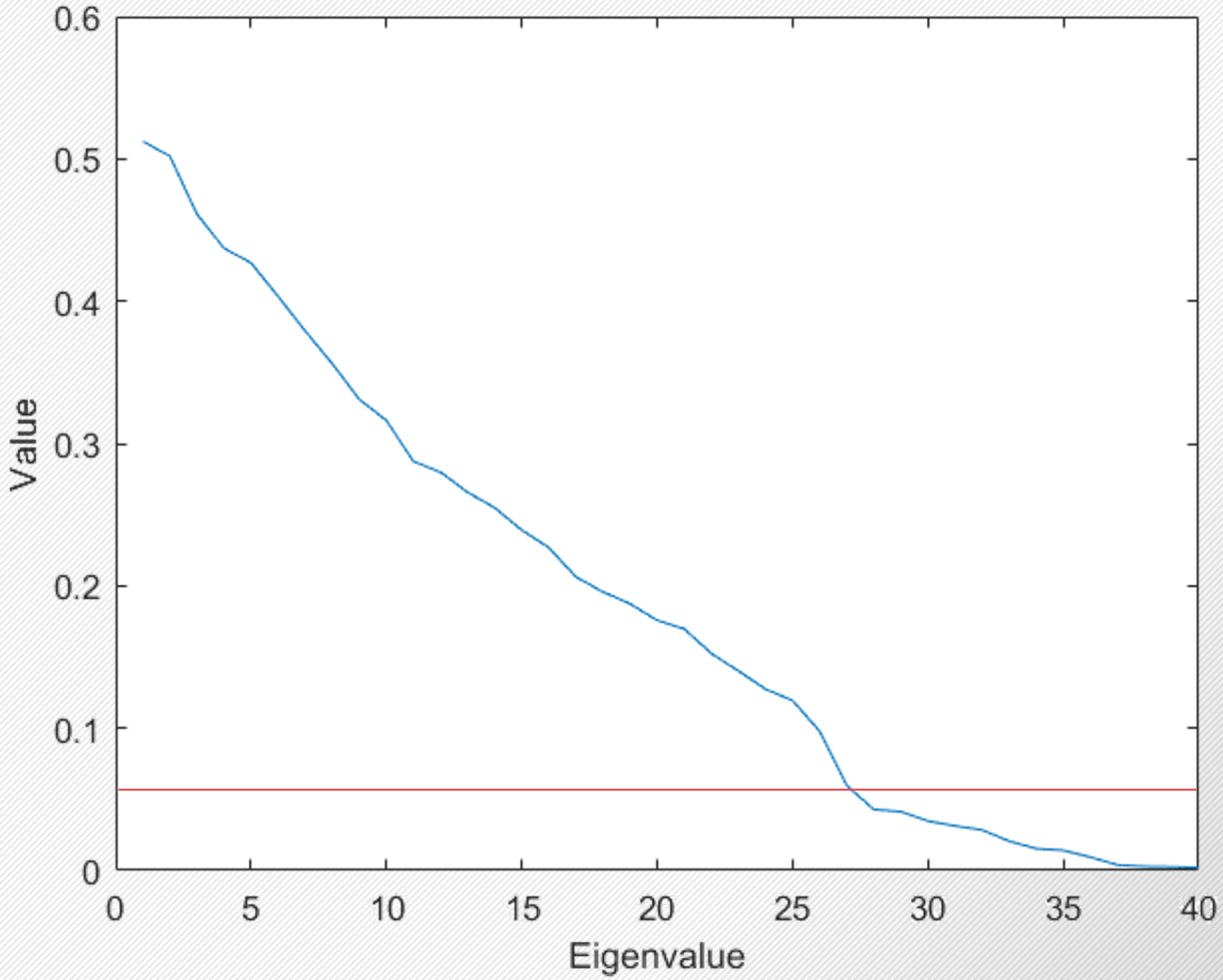
Eigenvalue ~ 0.5

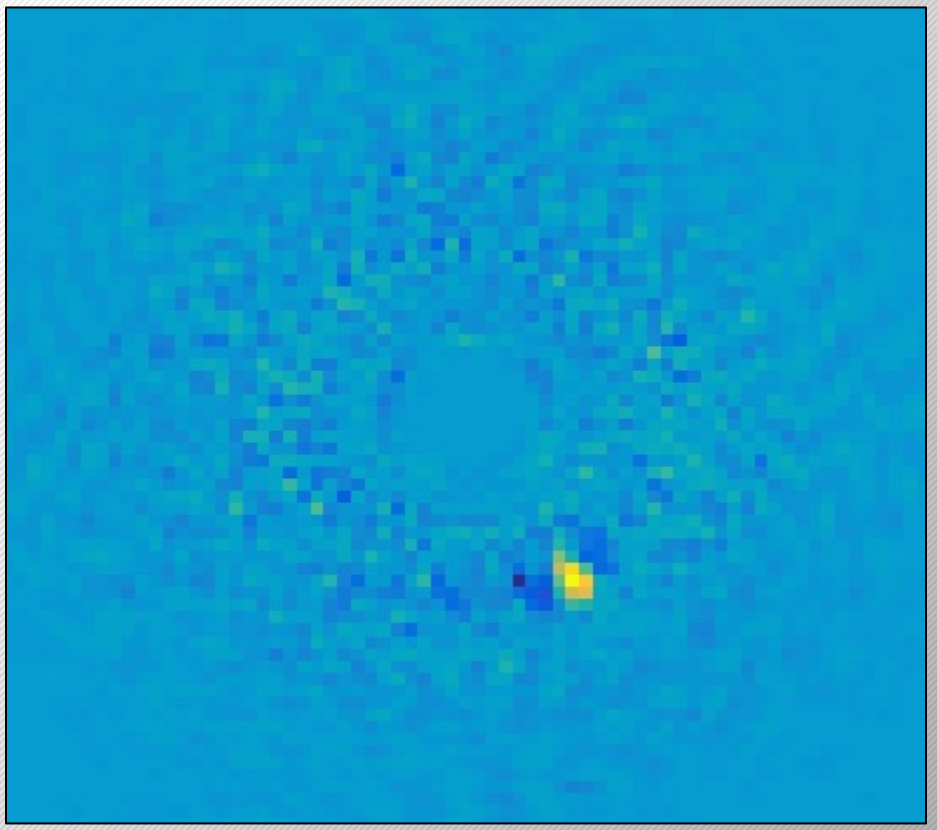


Minimum Eigenvalue

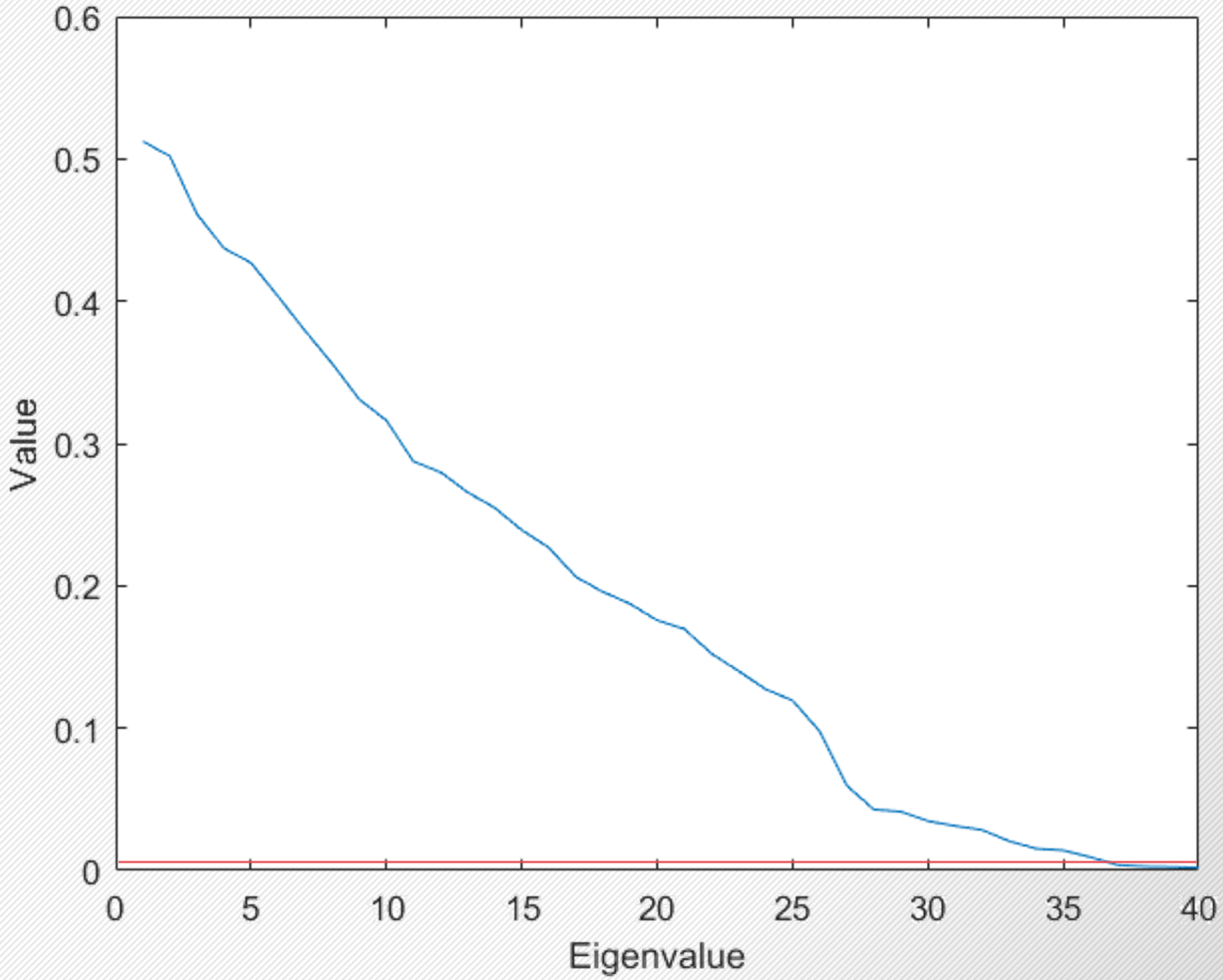


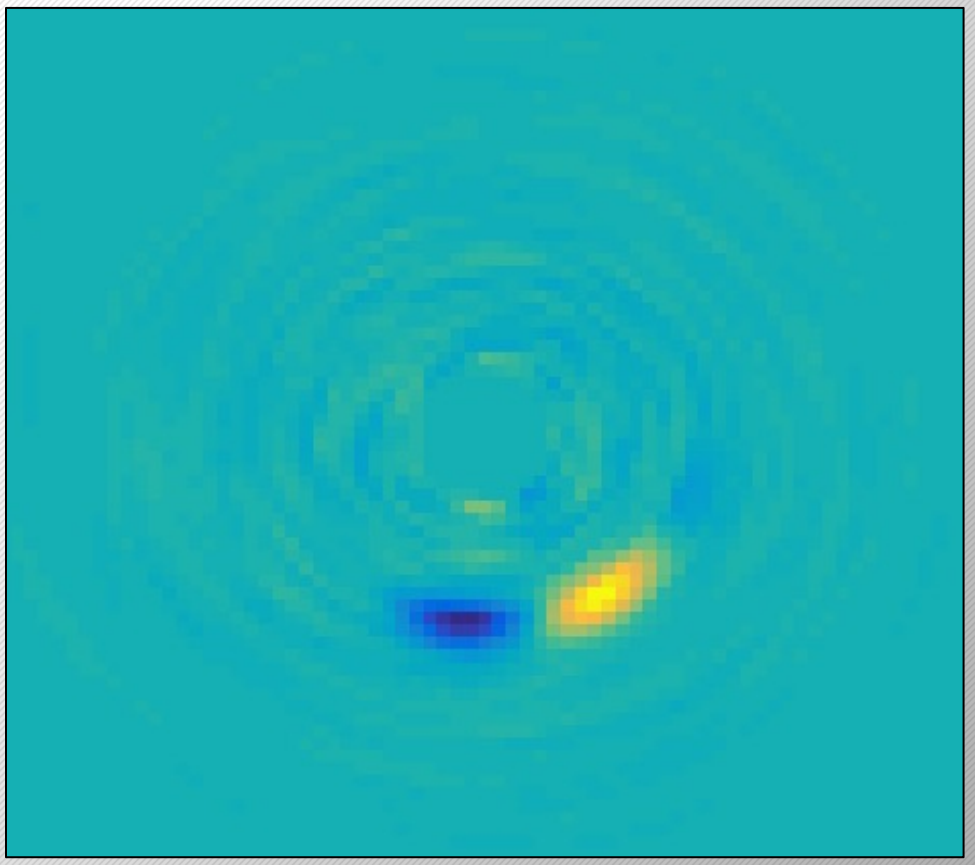
Threshold – Too High, 0.05



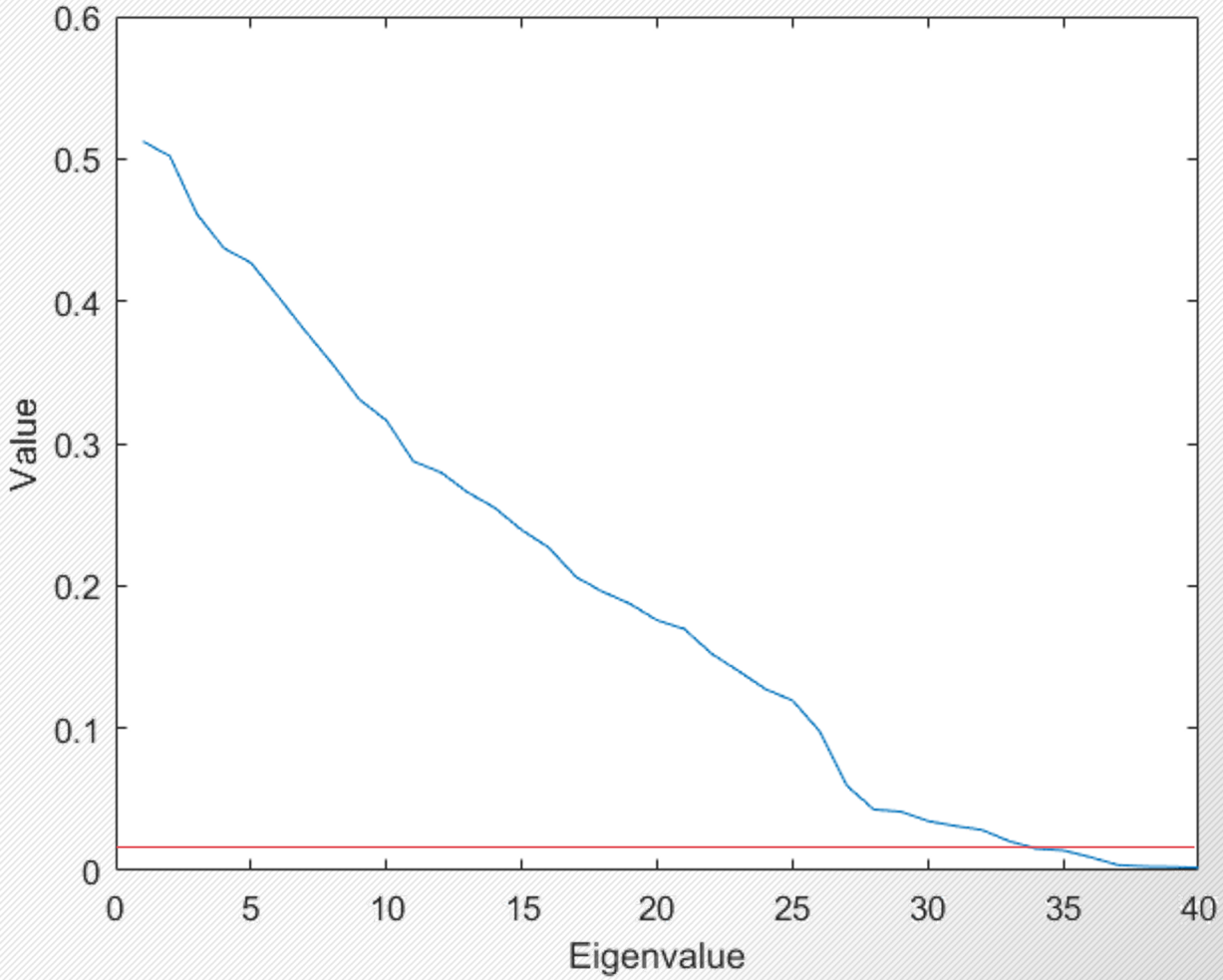


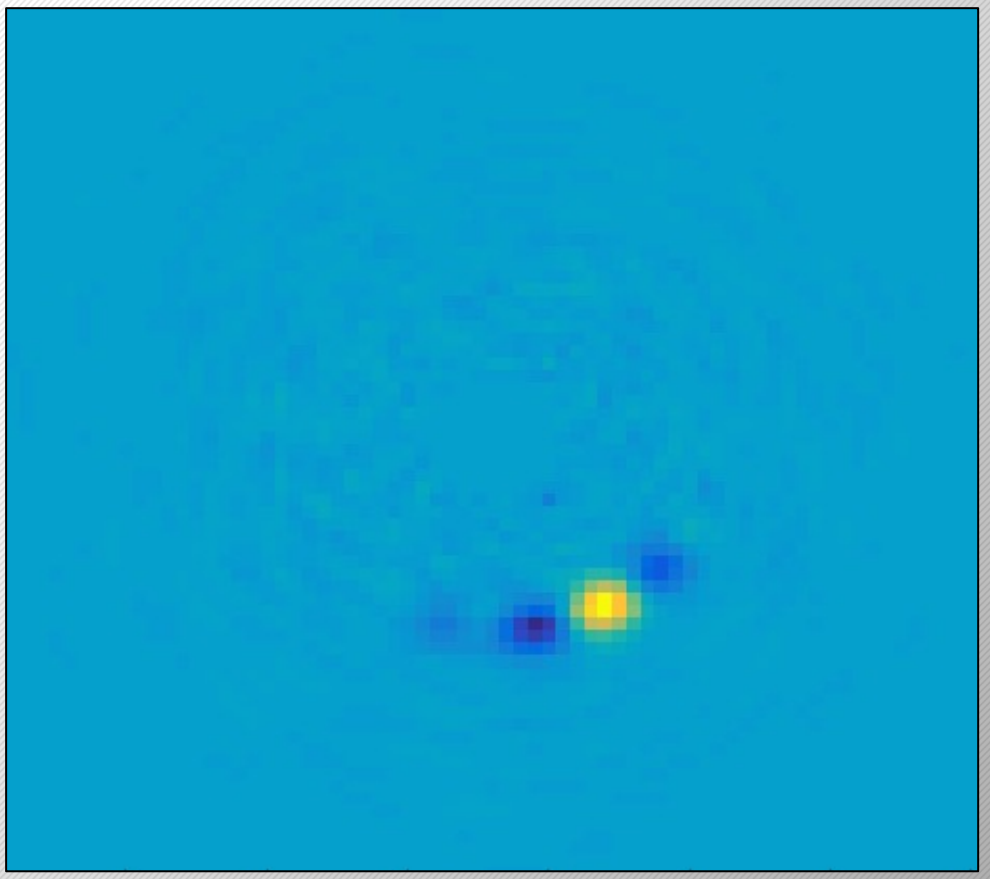
