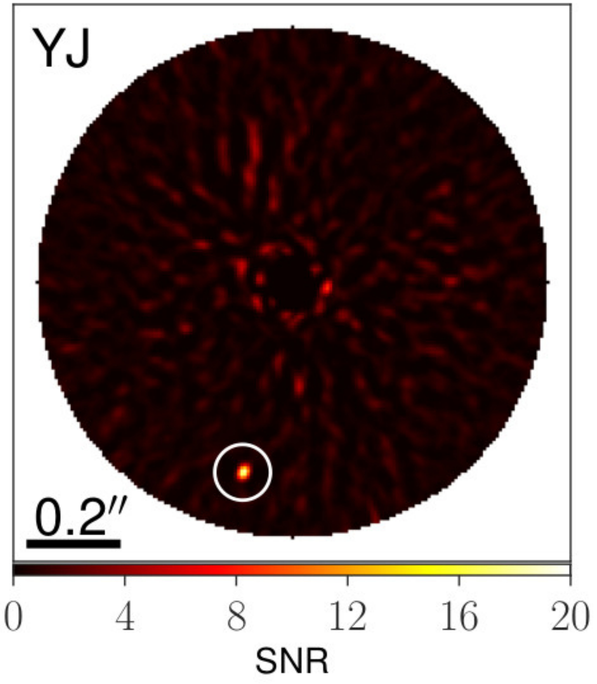
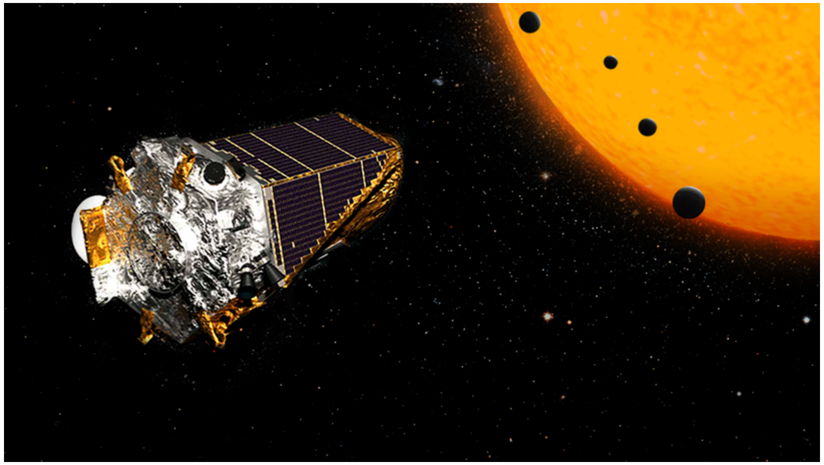
Application of transit light curve methods to direct imaging exoplanet detection

by Matthias Samland (MPIA)

Application of transit light curve methods to direct imaging exoplanet detection

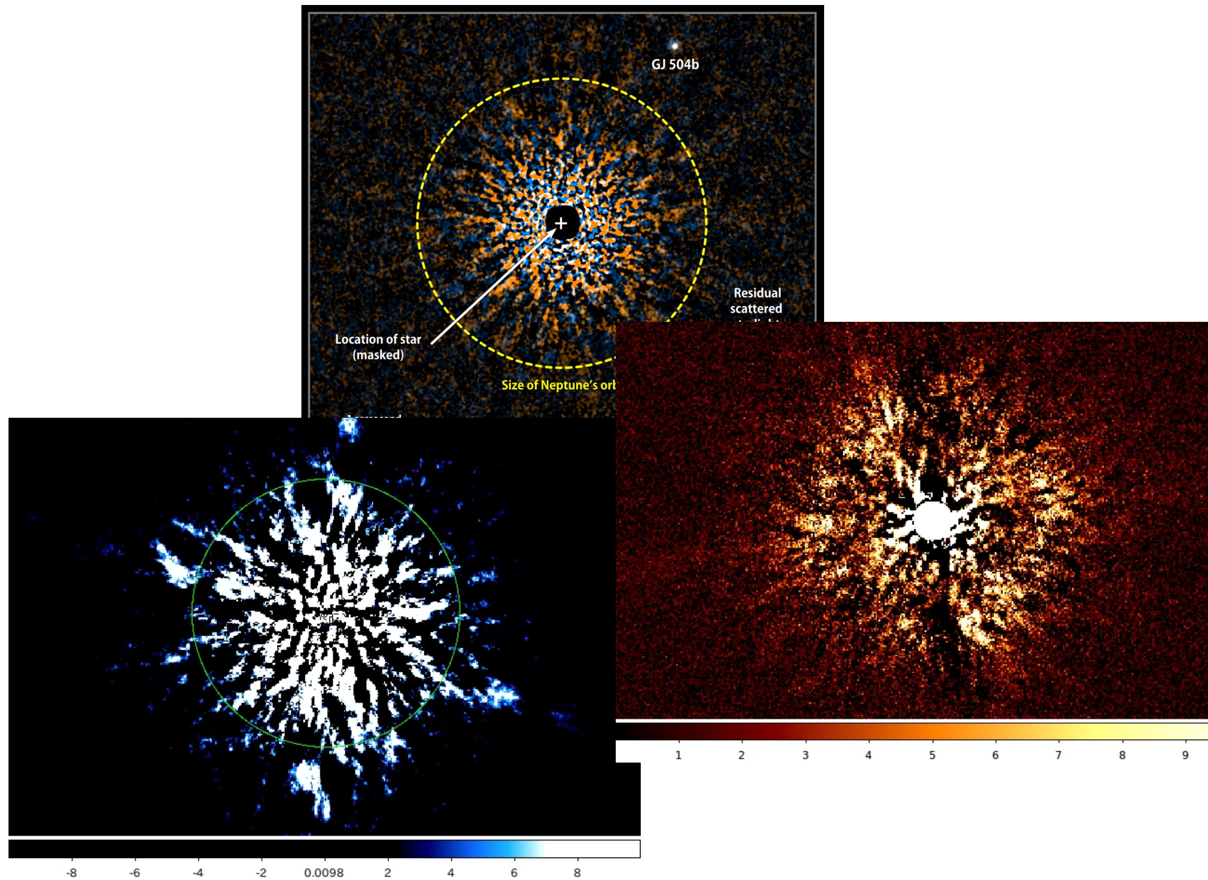


??? =

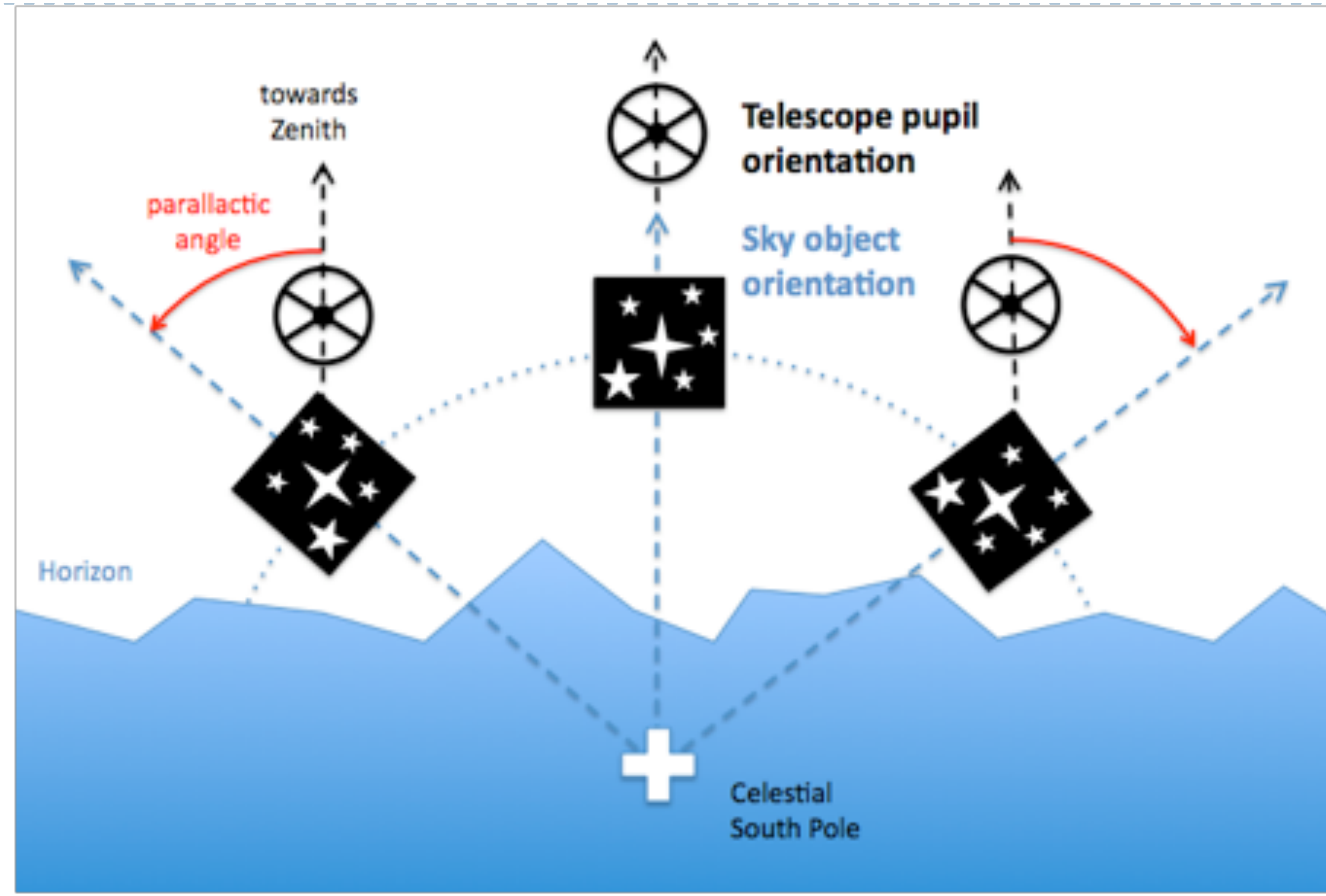


What's the problem?

