# Blind Source Separation Approaches for Exoplanet Signal Extraction

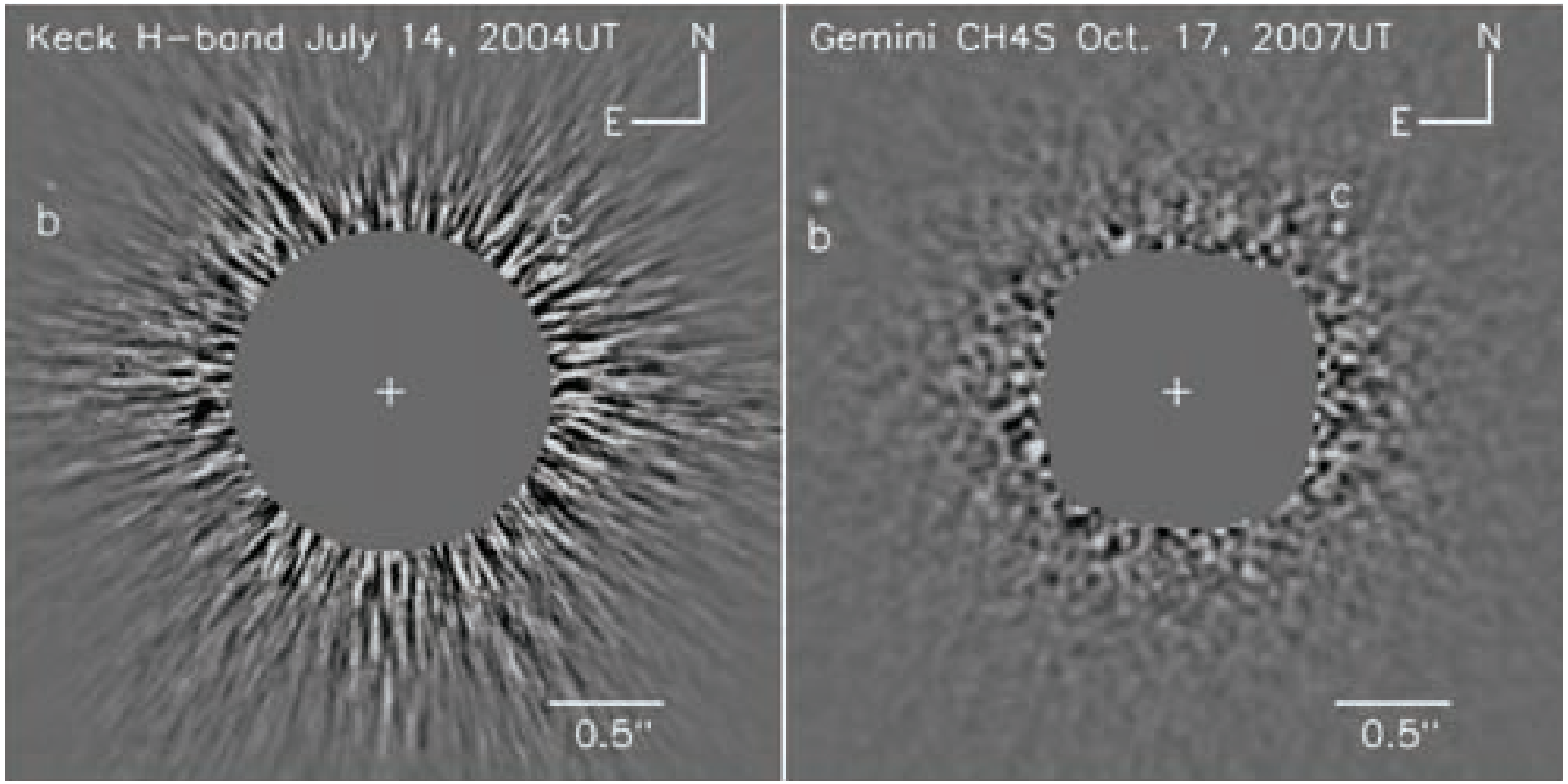
Paper 9605-26

Dmitry Savransky

Cornell University

August 12, 2015

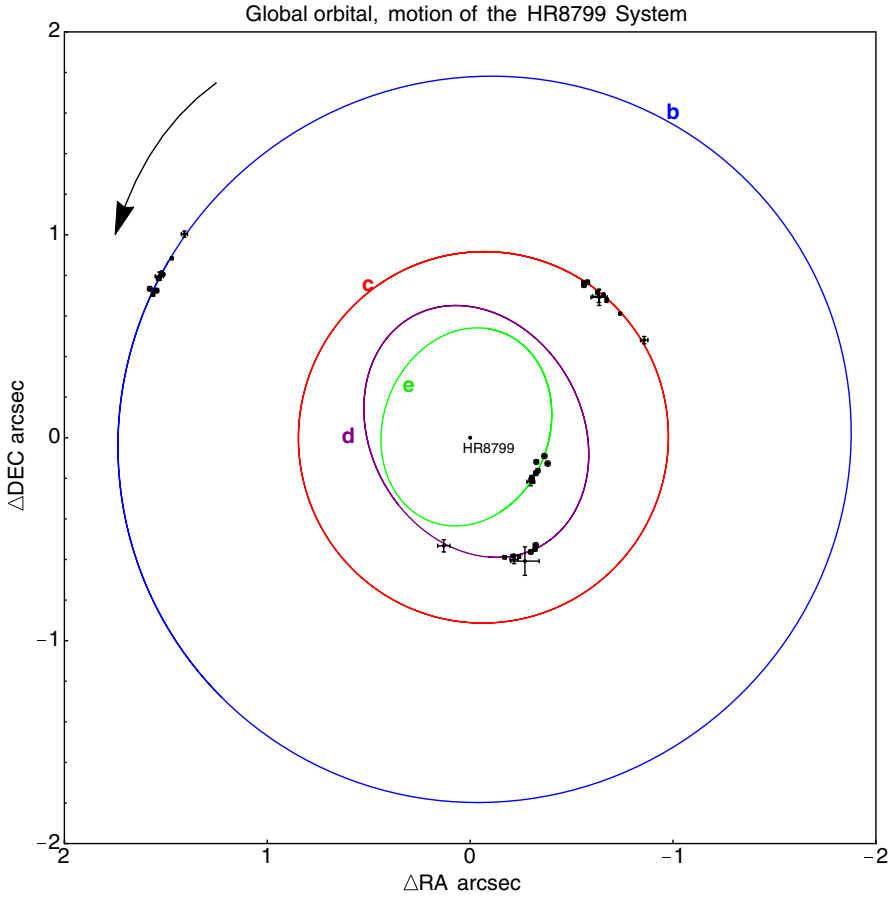
# Motivation



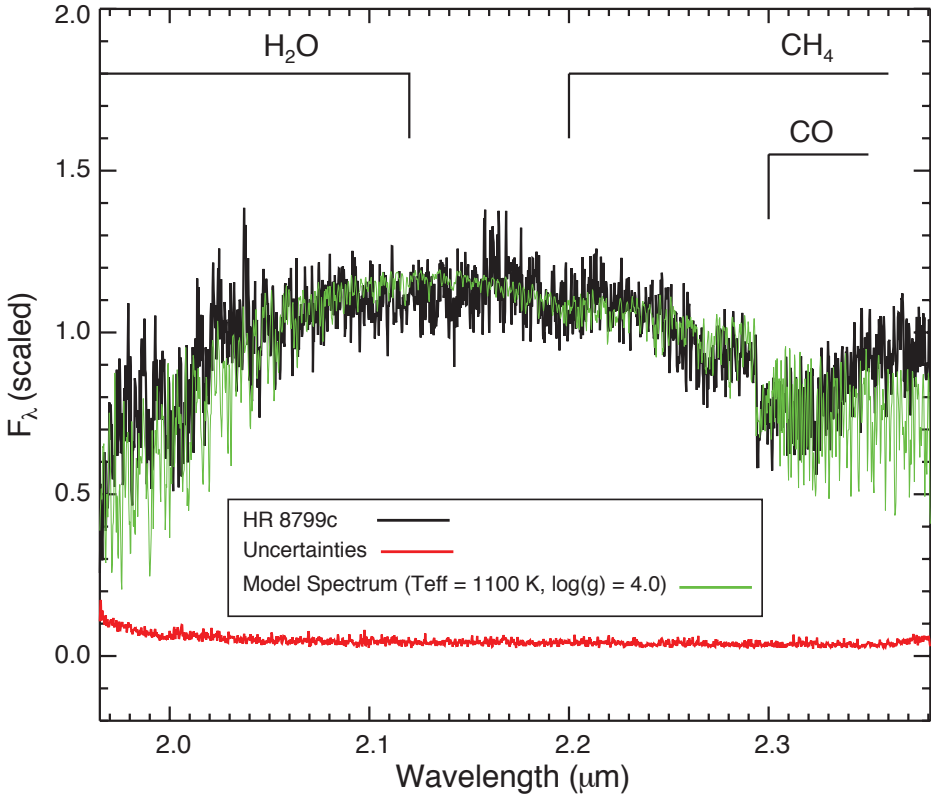

Images of the HR8799 system. [Marois et al., 2008]