Threshold – Too Low, 0.002





Threshold – Just Right, 0.005

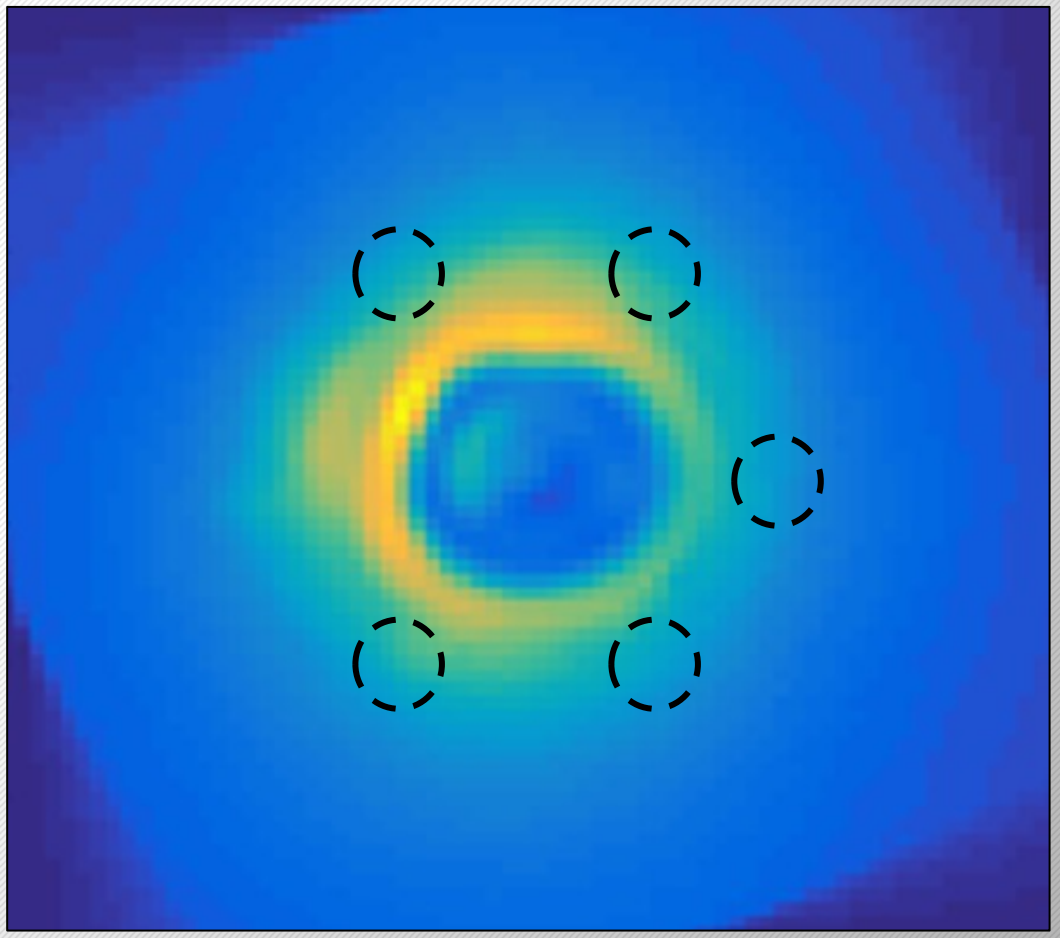




Data Sources

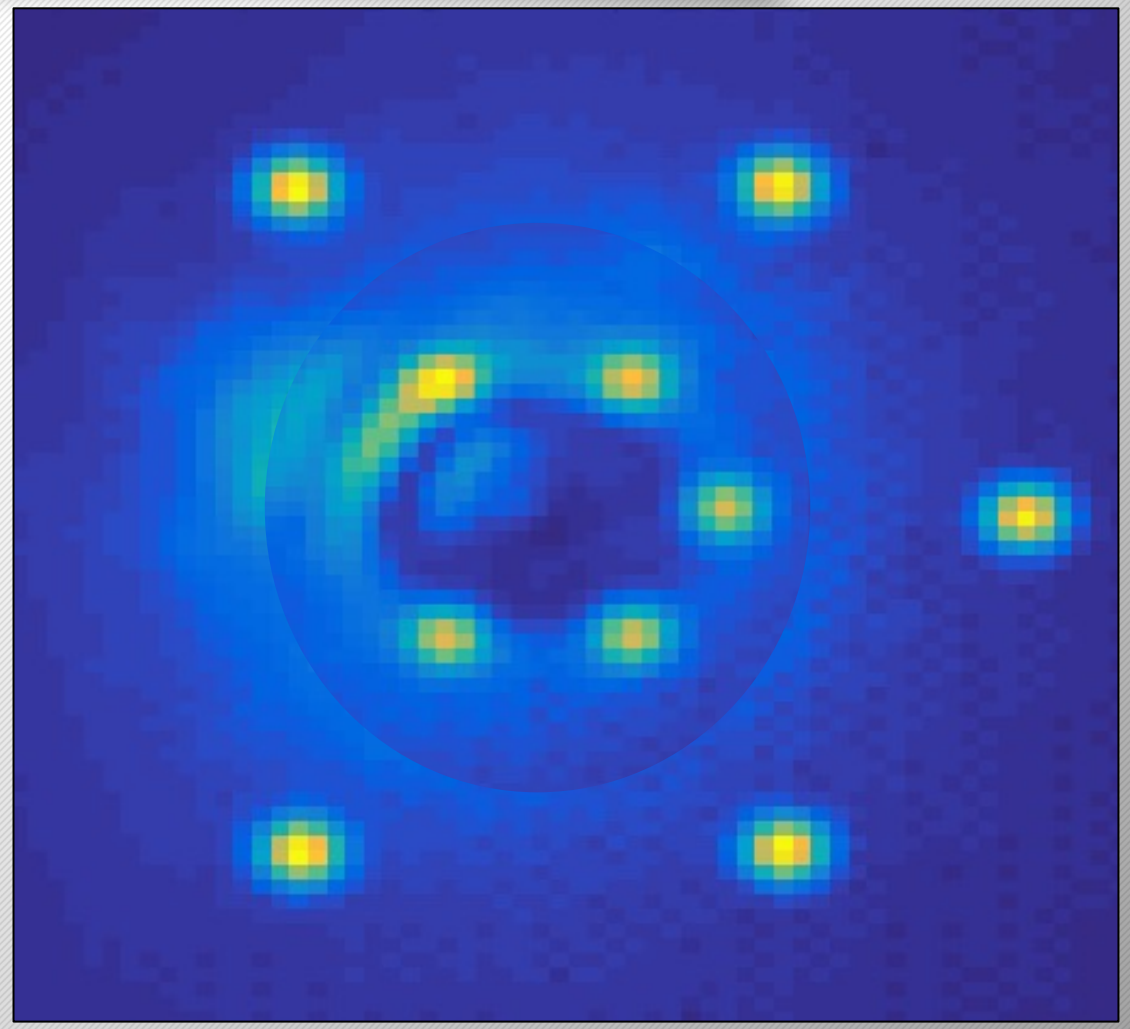
- GPIES, Nov 2015, β Pic b
- Limited to ADI
- Repeated analysis on HD 1466

- Planetary Injection
  - 2D Gaussian fit to β Pic b