- Contrast between companion and host star
  - Stellar Halo
  - Speckle noise

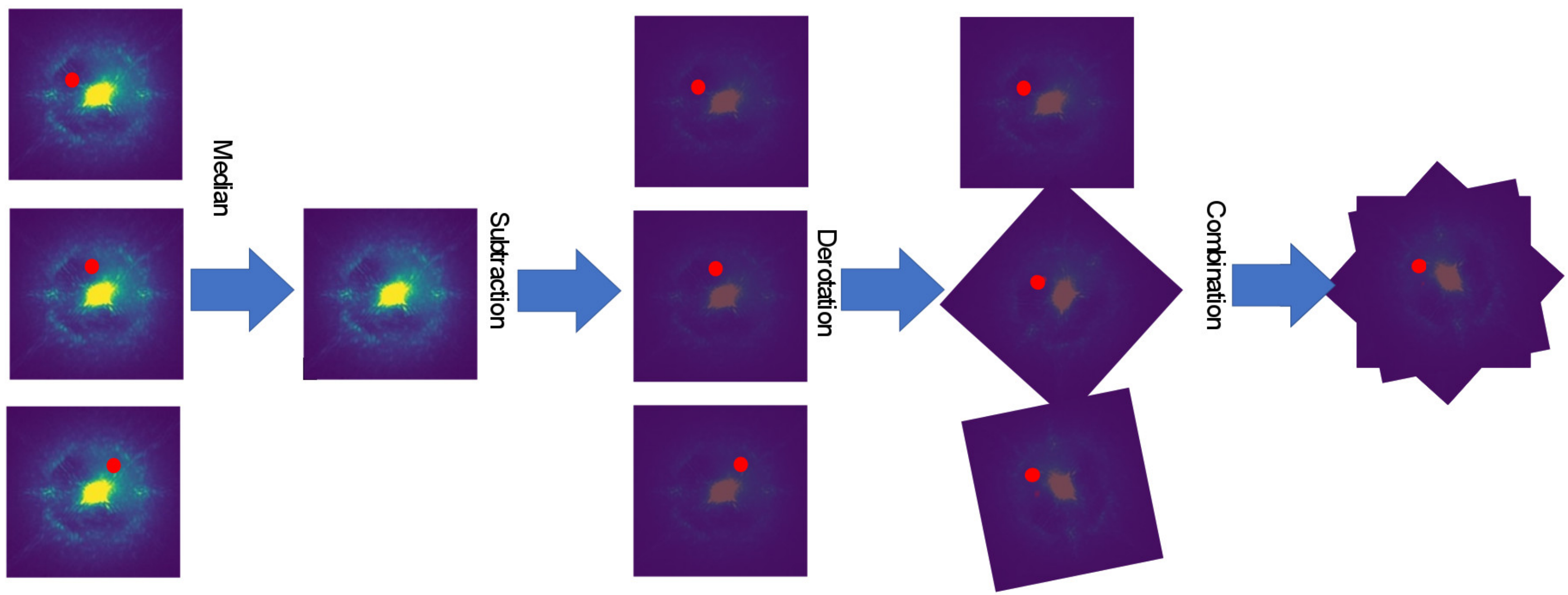


Angular Differential Imaging (ADI)



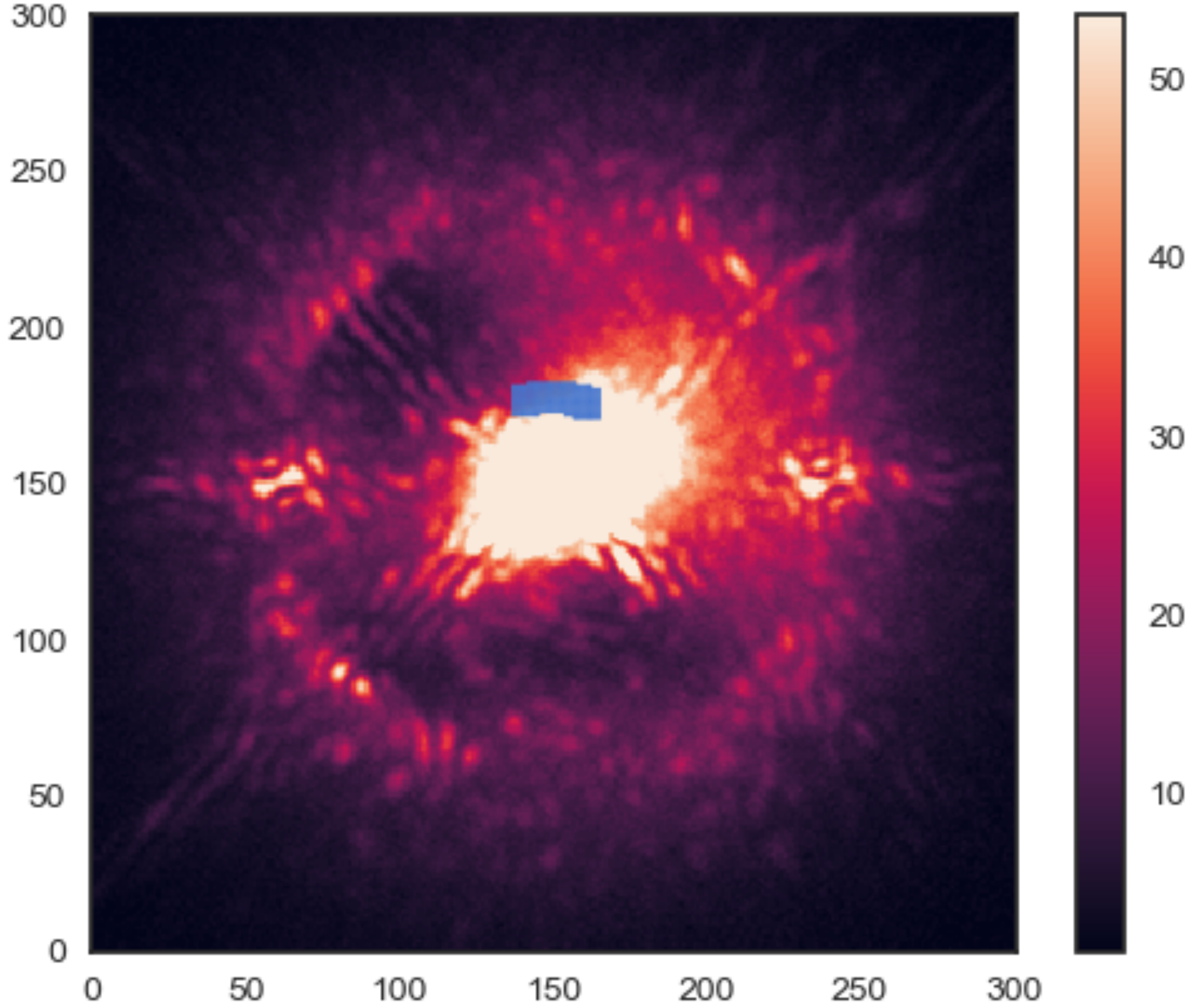
(Source: C. Thalmann)

Angular Differential Imaging (ADI)