We wish to detect exoplanets in coronagraphic imaging data

# We Want Precision Astrometry and Photometry

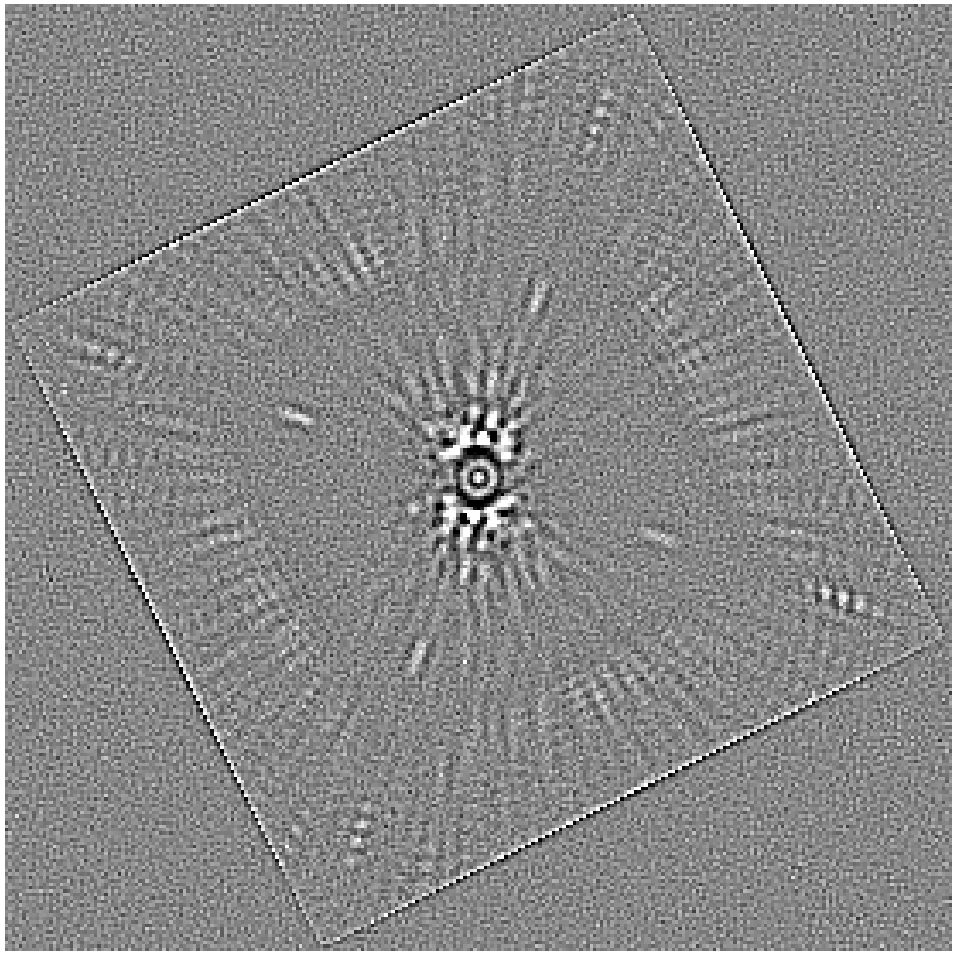



Orbital fits to HR 8799 system. [Pueyo et al., 2015]




High resolution ($\lambda/\Delta\lambda \approx 4000$) spectrum of giant planet HR 8799c with best-fit model spectrum. [Konopacky et al., 2013]