  - Same strength as β Pic b
  - Rotate with Parallactic Angle
  - 5 injected



Methodology

- Angular Separation
  - From inner ring to outer ring
  - Measurements averaged at given radius
  - Moving through noise regimes
- Varied signal strength
  - 0.5 to 4.5 percent of max value
  - Each set of 5 averaged together
- Iterated through different thresholds
  - Kept the strongest Signal-Noise Result



Evaluation Metrics

Signal - Noise Ratio

$$SNR_{i,j} = \frac{S_{i,j}}{var(N)}$$

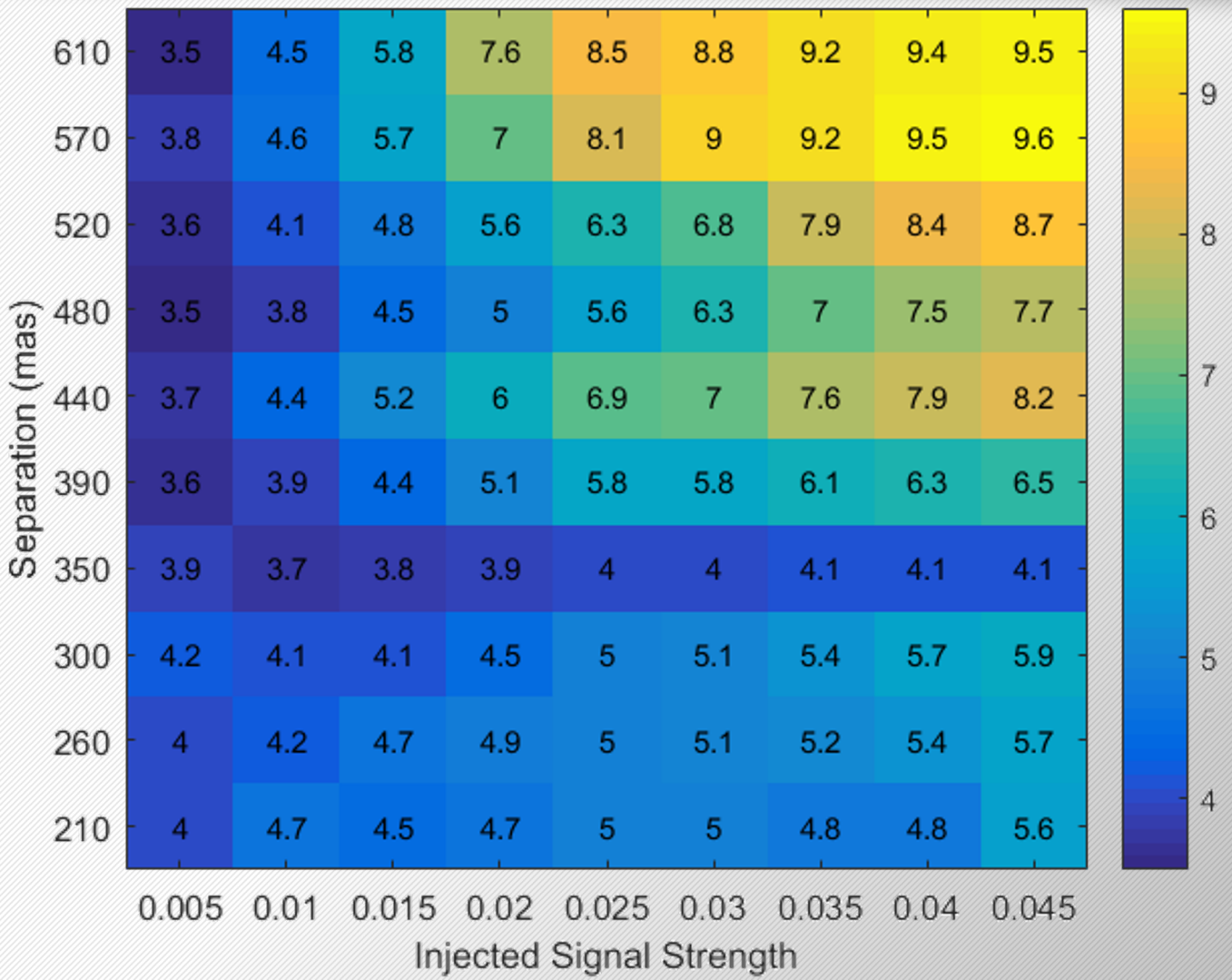
- Signal strength is peak of fit Gaussian
- Noise area is local section of annulus