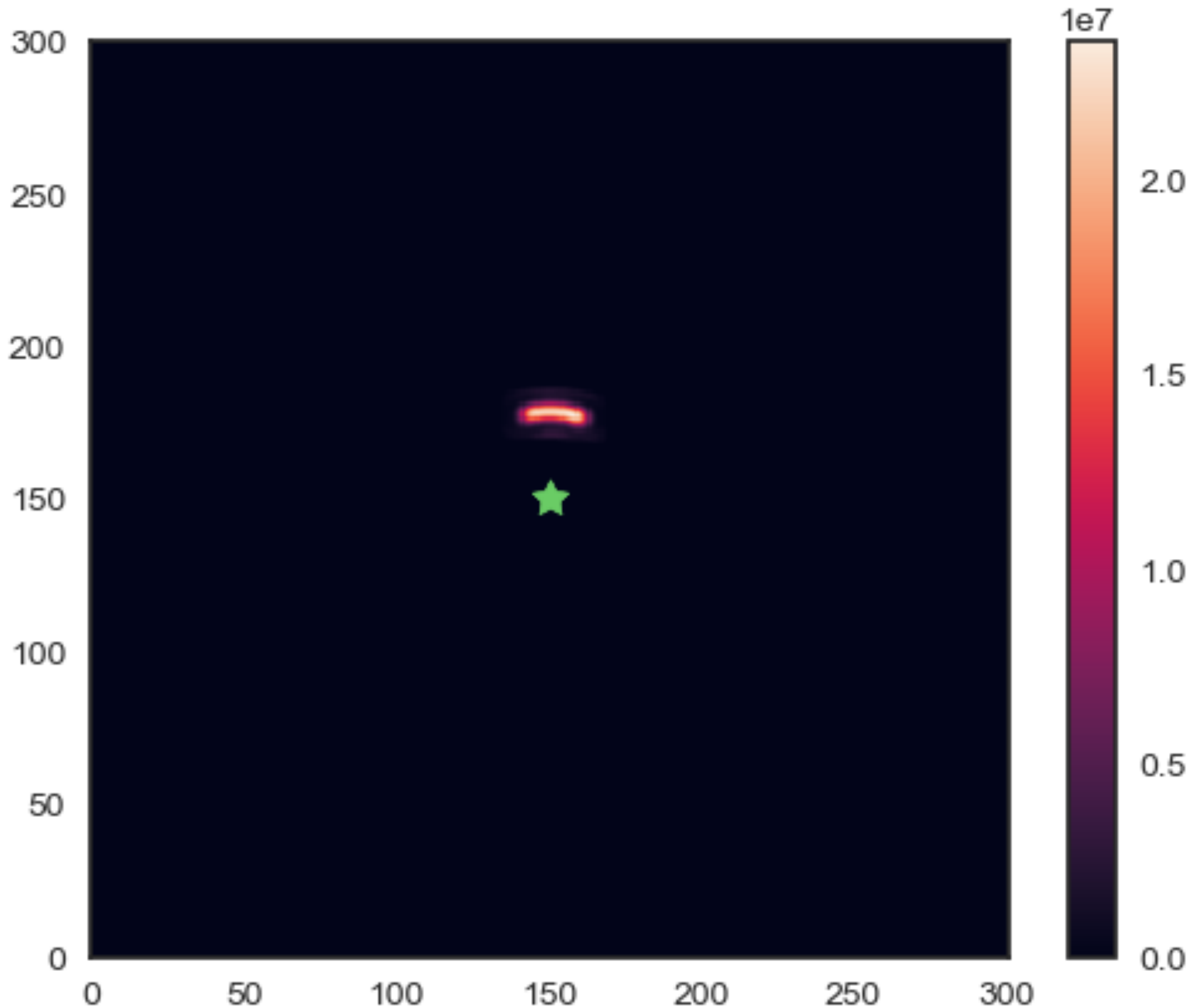


The light curve approach

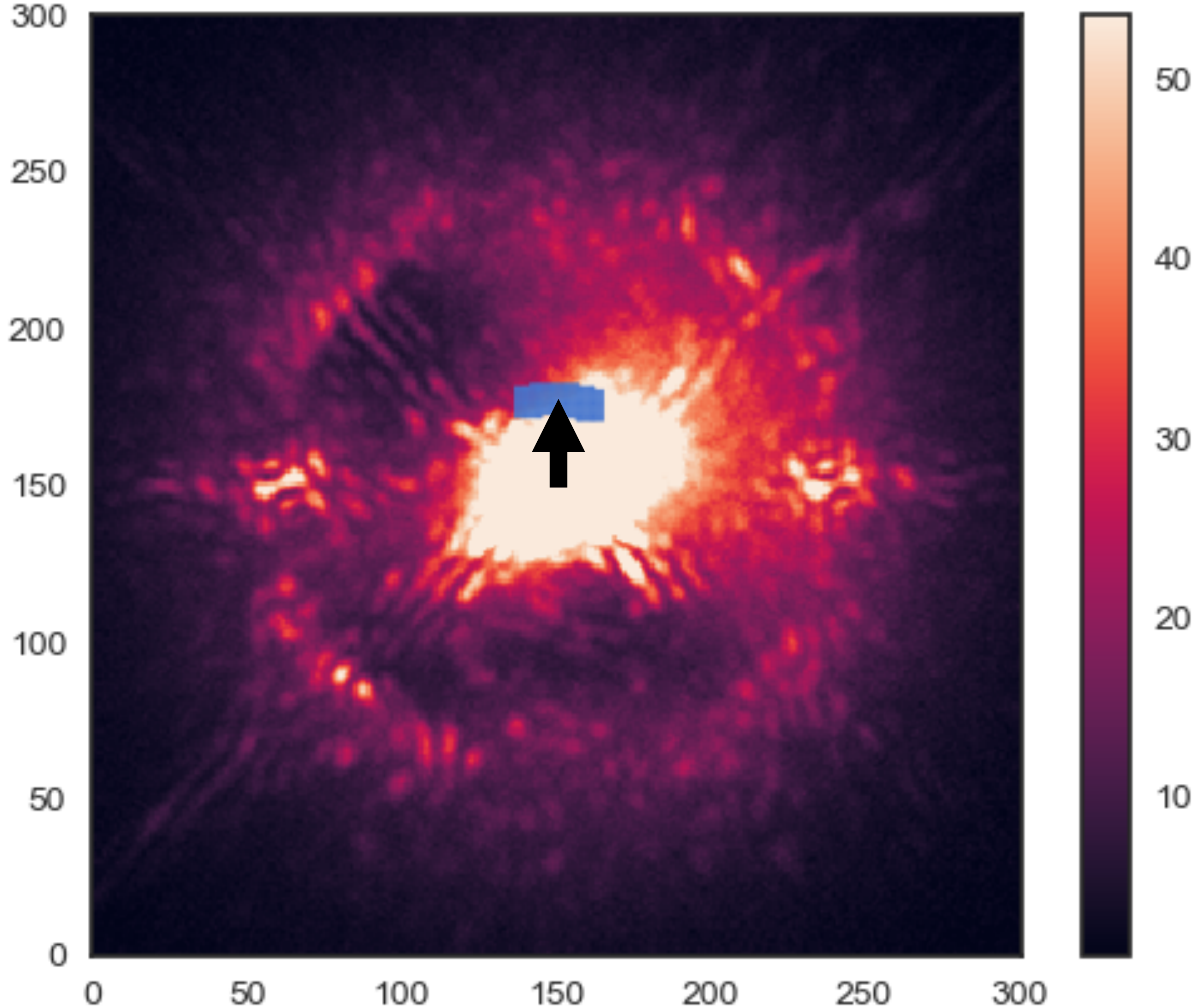
The light curve approach



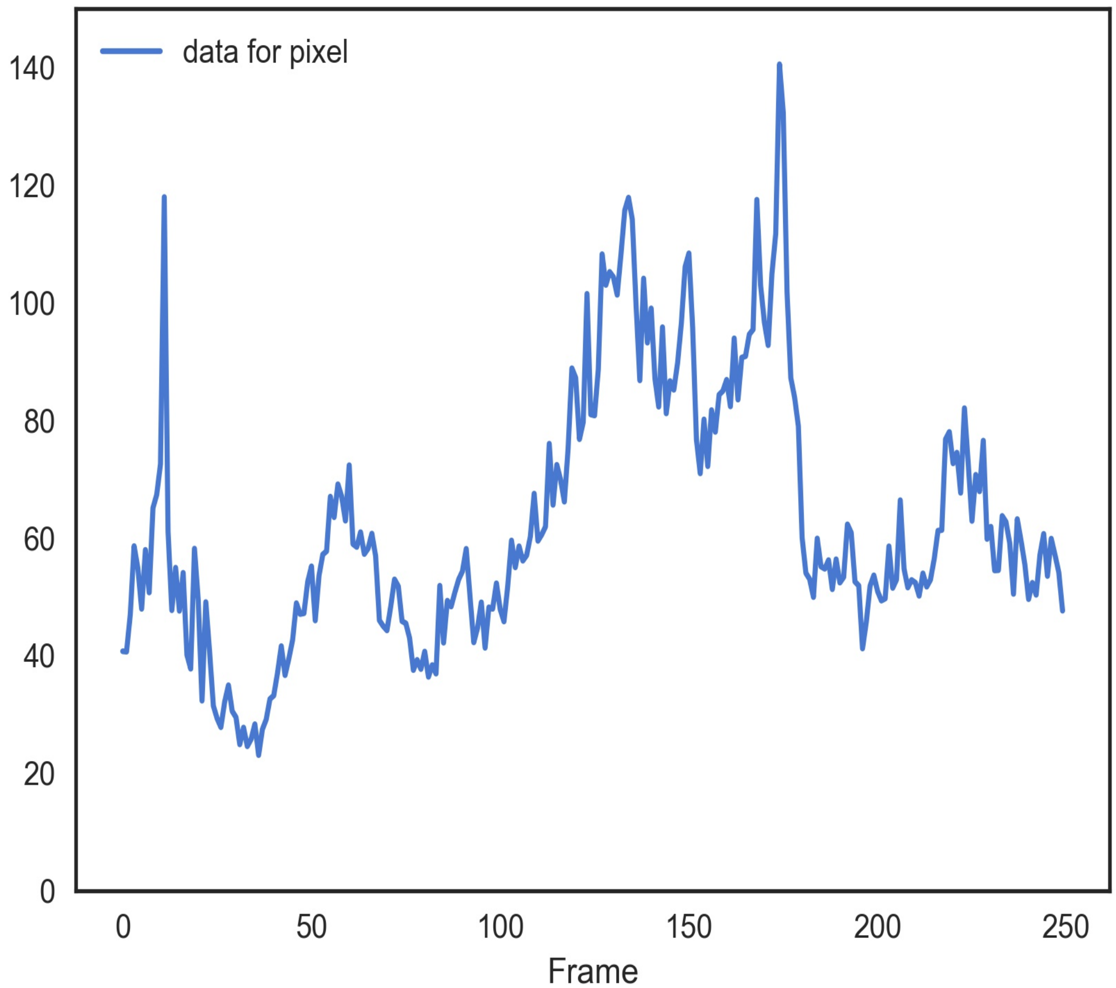
The light curve approach



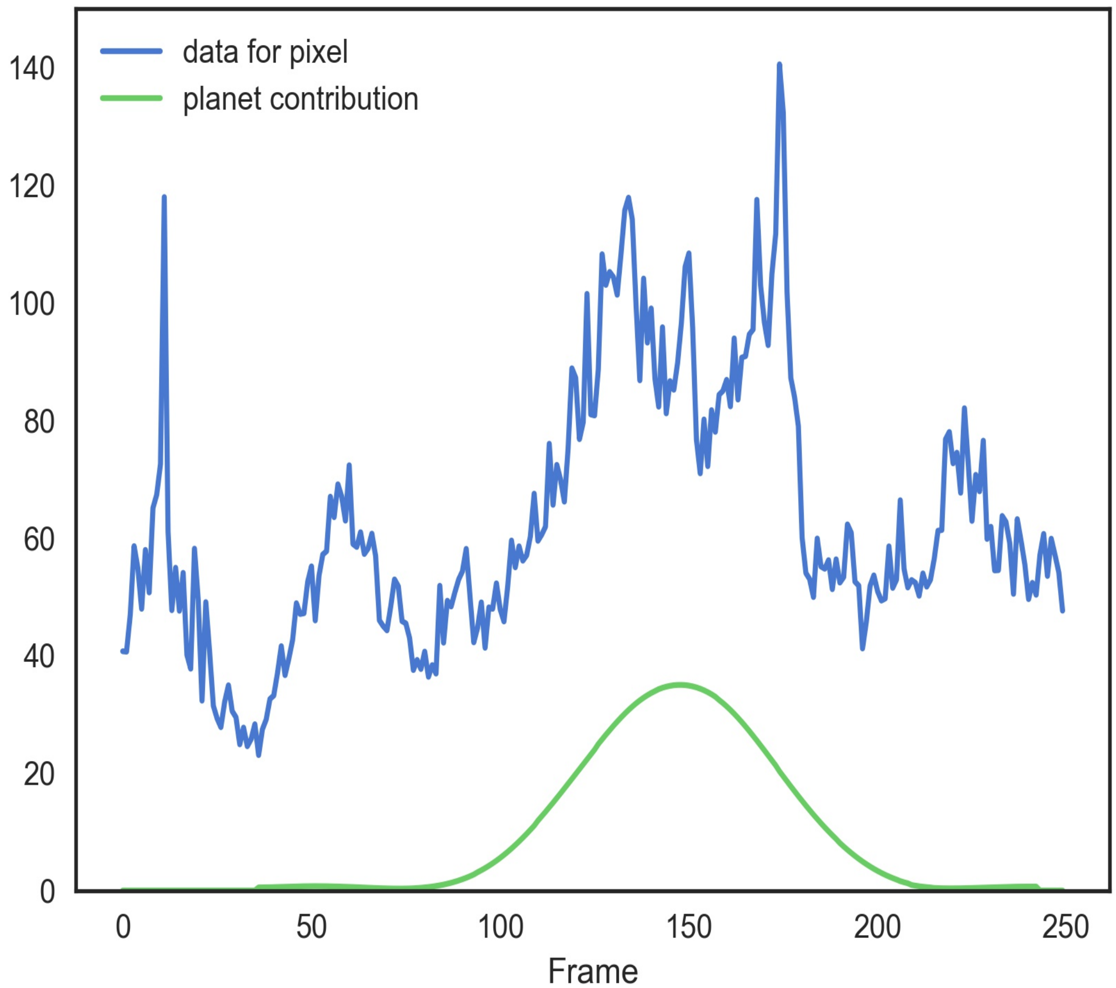
How does the light curve look?



How does the pixel light curve look?



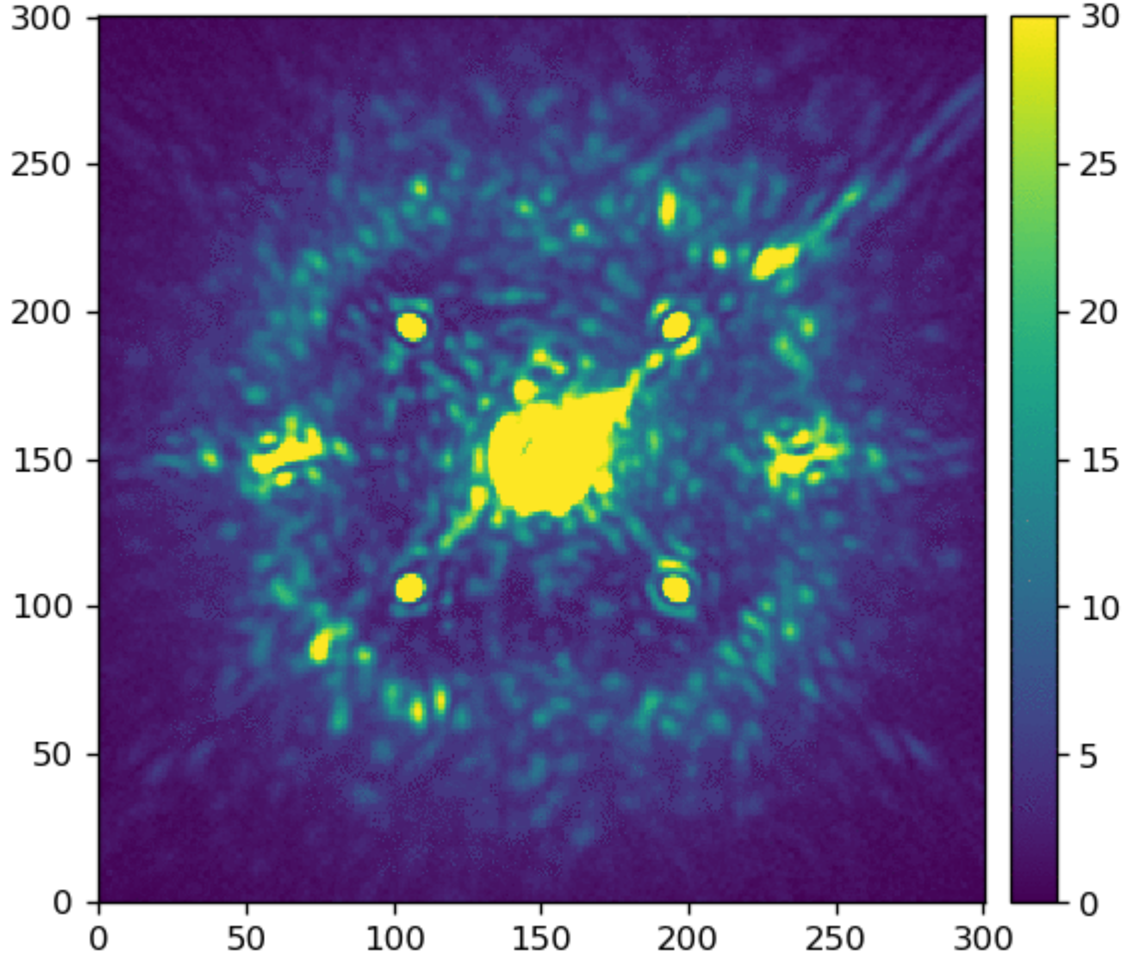
How does the pixel light curve look?