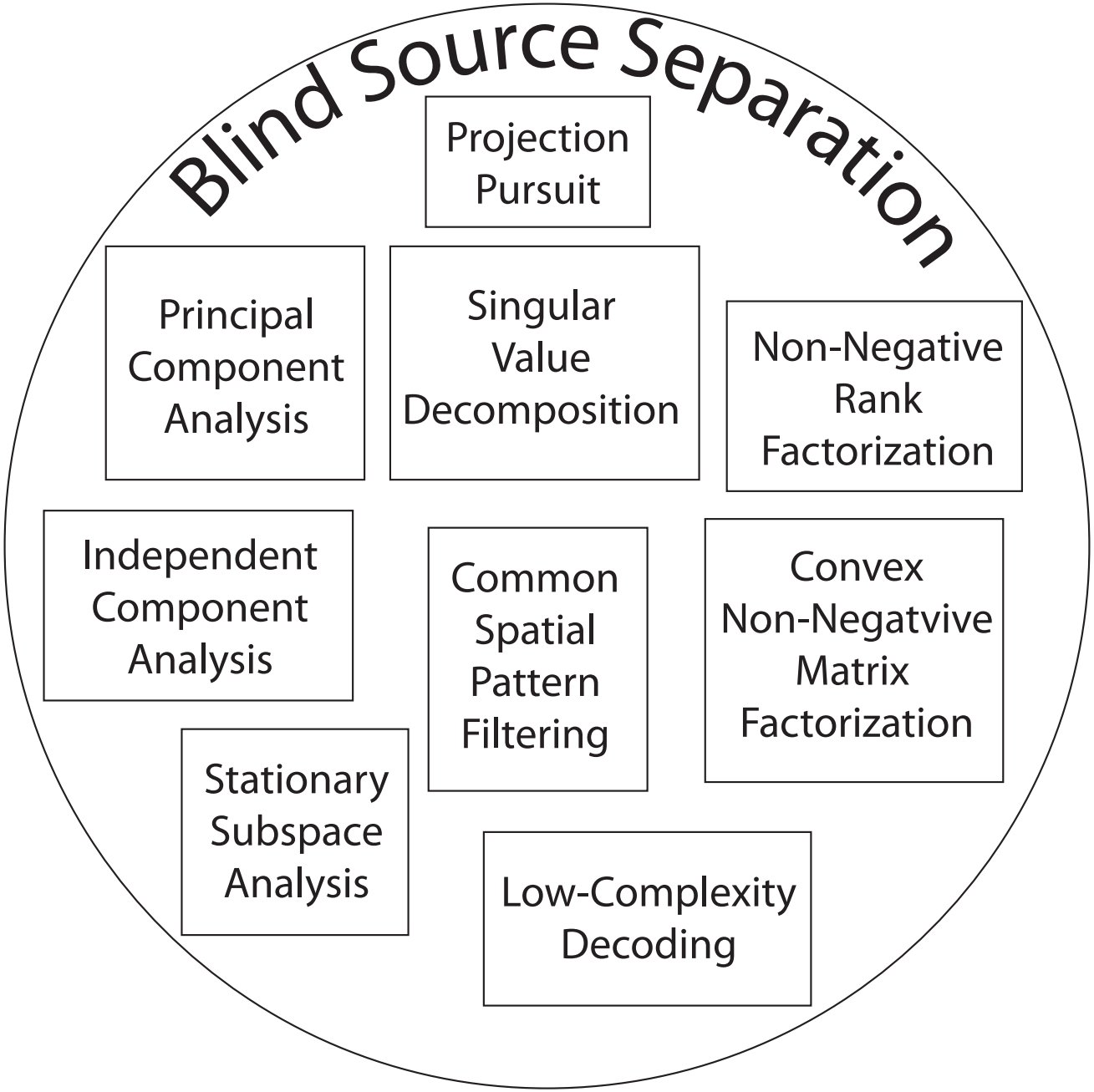
# Problem



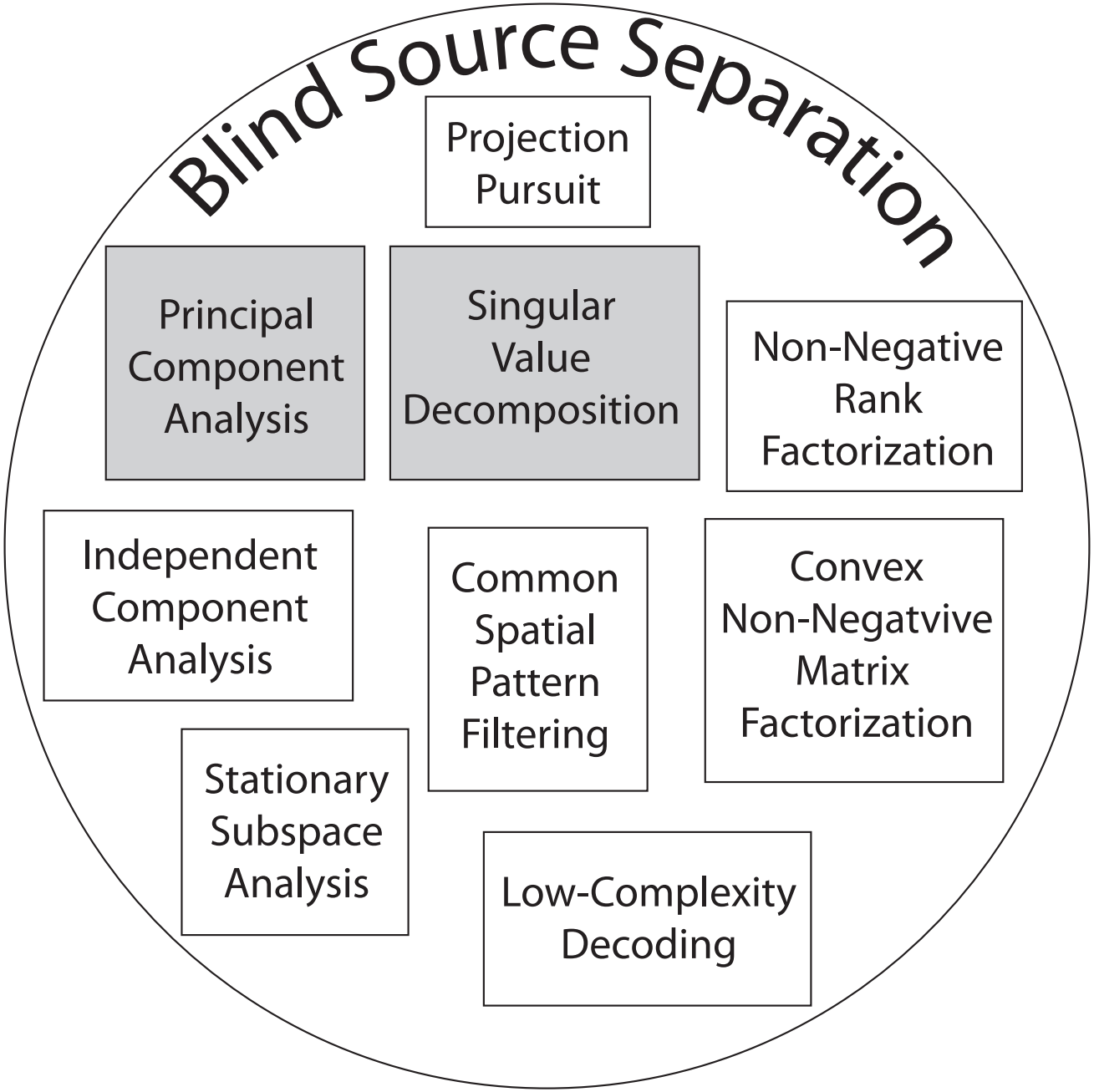
Highpass filtered simulated image

Non-Gaussian distributed speckle noise around the same magnitude as the planet signal that is correlated and evolving at multiple time scales