Astrometric Biases

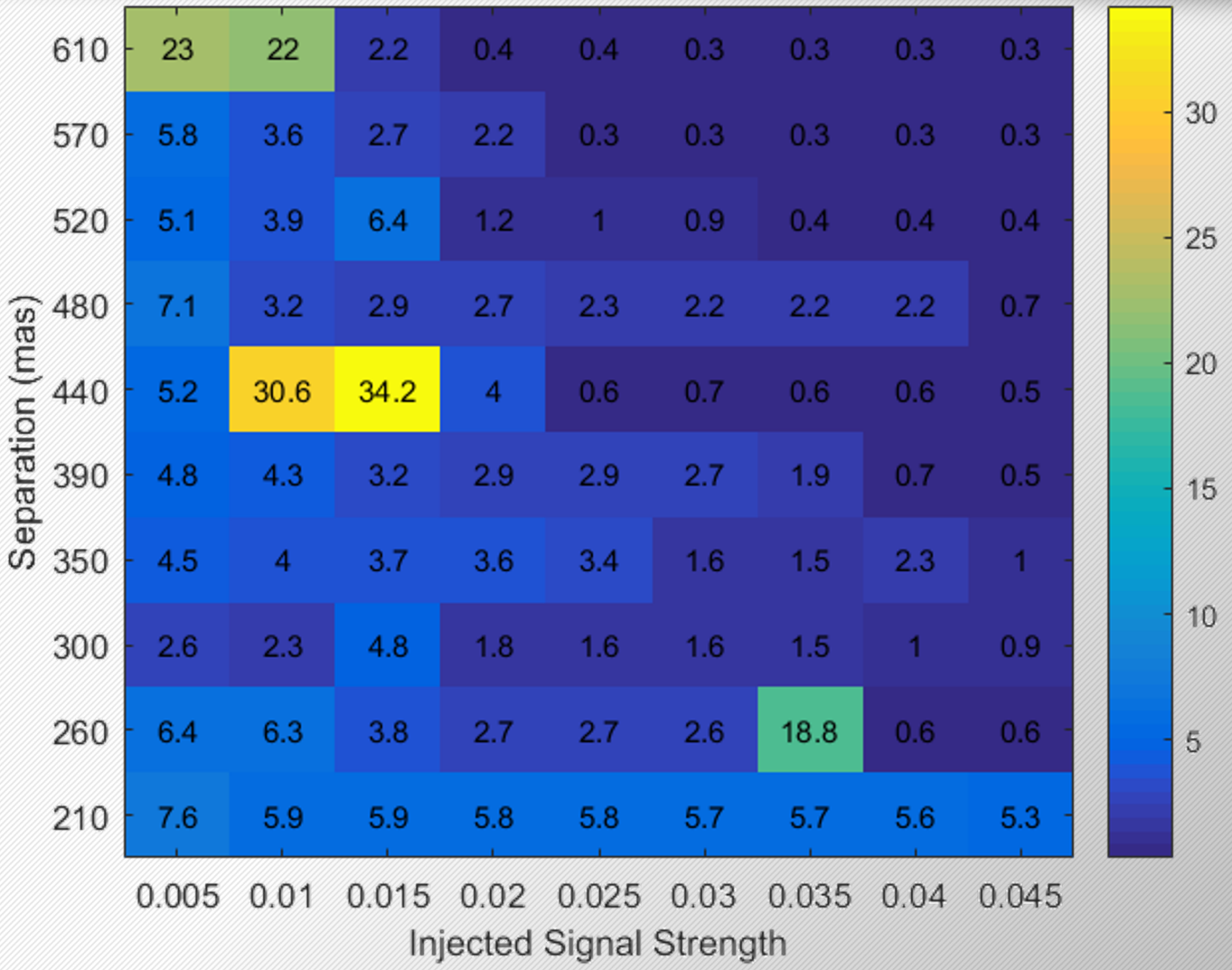
$$C[\tau_x, \tau_y] = \sum\sum S[x,y]T[x-\tau_x, y-\tau_y]$$