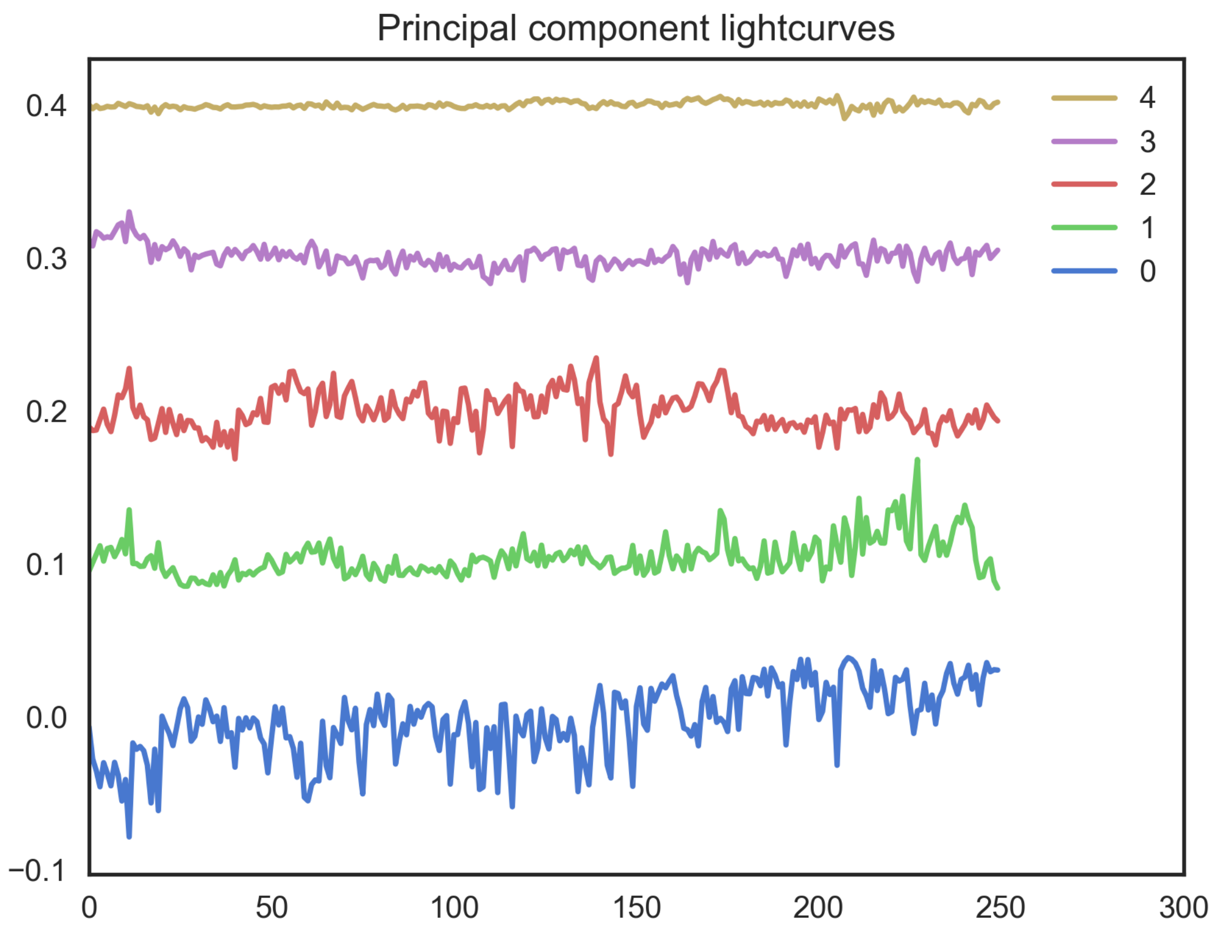
How does the noise model look like?

- Take all other pixels not affected by planetary signal
- Decompose their temporal behavior into principle components (PCA) to form the basis vectors in which to represent the systematics
  - You can call them "eigen lightcurves" to sound fancy

How does the noise model look like?



How does the noise model look like?

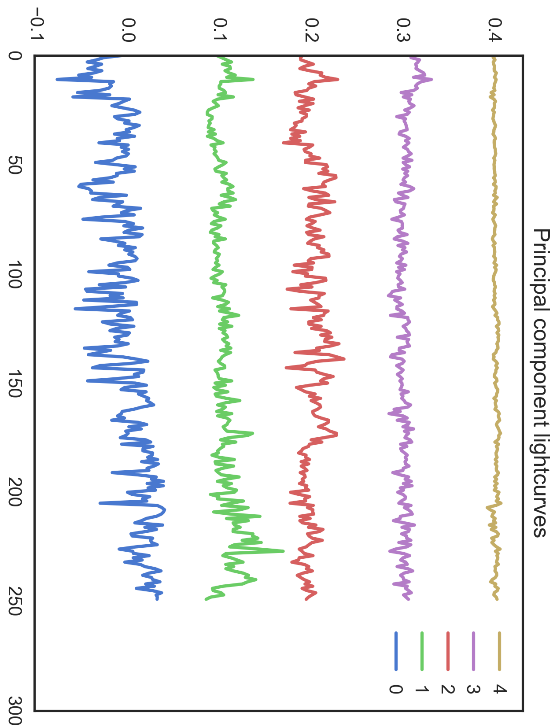


How does the noise model look like?

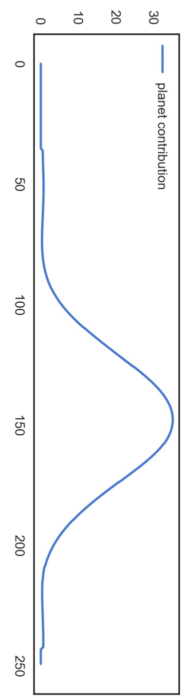
Regressor matrix

Weights

Data

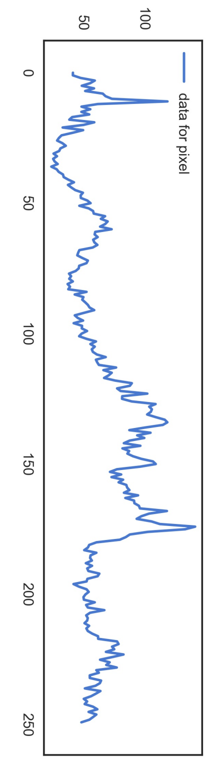


PCA systematics lightcurves
(+ constant offset)



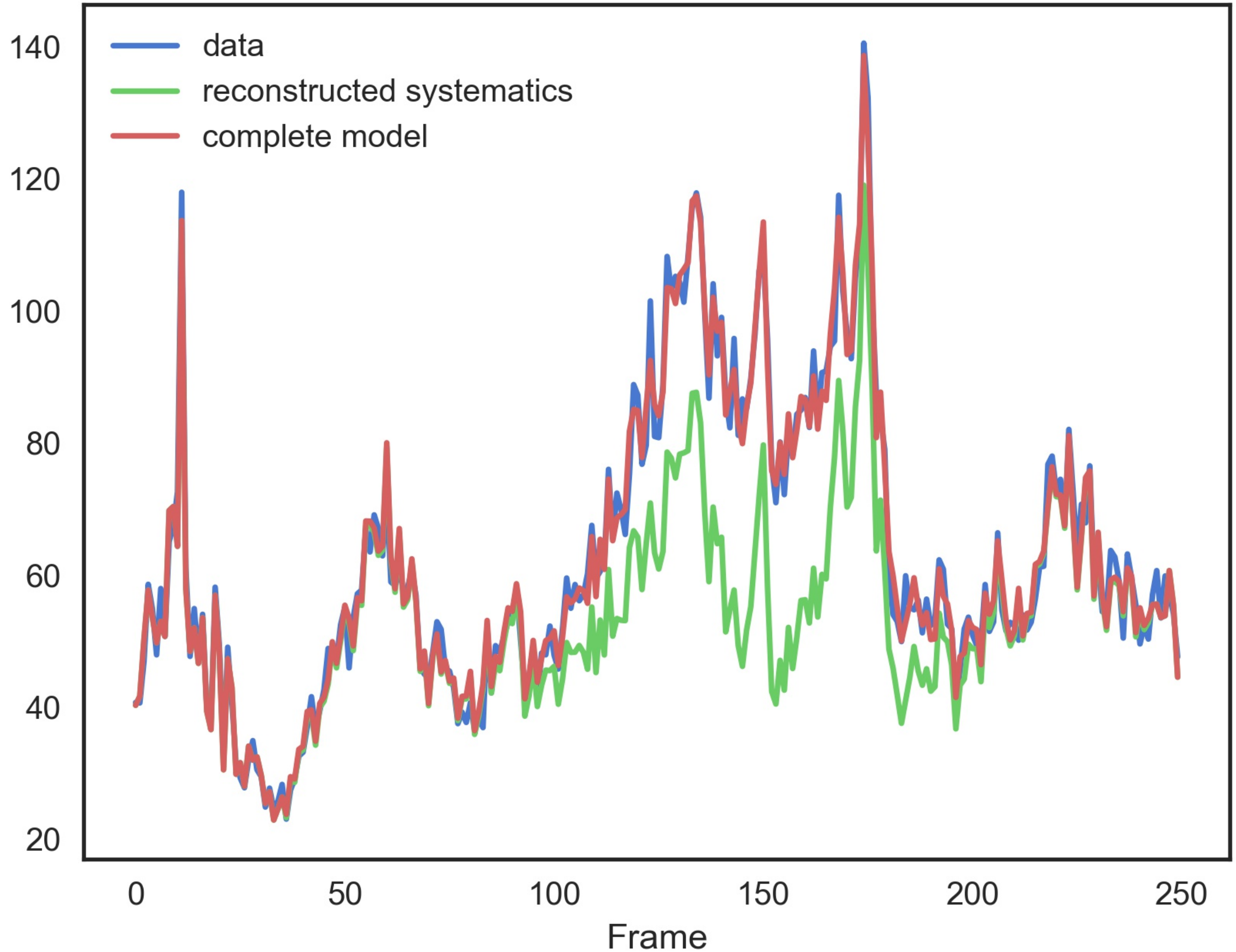
Transit signal

$$\begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_{n-1} \\ v_n \end{bmatrix} =$$