# This is a Blind Source Separation Problem...

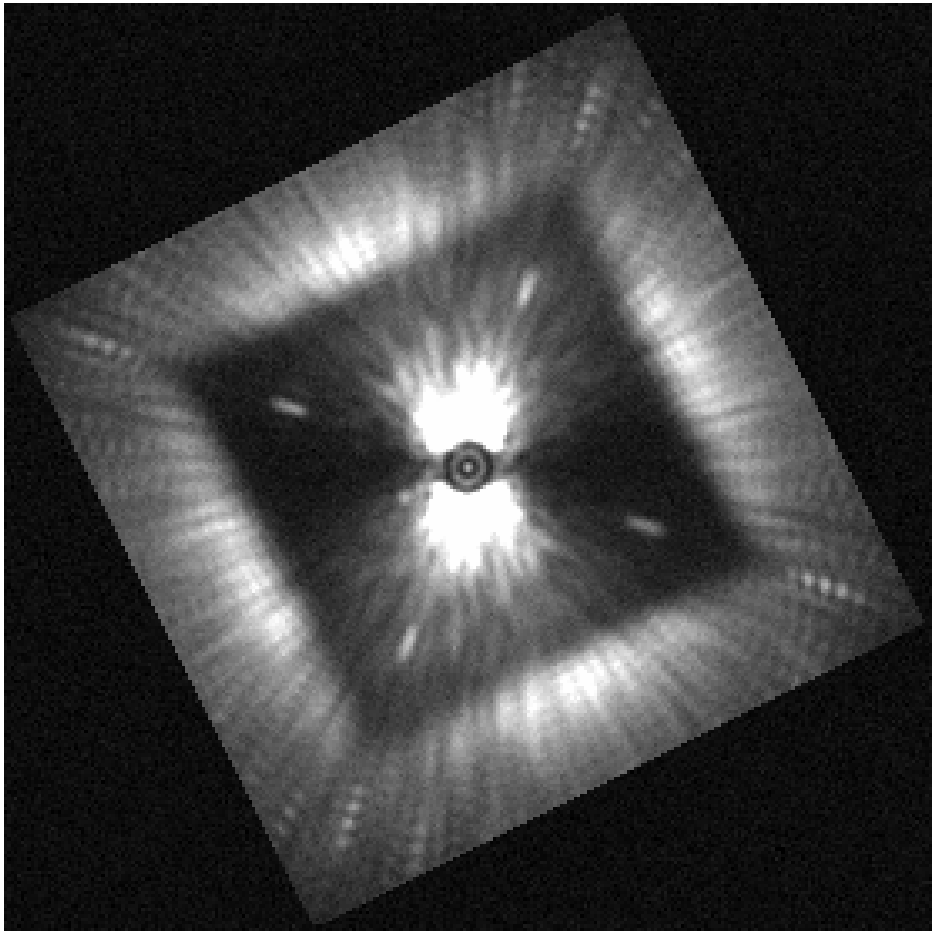


# ...But Most Work Has Focused On One Subclass

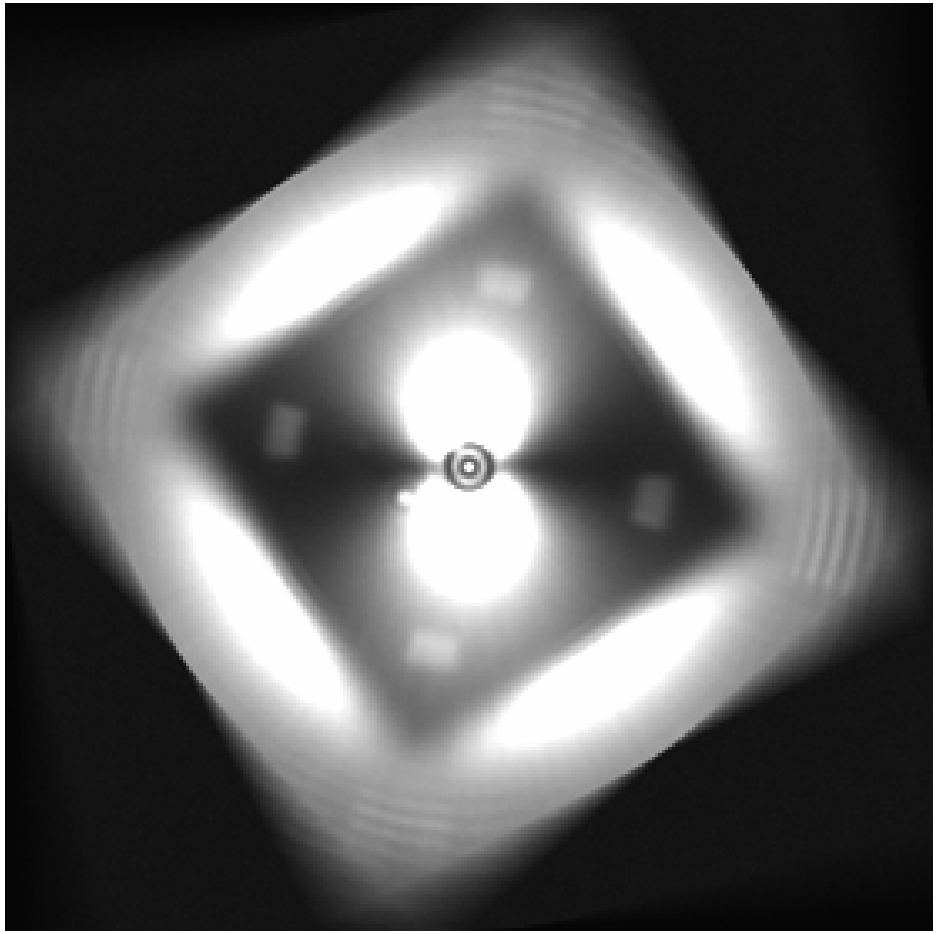


# The Data

# A Sample Data Set



Single exposure.

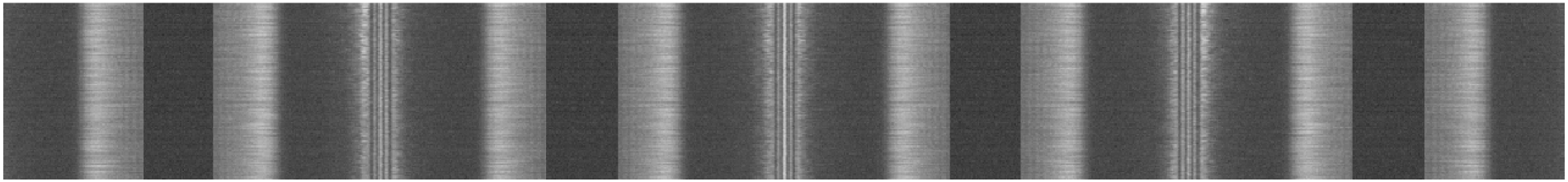


Sum of all exposures

Sample images from a simulated ADI/SDI data set

See: [Lawson et al., 2012]. Simulations by Lisa Poyneer.