- Matched filter
- Point of maximum cross-correlation

Signal to Noise Ratio

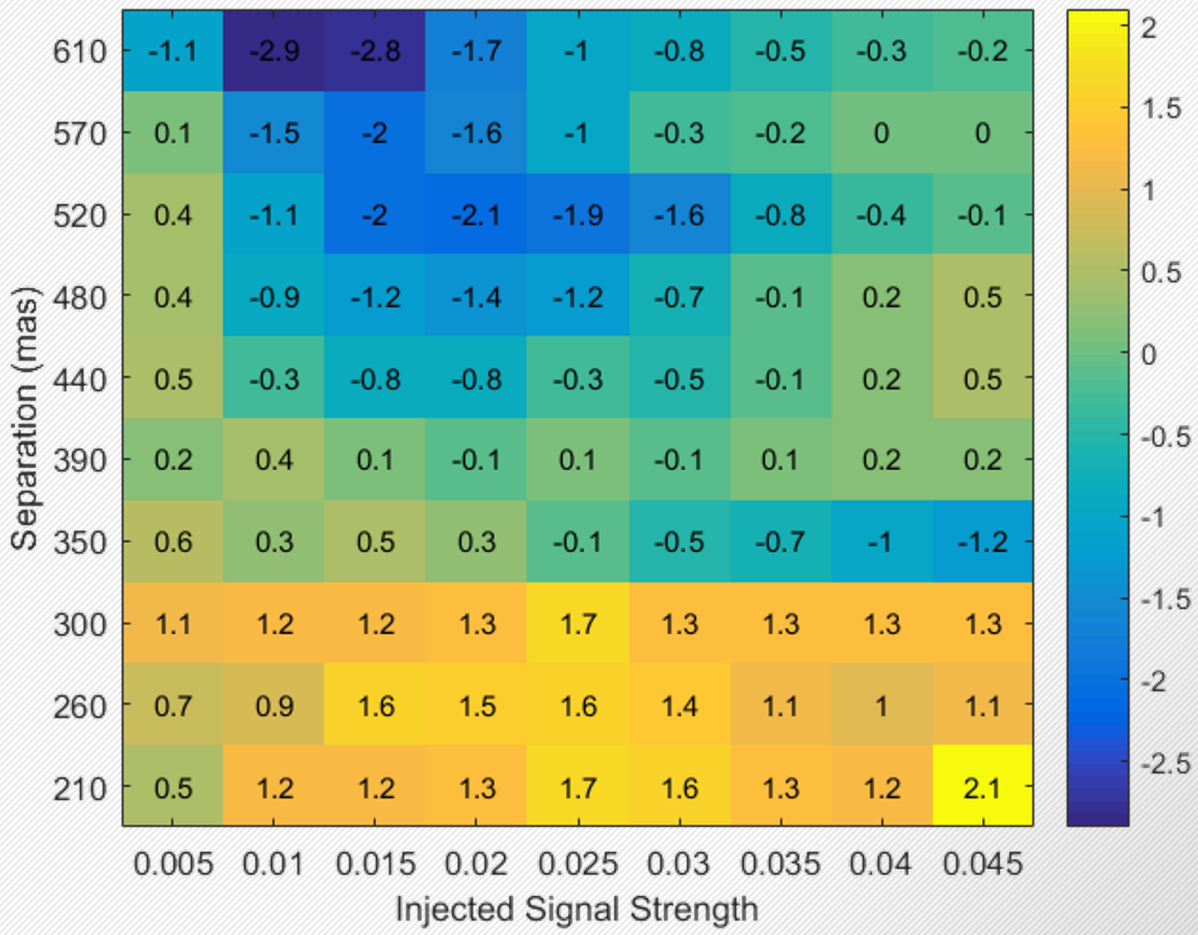


Centroiding Error

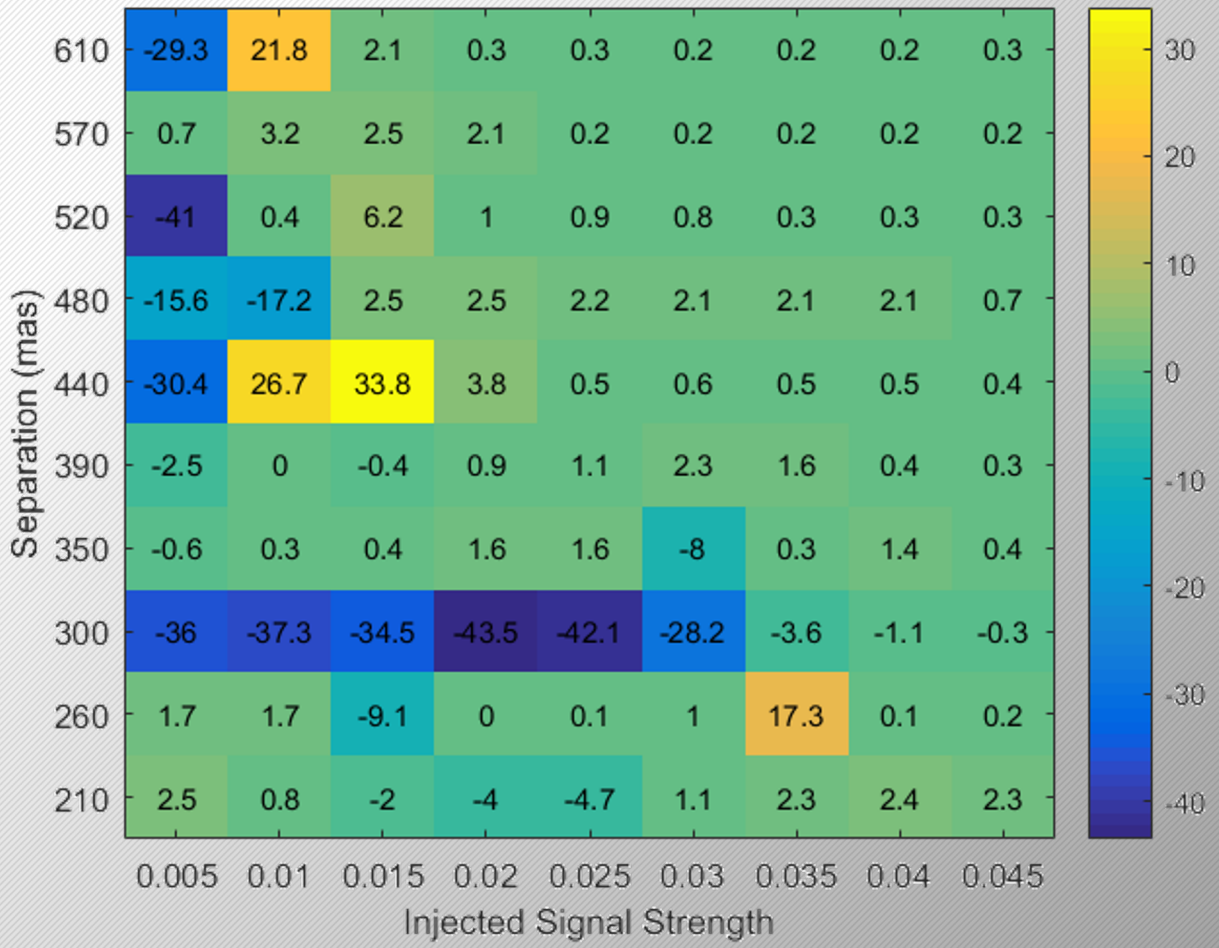


CSP – KLIP Comparison, Beta Pic

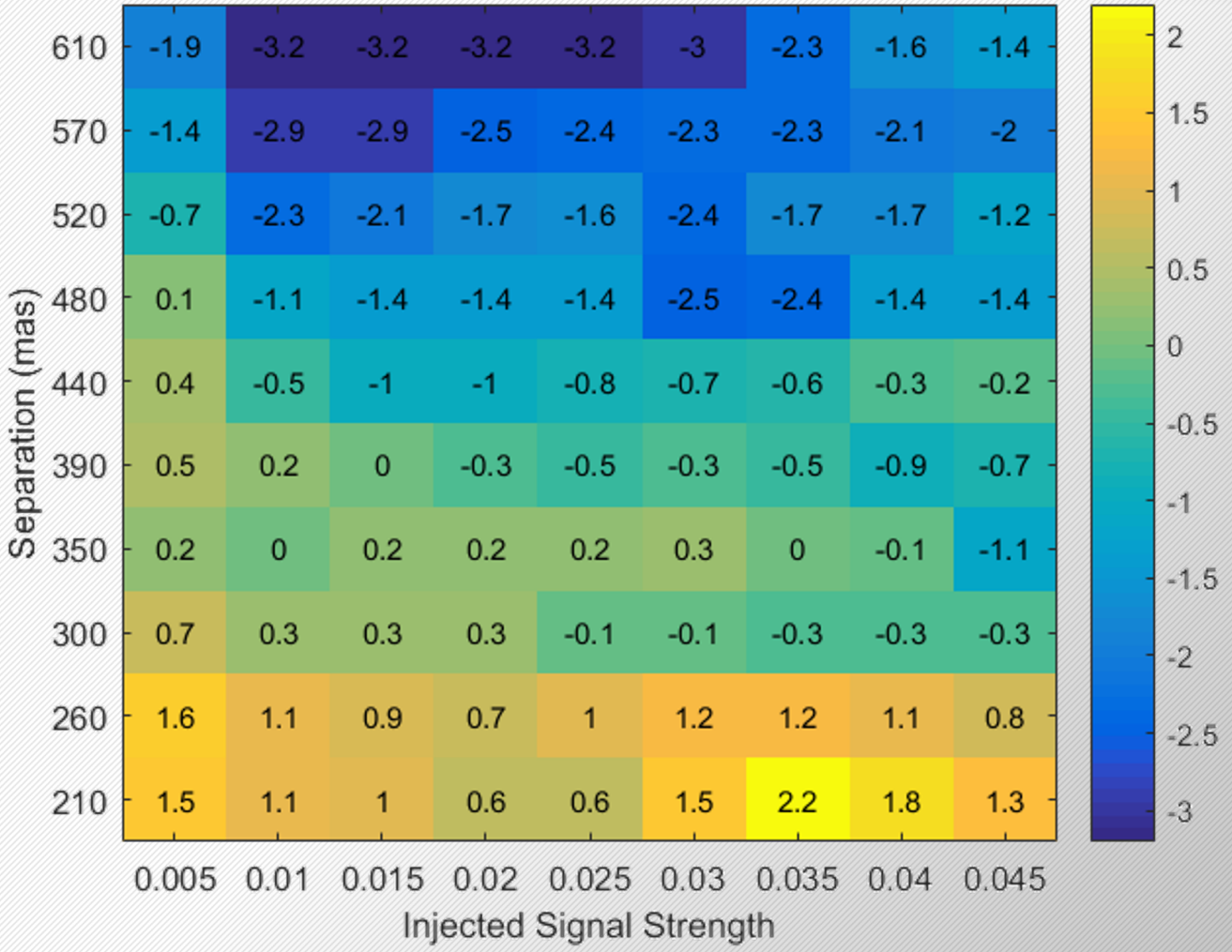
SNR



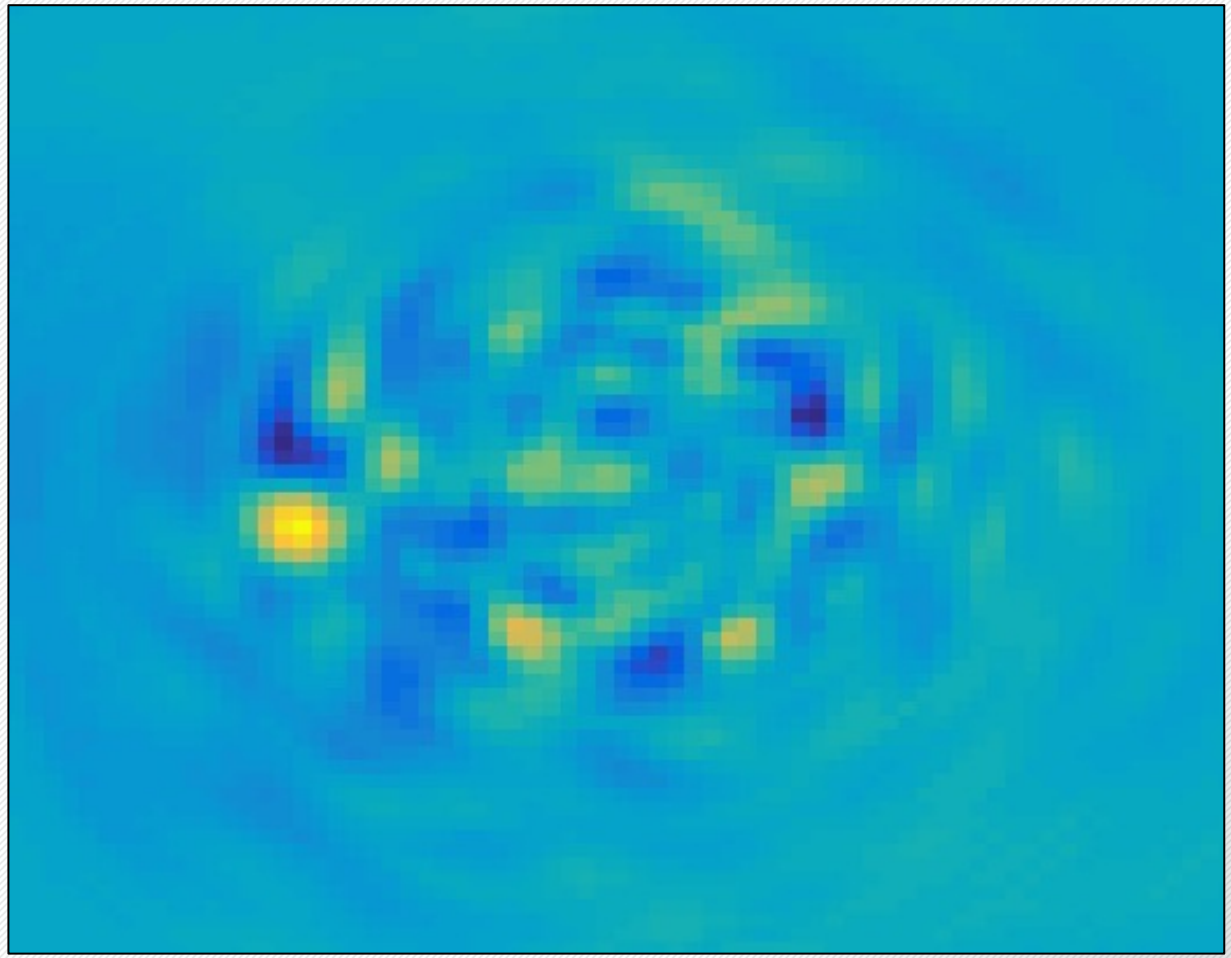
Centroiding Error

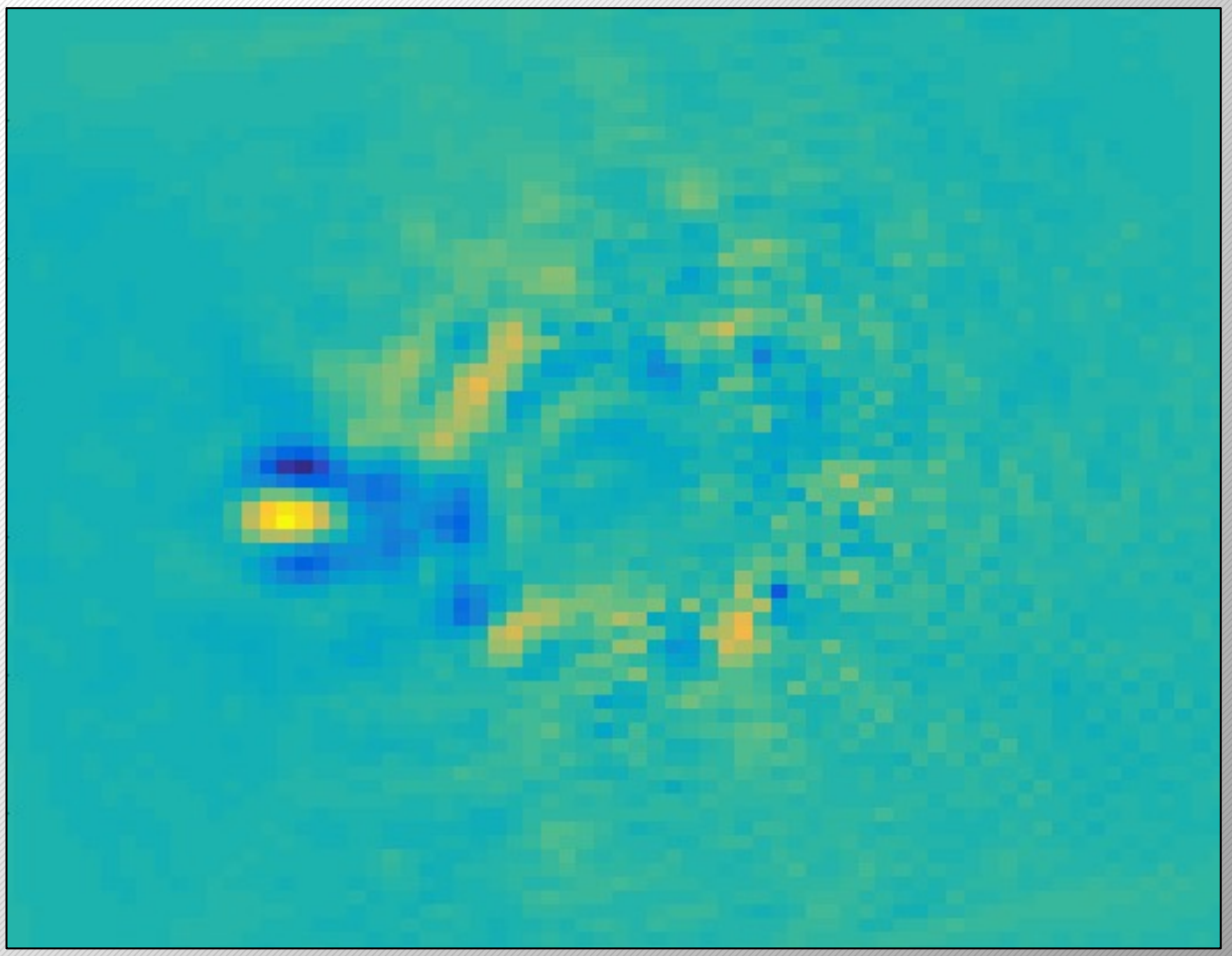


CSP – KLIP SNR Comparison, HD 1466

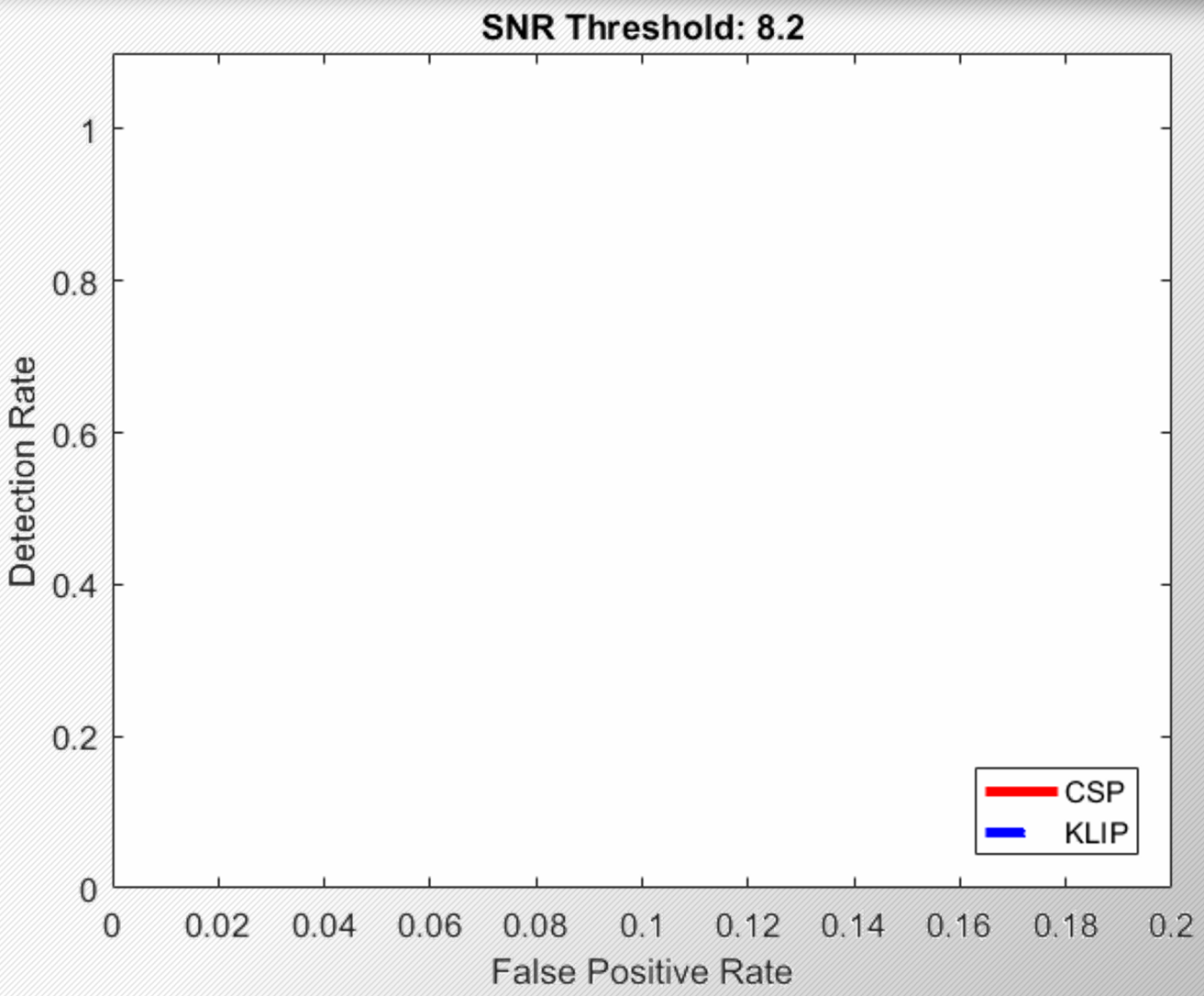


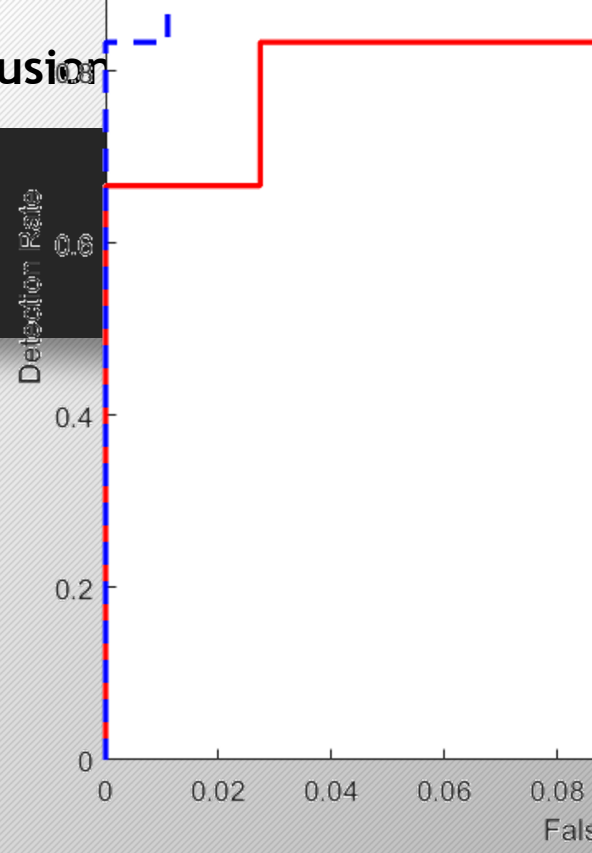
Images (Left: CSP, Right: KLIP)