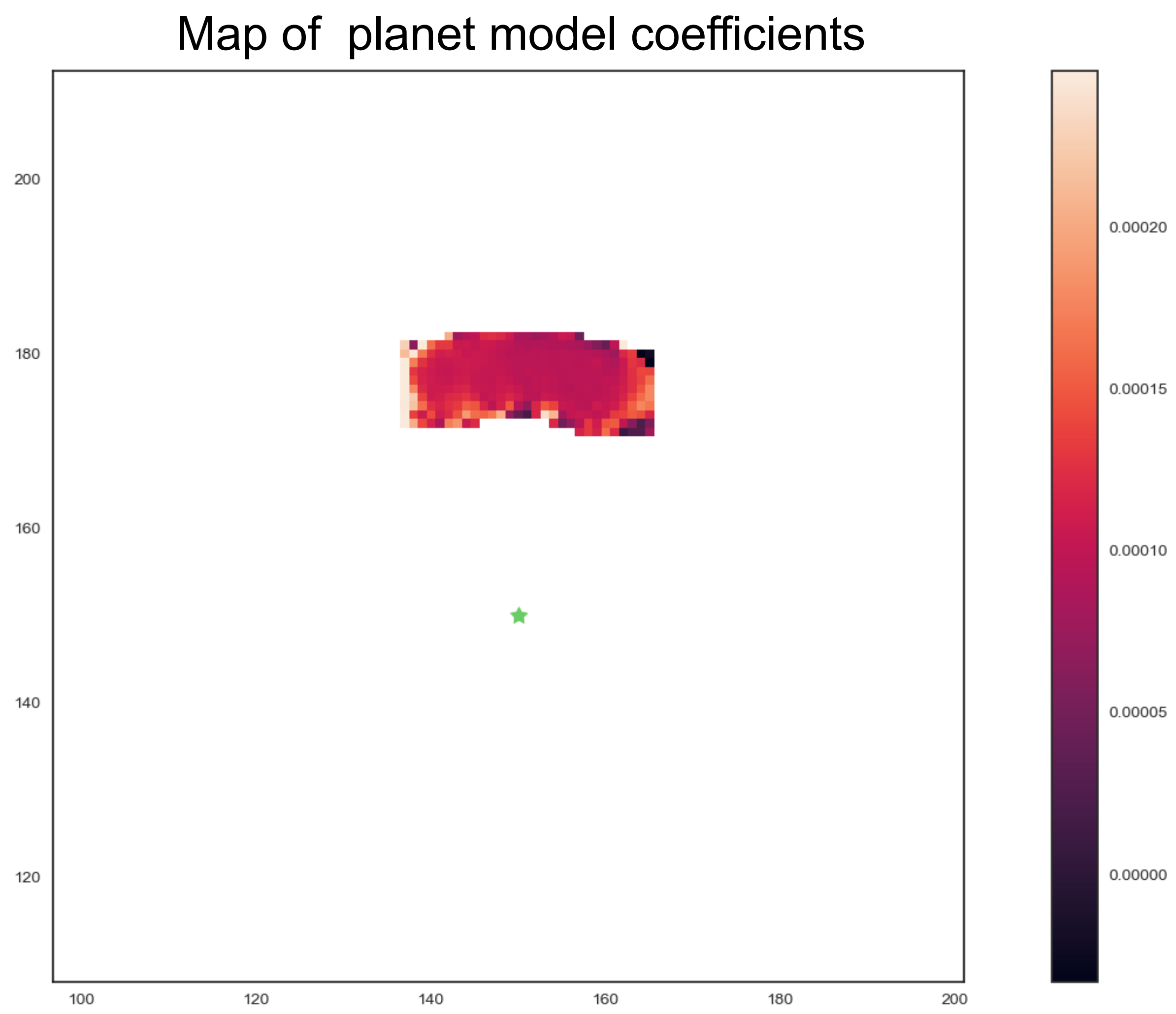


Planet model coefficient = contrast

Result of our modeling.
It works actually really well!?



Result of our modeling.
It works actually really well!?



Divide and conquer with negative signal injection

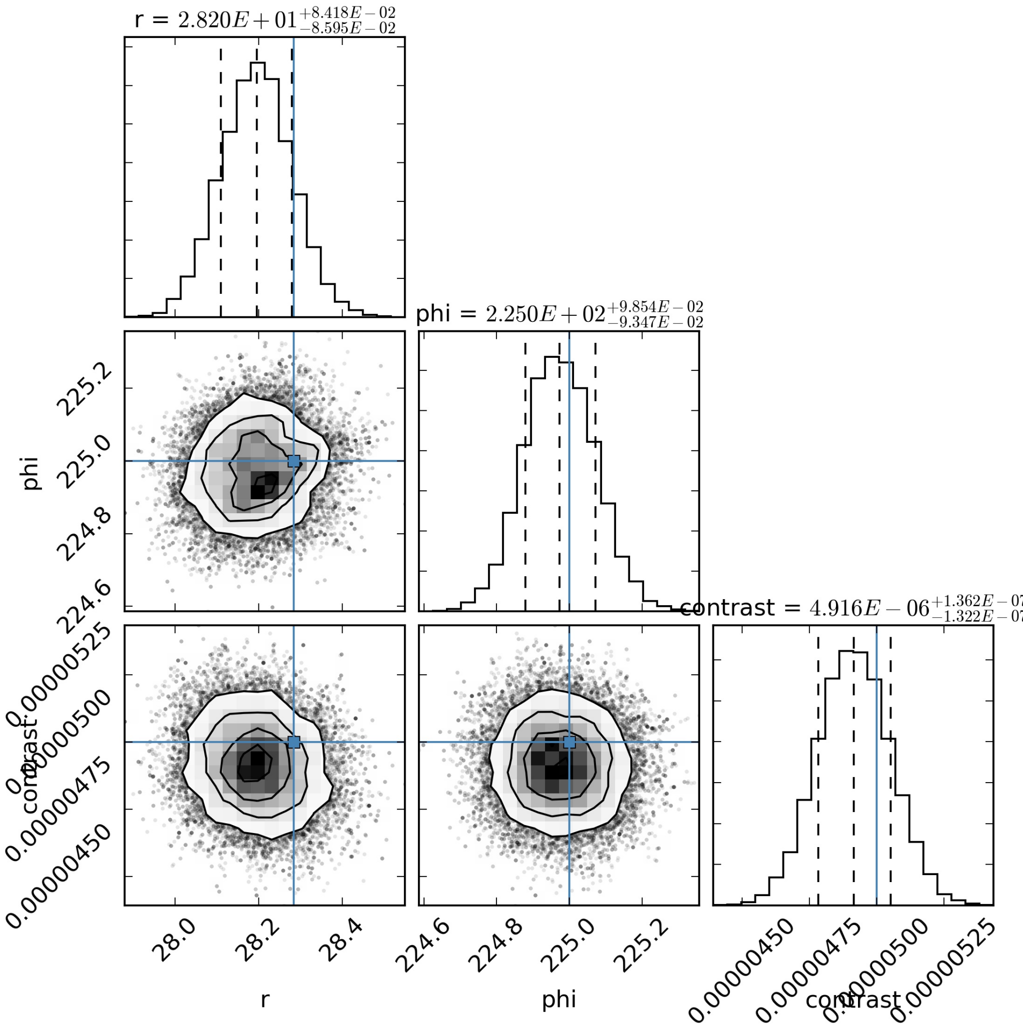
- First get rid of planet signal
- Then fit systematics
    - Optimize planet model parameters with MCMC

Divide and conquer with negative signal injection

Evolution of
MCMC chain

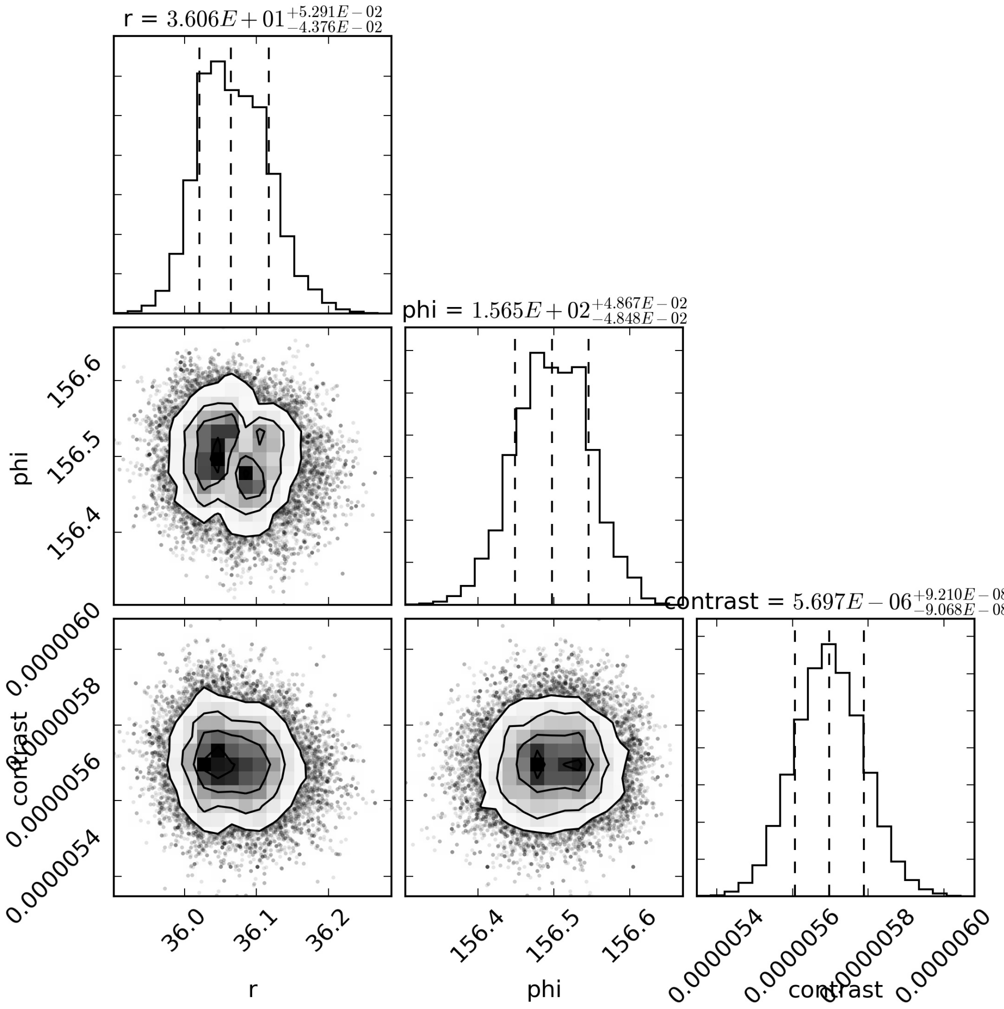
planet @
R = 28.28 pix
Phi = 225 deg
5e-6 contrast