# Some Formalism



$$\bar{R} \triangleq [\bar{\mathbf{r}}_1, \bar{\mathbf{r}}_2, \ldots, \bar{\mathbf{r}}_n]^T \in \mathbb{R}^{n \times p} \quad \text{for} \quad \bar{\mathbf{r}}_i \triangleq \mathbf{r}_i - \mu(\mathbf{r}_i) \in \mathbb{R}^p$$

$$S \triangleq \frac{1}{p-1} \bar{R}\bar{R}^T \in \mathbb{R}^{n \times n}$$

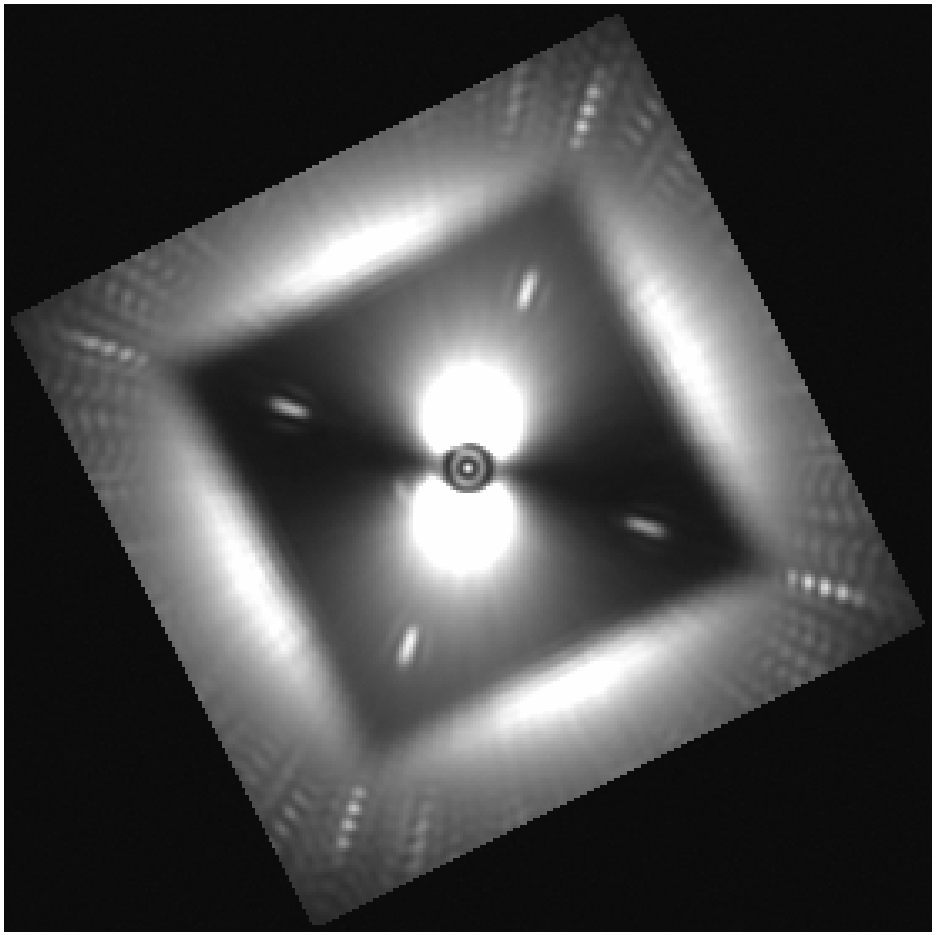
$$\bar{R}^T \mathbf{c} = \mathbf{t}$$

$$\tilde{\mathbf{c}} = (\bar{R}\bar{R}^T)^{-1} \bar{R}\mathbf{t}$$

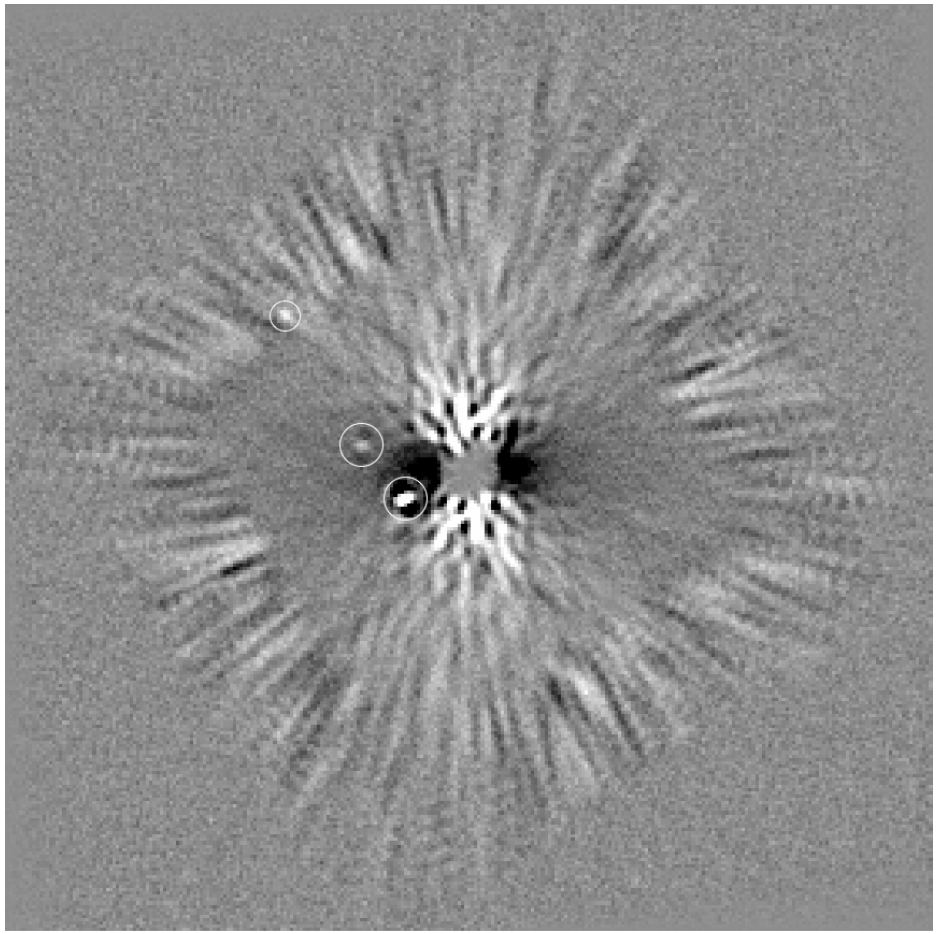
$$\hat{\mathbf{s}} = \left( I - \bar{R}^T \frac{S^{-1}}{p-1} \bar{R} \right) \mathbf{t}$$

See: [Lafrenière et al., 2007].

# Principal Component Analysis



First KL mode.