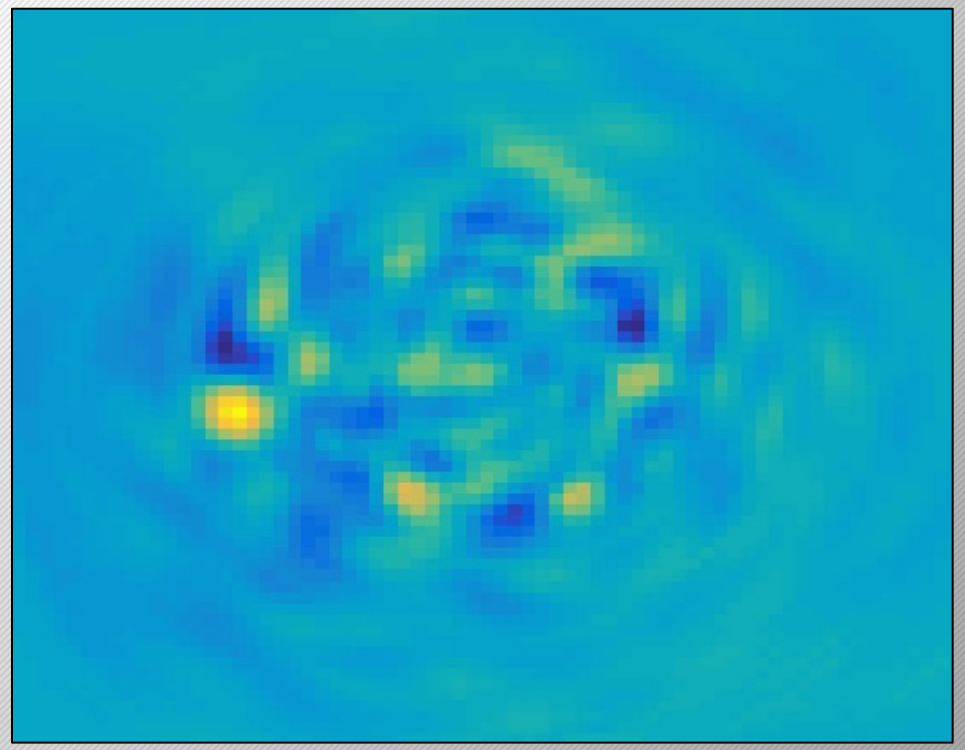
ROC Curve


SNR Threshold: 8.2
Detection Rate
False Positive Rate
0
0.2
0.4
0.6
0.8
1
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
CSP
KLIP


Detection Rate
0
0.2
0.4
0.6
0.8
0
0.02
0.04
0.06
0.08

Conclusions and Future Work

- Common Spatial Pattern Filtering can be used to extract planet signals from direct imaging
- Tentatively, CSP has higher SNR near inner working angle
- Higher rate of false positives



- Matched Filter