26 components

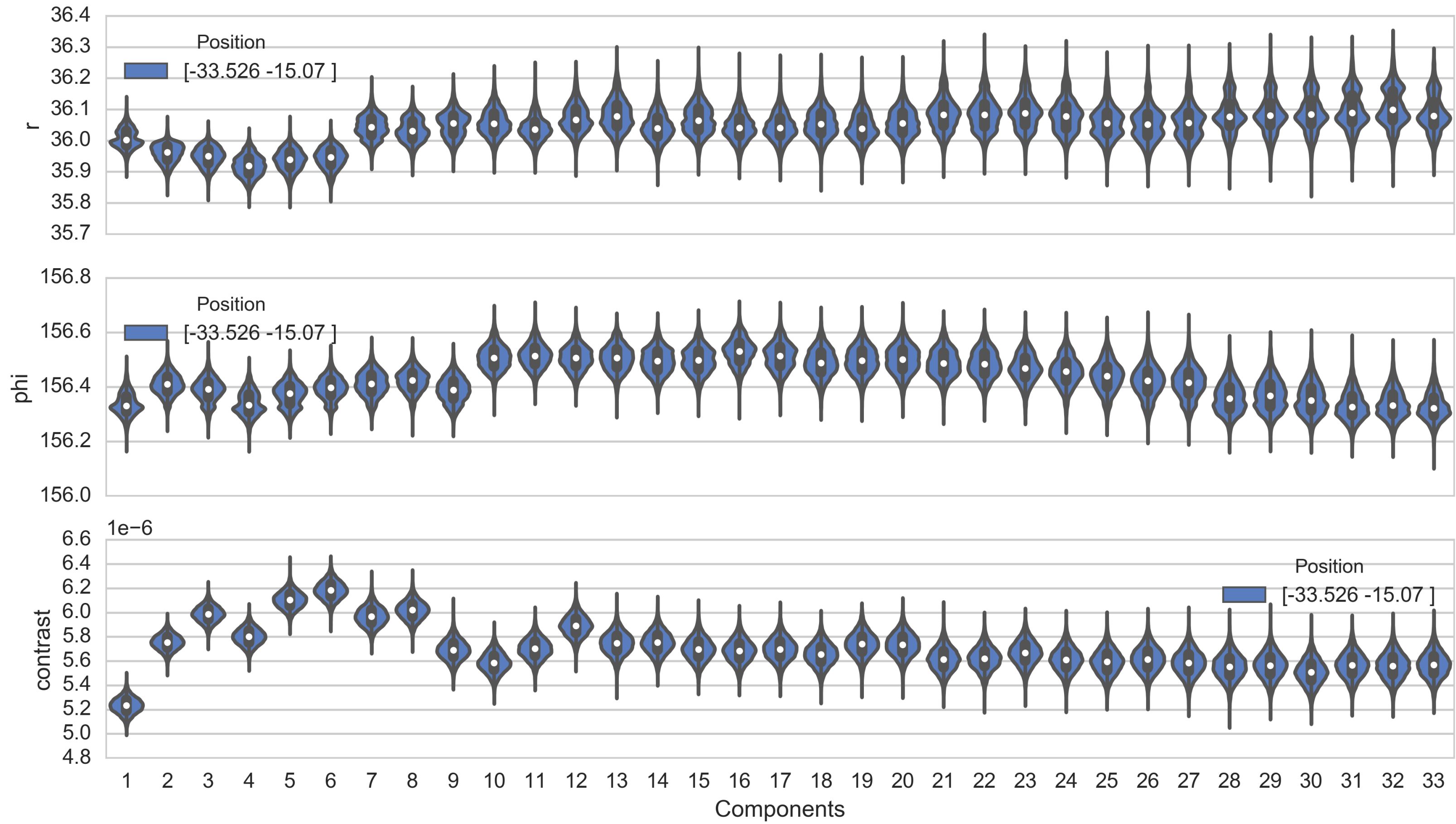


A real planet signal: 51 Eridani b

using
15 components

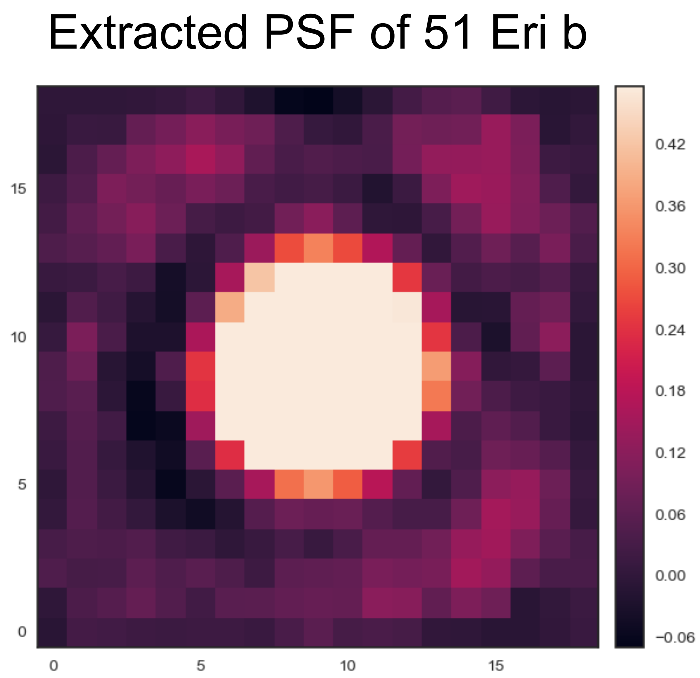


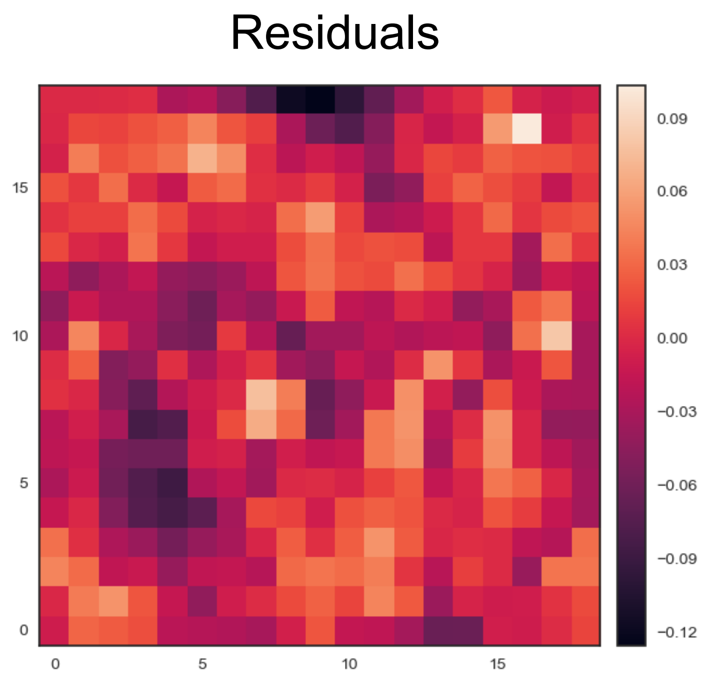
A real planet signal: 51 Eridani b



Extracted signal of 51 Eridani b

Extracted signal of 51 Eridani b





Conclusion

- Problems in high-contrast imaging very similar to transit spectroscopy! Maybe we should talk more with each other.
- Non-local, co-temporal models open new opportunities when self-subtraction is a real problem
  - disks?
  - very close separations?

Thank you for your attention!

The light curve approach

- Change paradigm from a spatial to temporal perspective
- The planet is "transiting" over the detector!
  - Planet signal turns into a characteristic "positive" light curve shape
  - Switch to using a "non-local" noise model, the temporal behavior of the noise across the image has a common underlying cause (atmosphere, optics)

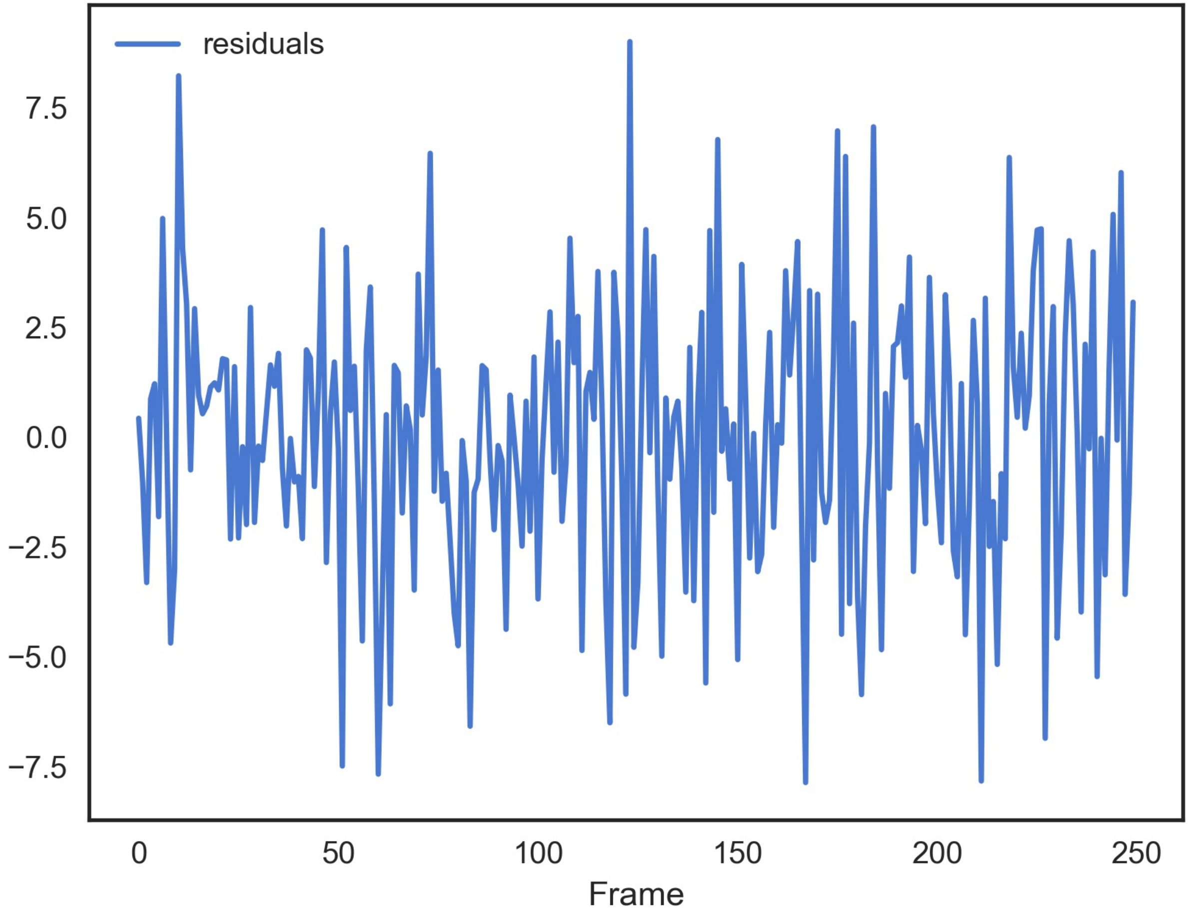
… but there is a problem.

- Every pixel is fitted independently with the respective light curve shape for that pixel
  - We get a different value for the contrast (weight) for the model for each pixel
  - But there is one underlying generative model
  - Only one weight should be fit to ALL pixels
  - How to do this…?

A possible alternative. Divide and conquer with MCMC.

- Subtract the transit model for planet of certain position and brightness FIRST.
    - One consistent underlying (2D+time) model of planet
- Fit systematic model only
- Measure residuals
- Repeat at each MCMC step for different planet models
    - Get both the position and brightness distribution at the same time

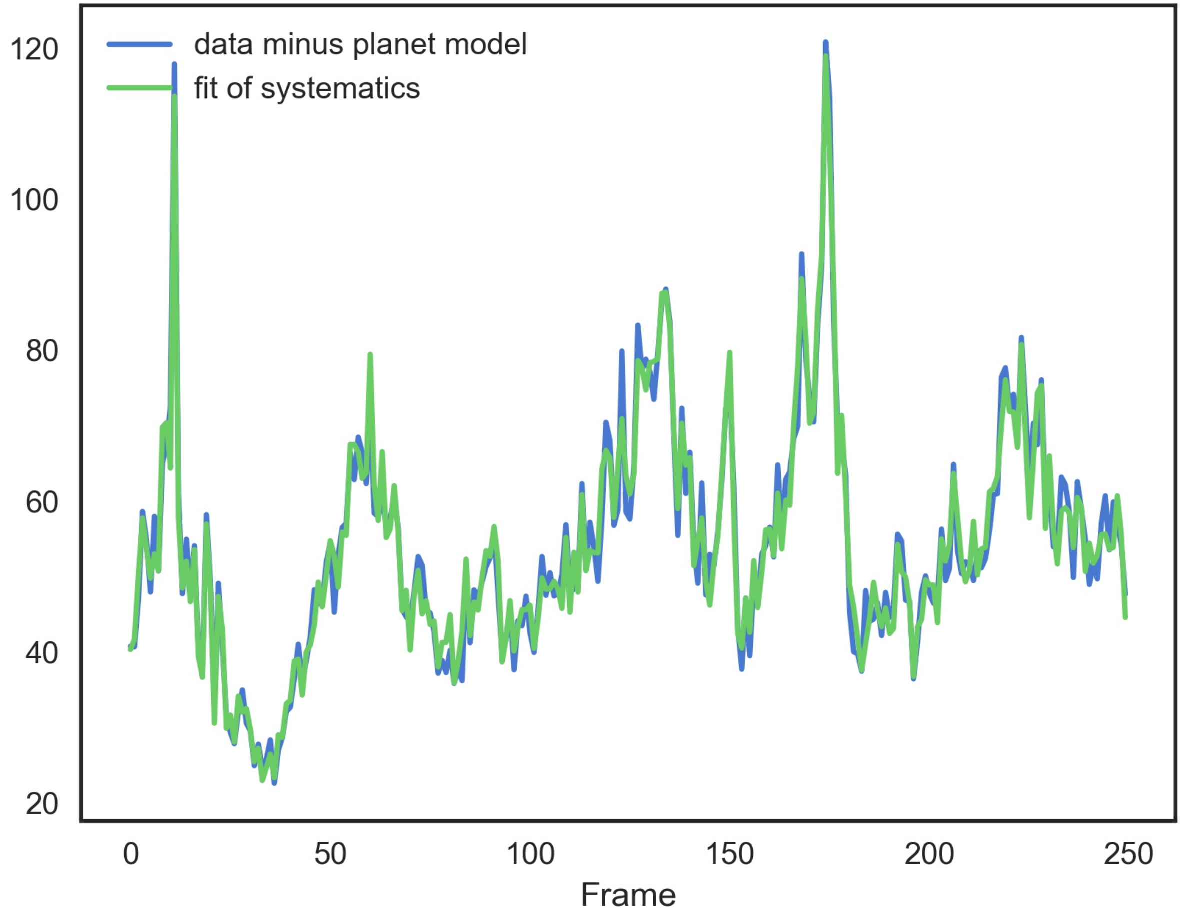
Result of our modeling.
It works actually really well!?