PCA processing output.

$$Z_k \triangleq \begin{bmatrix} I_{k\times k} & \mathbf{0}_{k\times(n-k)} \end{bmatrix} \frac{\sqrt{\Lambda^{-1}}}{\sqrt{p-1}} \Phi^T \bar{R} \qquad \hat{\mathbf{s}} = \left(I - \bar{Z}_k^T \bar{Z}_k\right) \bar{\mathbf{t}}$$

See: [Soummer et al., 2012, Pueyo et al., 2015, Savransky, 2015]

# Independent Component Analysis

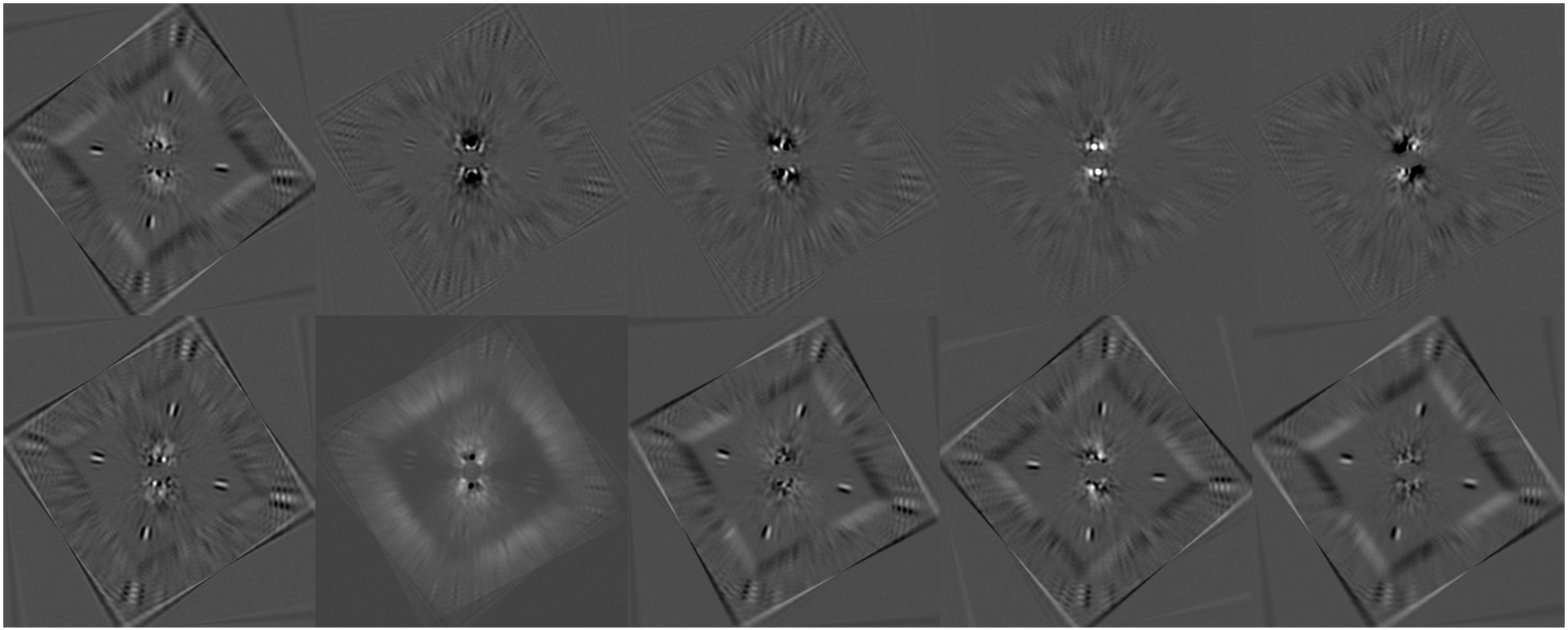
- Separate noisy multivariate sample into a mixture of statistically independent, non-Gaussian signals
- Find a linear transformation $A$ such that:

$$\mathbf{t} = A\mathbf{s}$$

  for vector of unknown, independent source signals $\mathbf{s}$.
- For set of independent model CDFs, $\phi$, unmixing matrix $A^{-1}$ is found by maximizing joint entropy of $\phi(A^{-1}\mathbf{t})$.
- $A$ found numerically via gradient descent or equivalent method

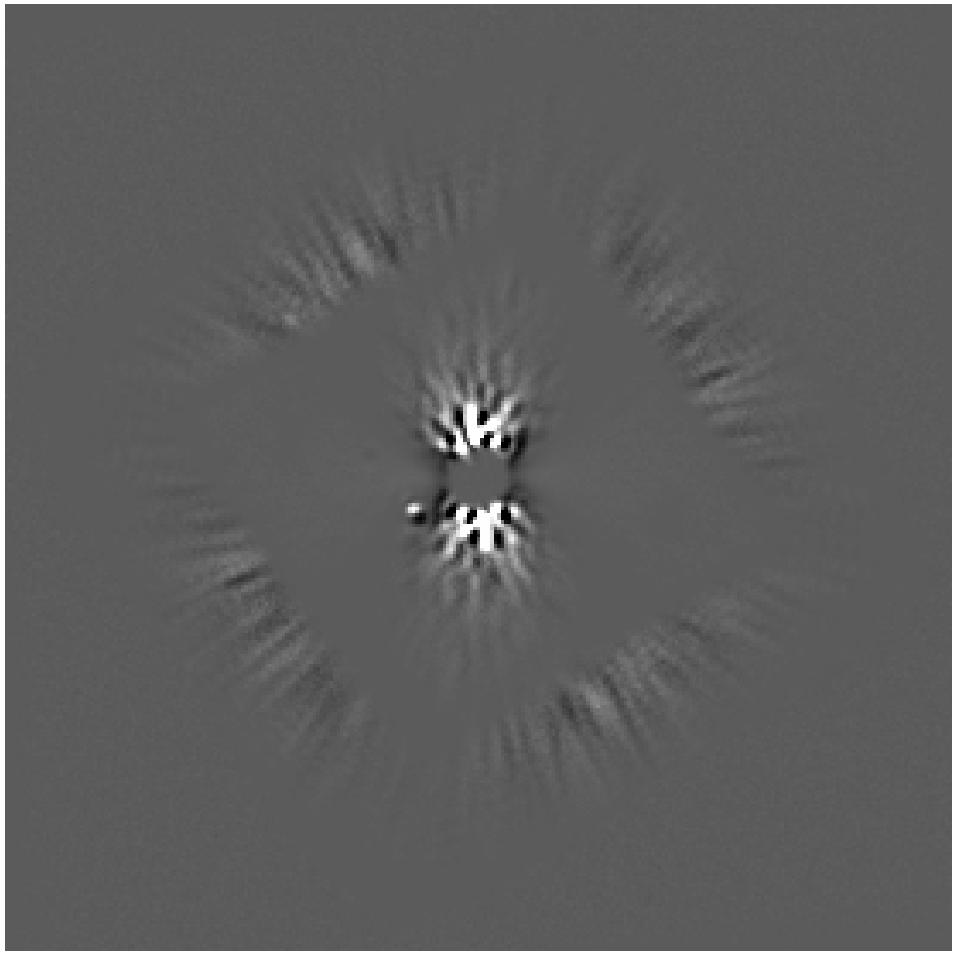
See: [Hyvärinen and Oja, 1997, Yilmaz et al., 2006]