- Validate on more star backgrounds
- Develop procedure for SDI inclusion
- Optimally sized regions

Acknowledgements

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- Dmitry Savransky
- Christian Delacroix
- Joyce Fang
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  - J.B. Ruffio

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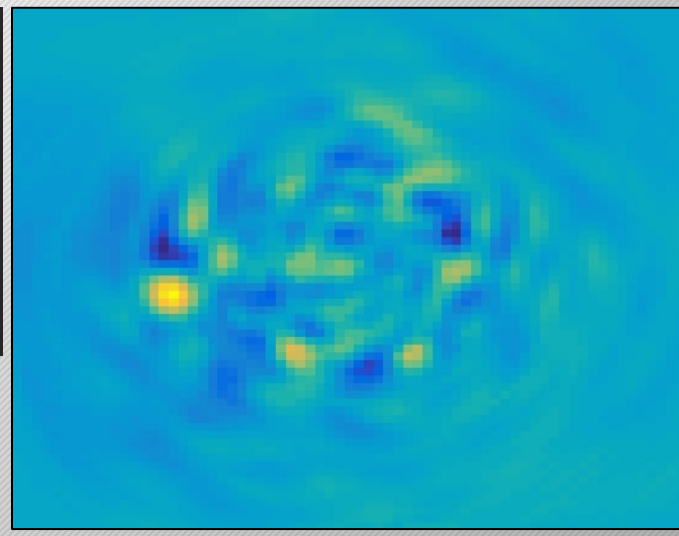
Planet signal extraction from direct imaging using common spatial pattern filtering



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