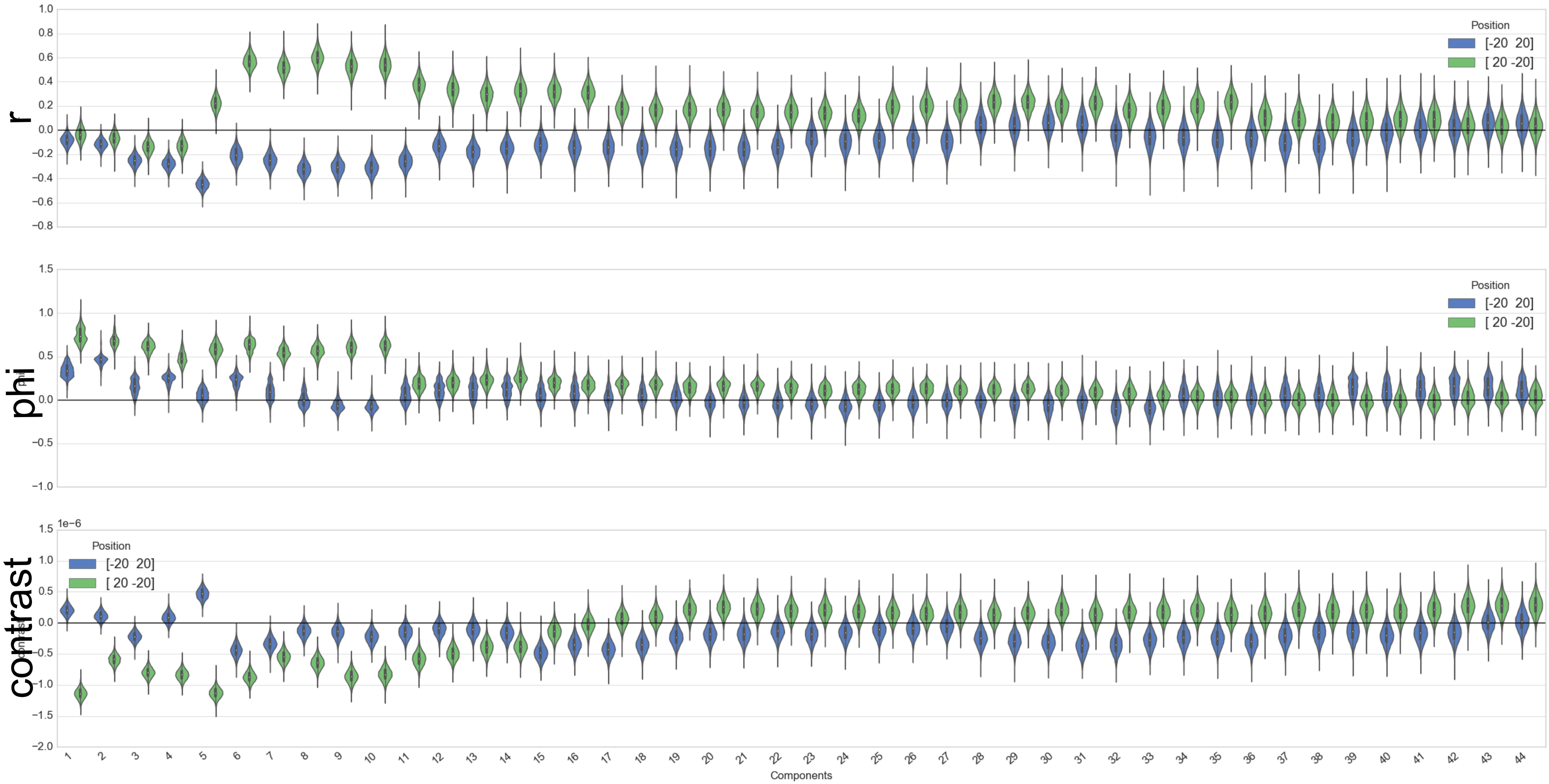
Next steps, still a lot to do

- Direct comparison between this algorithm and current alternatives.
  - Works better at close separations? I hope so.
  - Self-subtraction not an issue
    - Co-temporal, but non-local noise model
- How to decide number of regressors to fit?
- ...

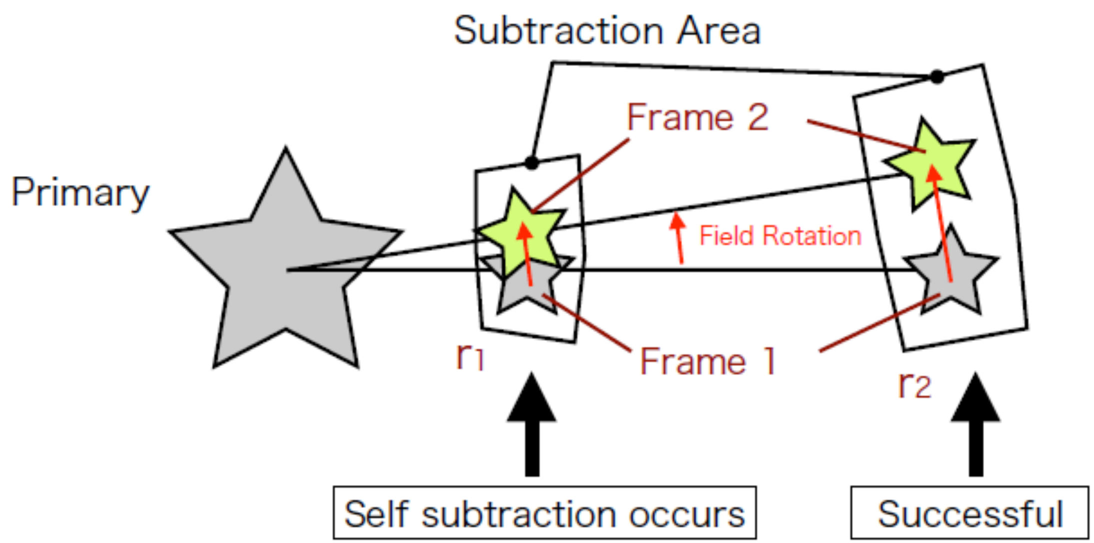
A possible alternative. Divide and conquer with MCMC.



A possible alternative.
Divide and conquer with MCMC.



Self-Subtraction vs Correlation

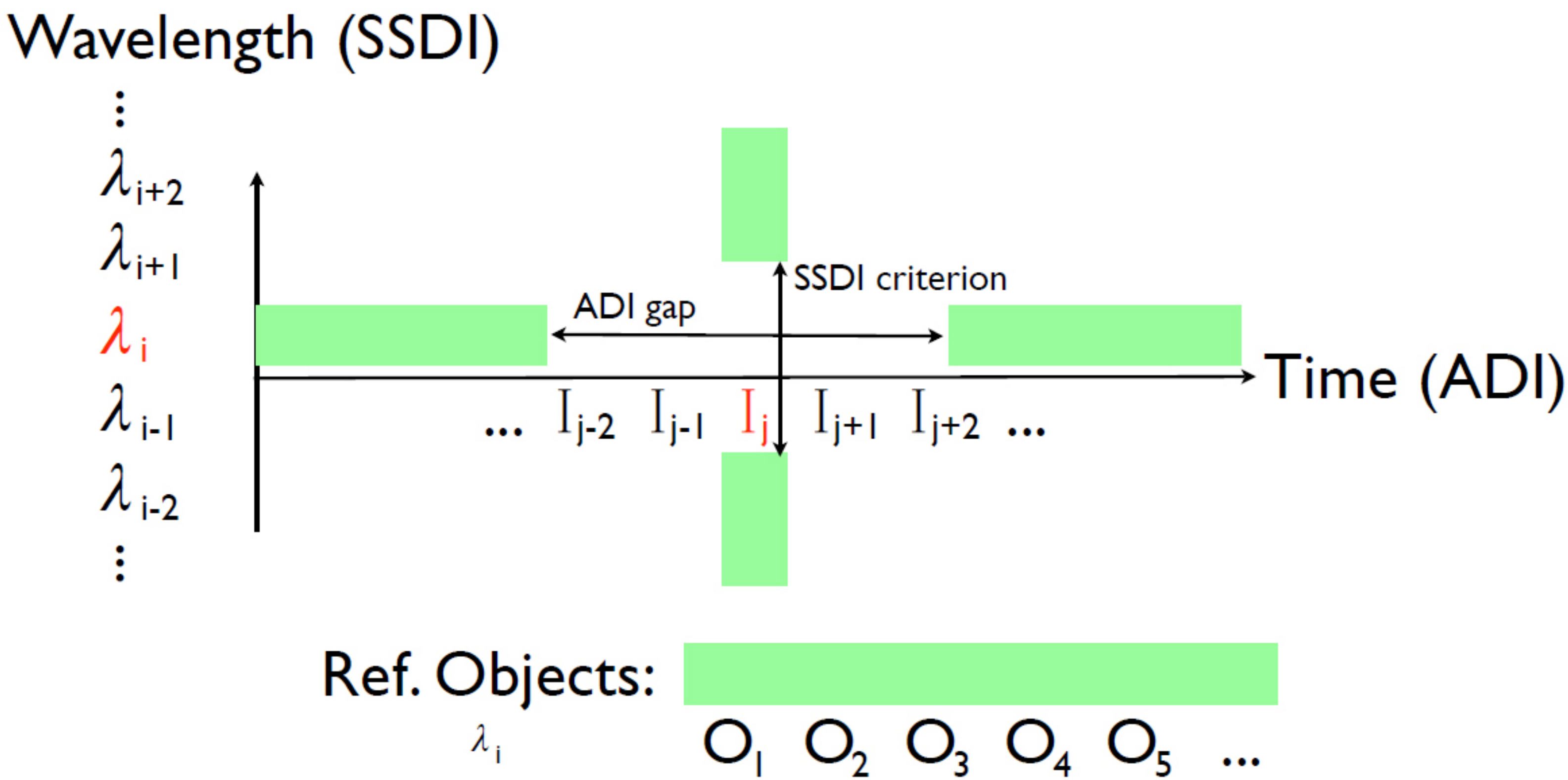


Source: Kandori

Define minimum displacement for substraction:
Exclude frames with displacement due to field rotation of less than a certain angle