# ICA Fames



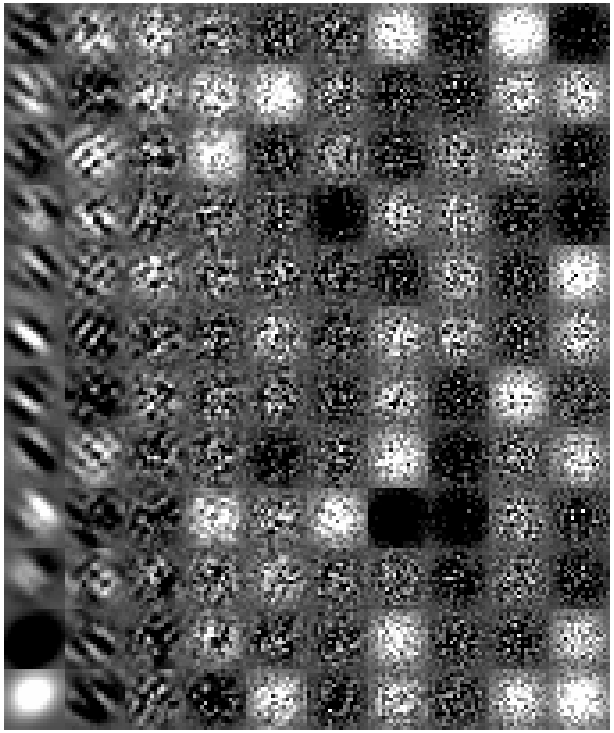
10 Independent components of data

# ICA Result 1

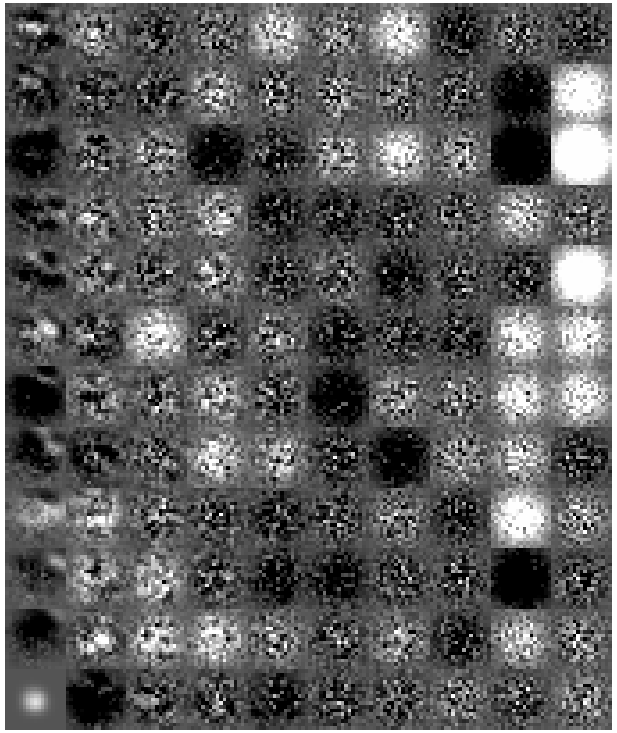


Summation of all subtracted ICA images. Planet 2 is completely self-subtracted, but other two are recovered with half of astrometric biasing of PCA.

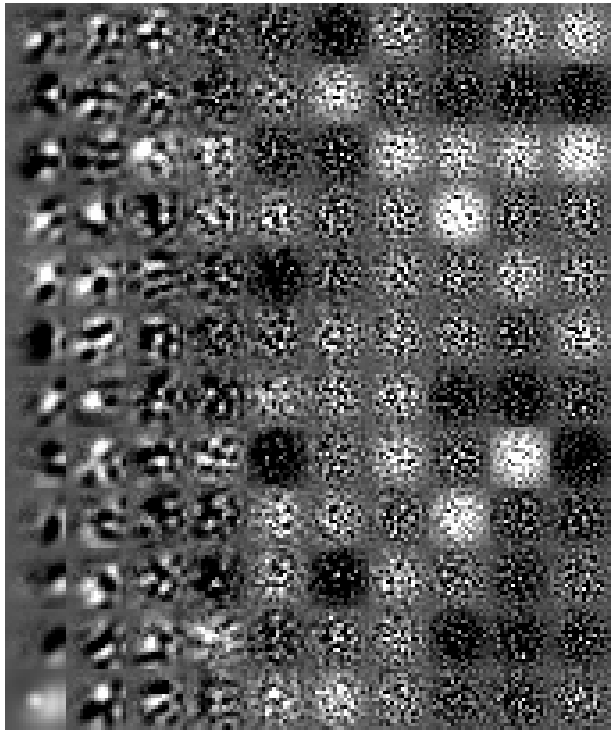
# ICA Result 2



First planet.



Second planet.



Third planet.

ICA channels of subframes centered on first, second, and third planets in a derotated image stack

All three planets recovered in bottom left-hand channel.

# Common Spatial Pattern Filtering

- Separate additive mixture of signals by maximizing variance between two windows of the signal
- For windows $\mathbf{x}_1$, $\mathbf{x}_2$ find vector $\mathbf{W}$ such that:

$$\mathbf{W} = \arg\max_{\mathbf{W}} \frac{\|\mathbf{W}\mathbf{x}_1\|}{\|\mathbf{W}\mathbf{x}_2\|}$$

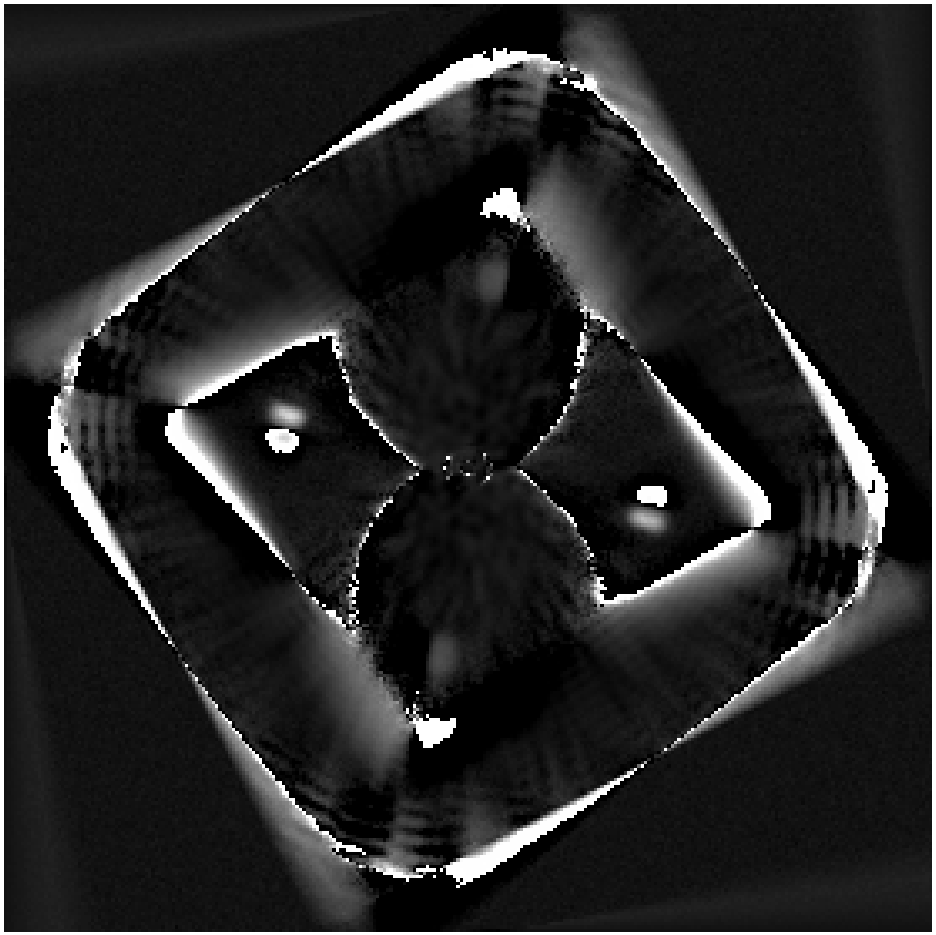
- Equivalent to simultaneous diagonalization of two covariances
- Partition data into subsets $\bar{R}_1$ and $\bar{R}_2$ with covariances $S_1$ and $S_2$
- Define $Q$ as:

$$S_2^{-1} S_1 = Q \Lambda Q^{-1}$$

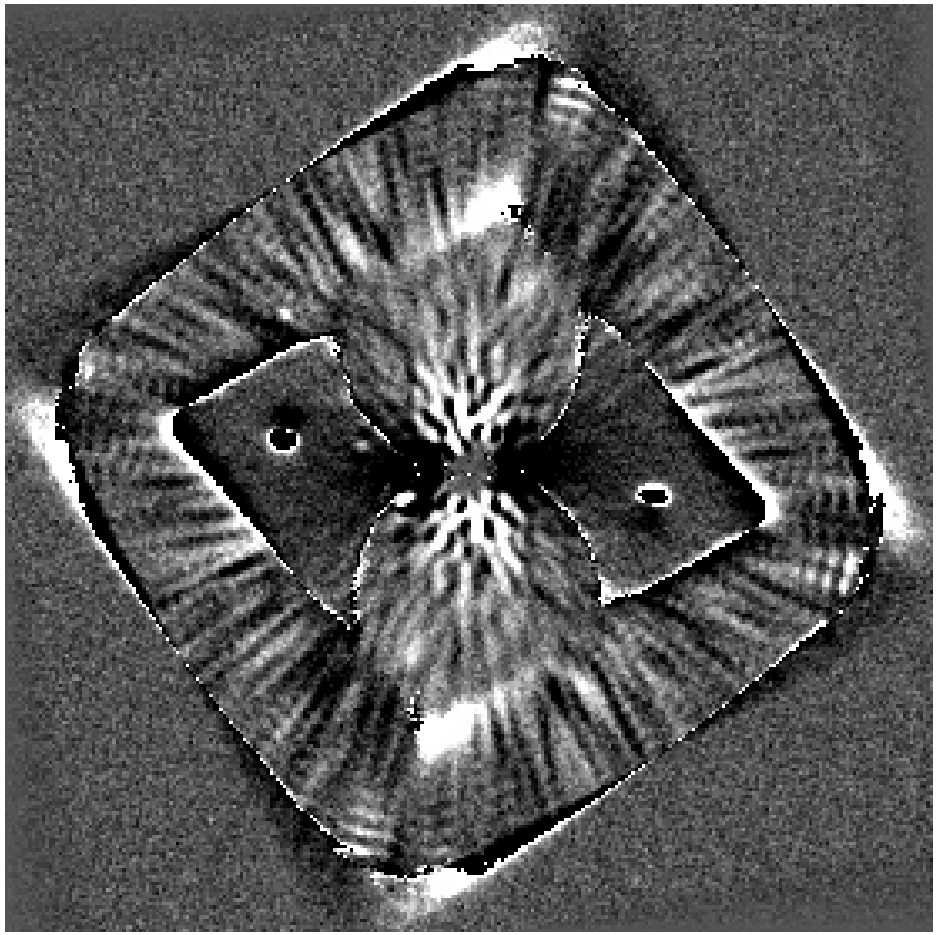
- $\mathbf{W}$ is the first column of $Q$

See: [Ang et al., 2008, Kang et al., 2009]

# CSP Filter Result



CSP significance map.



Convolution with PCA output.

CSP derived window function applied to data set from summation of subtracted images. Planet SNR increased by factor of 1.28

# Conclusions

- ICA can systematically decrease astrometric biasing, but suffers greater photometric biasing than PCA and has a higher computational cost
- CSP can correct for throughput loss but does not work as an astrometrically accurate detection method on its own for point sources
- Both are complementary to PCA (use PCA as pre-processing)
- Next: ROCs and other BSS algorithms

# References I


Ang, K. K., Chin, Z. Y., Zhang, H., and Guan, C. (2008).
Filter bank common spatial pattern (fbcsp) in brain-computer interface.
In *Neural Networks, 2008. IJCNN 2008.(IEEE World Congress on Computational Intelligence). IEEE International Joint Conference on*, pages 2390–2397. IEEE.

Hyvärinen, A. and Oja, E. (1997).
A fast fixed-point algorithm for independent component analysis.
*Neural computation*, 9(7):1483–1492.

Kang, H., Nam, Y., and Choi, S. (2009).
Composite common spatial pattern for subject-to-subject transfer.
*Signal Processing Letters, IEEE*, 16(8):683–686.

Konopacky, Q. M., Barman, T. S., Macintosh, B. A., and Marois, C. (2013).
Detection of carbon monoxide and water absorption lines in an exoplanet atmosphere.
*Science*, 339(6126):1398–1401.

Lafrenière, D., Marois, C., Doyon, R., Nadeau, D., and Artigau, E. (2007).
A new algorithm for point-spread function subtraction in high-contrast imaging: A demonstration with angular differential imaging.
*The Astrophysical journal*, 660(1):770–780.

Lawson, P. R., Frazin, R., Barrett, H., Caucci, L., Devaney, N., Furenlid, L., Gładysz, S., Guyon, O., Krist, J., Maire, J., Marois, C., Mawet, D., Mouillet, D., Mugnier, L. M., Perrin, M. D., Poyneer, L. A., Pueyo, L., Savransky, D., and Soummer, R. (2012).
On advanced estimation techniques for exoplanet detection and characterization using ground-based coronagraphs.
In *Proc. SPIE*, SPIE Astronomical Telescopes+ Instrumentation, pages 844722–844722. International Society for Optics and Photonics.

# References II


Marois, C., Macintosh, B., Barman, T., Zuckerman, B., Song, I., Patience, J., Lafreniere, D., and Doyon, R. (2008).
Direct imaging of multiple planets orbiting the star HR 8799.
*Science*, 322(5906):1348.

Pueyo, L., Soummer, R., Hoffmann, J., Oppenheimer, R., Graham, J., Zimmerman, N., Zhai, C., Wallace, J., Vescelus, F., Veicht, A., et al. (2015).
Reconnaissance of the hr 8799 exosolar system. ii. astrometry and orbital motion.
*The Astrophysical Journal*, 803(1):31.

Savransky, D. (2015).
Sequential covariance calculation for exoplanet image processing.
*The Astrophysical Journal*, 800(2):100.

Soummer, R., Pueyo, L., and Larkin, J. (2012).
Detection and characterization of exoplanets and disks using projections on Karhunen-Loeve eigenimages.
*The Astrophysical Journal Letters*, 755(2):L28.

Yilmaz, A., Javed, O., and Shah, M. (2006).
Object tracking: A survey.
*Acm computing surveys (CSUR)*, 38(4):13.