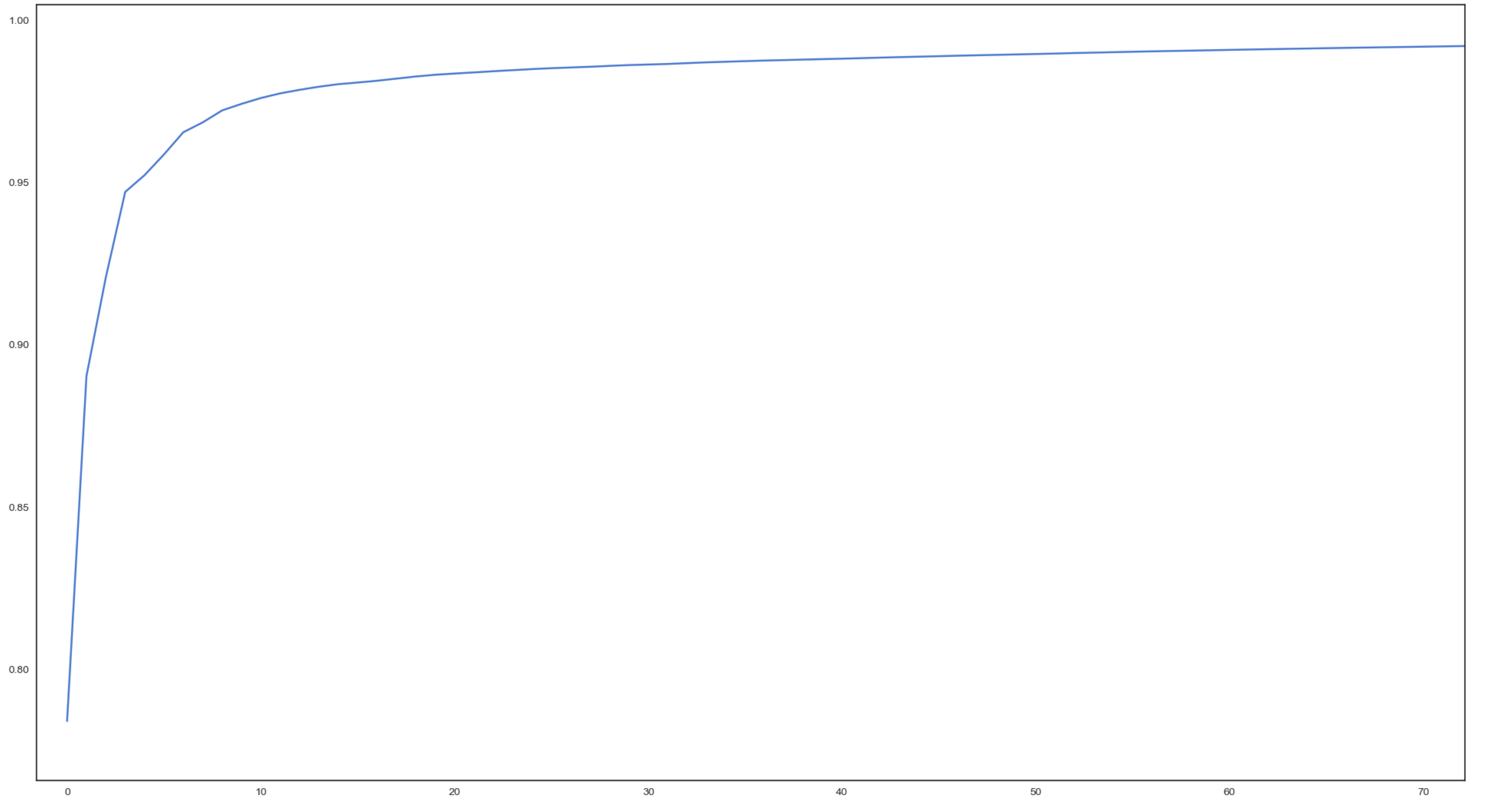
Self-subtraction vs correlation

- Training vs test set

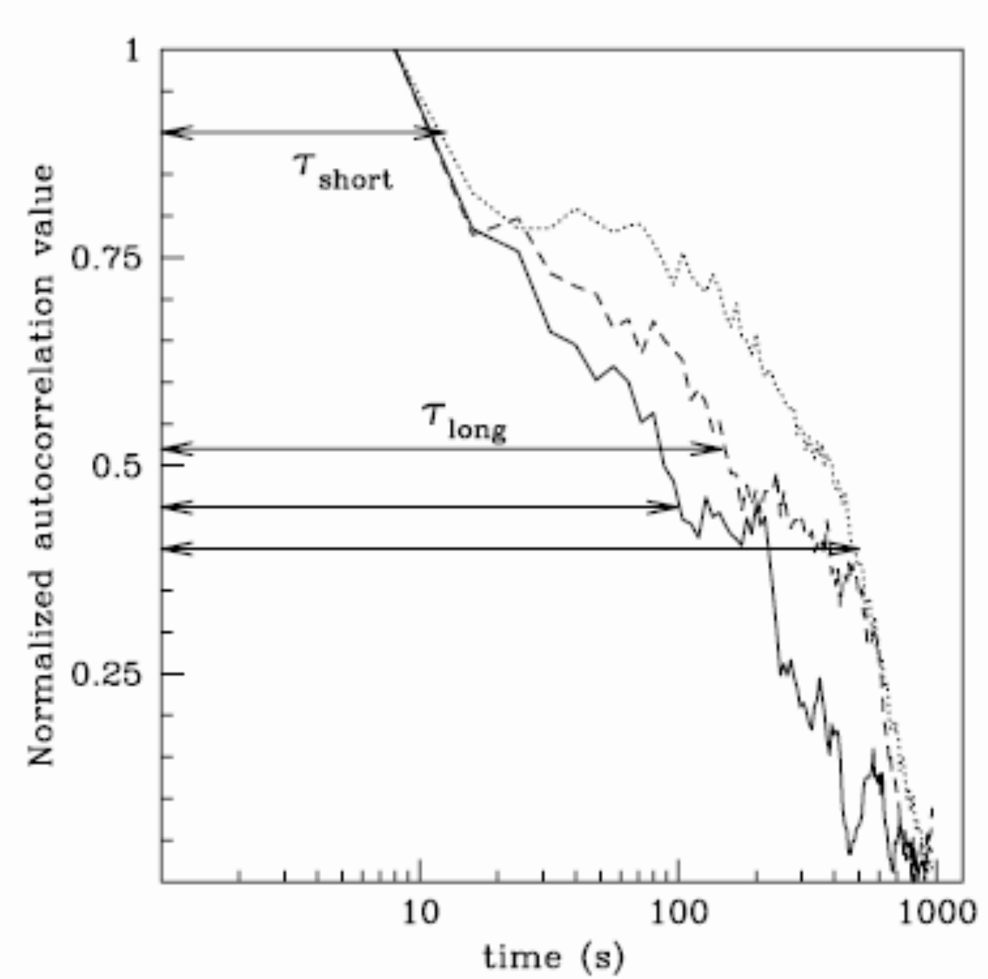


(Source: Marois et al 2010)

Cumulative Explained Variance per component

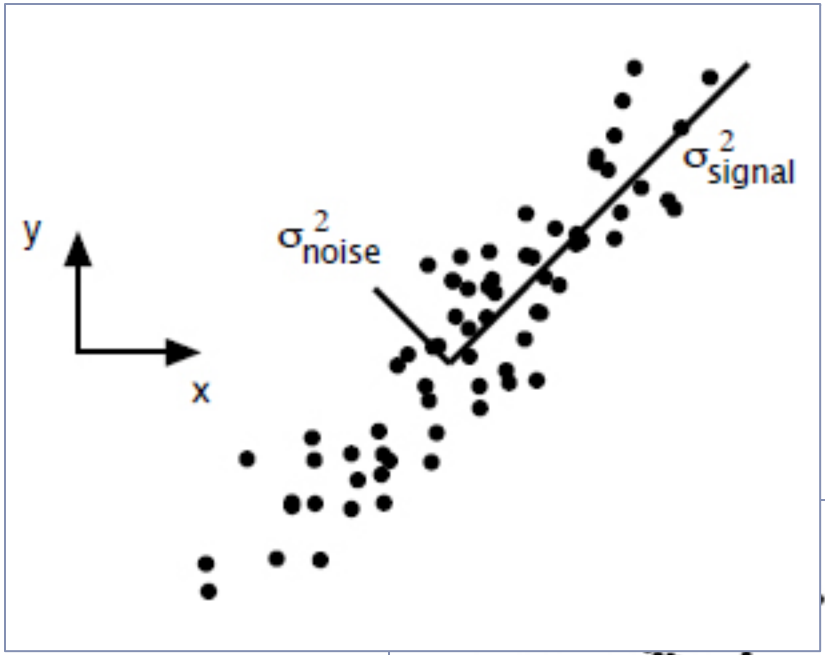


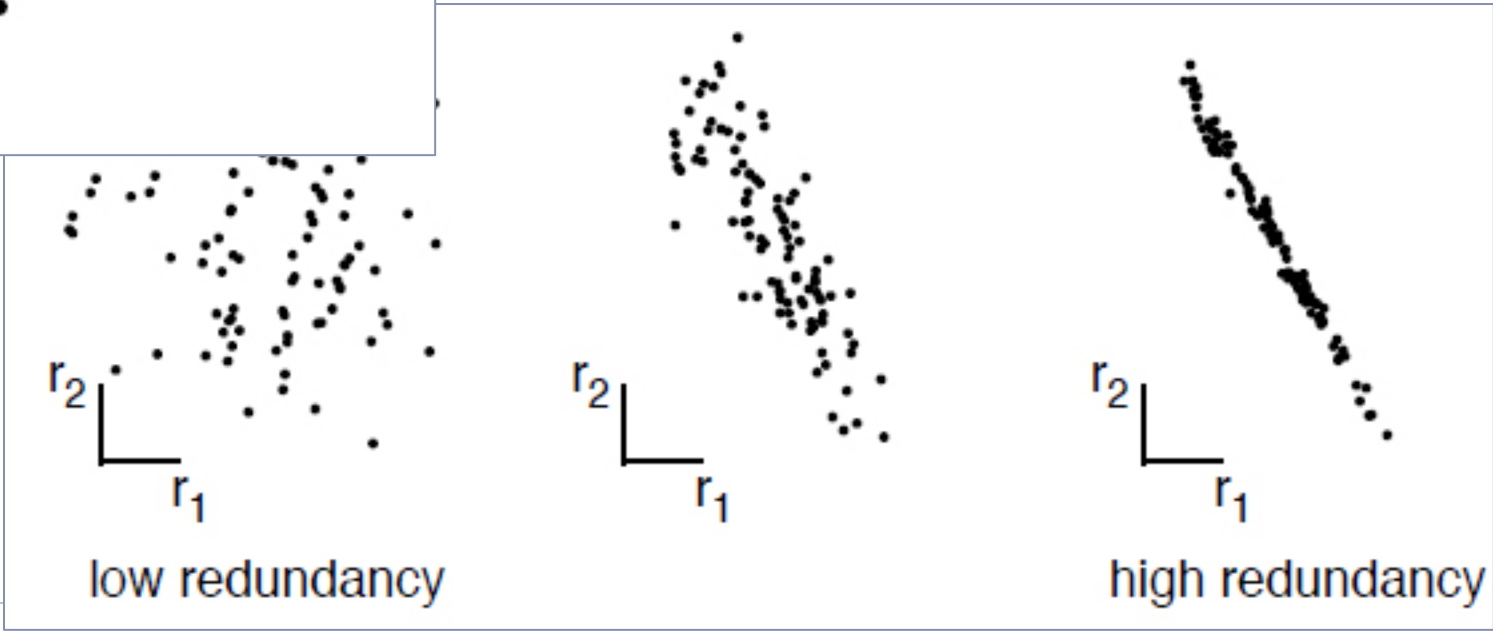
Speckle correlation



Hinkley et al 2007

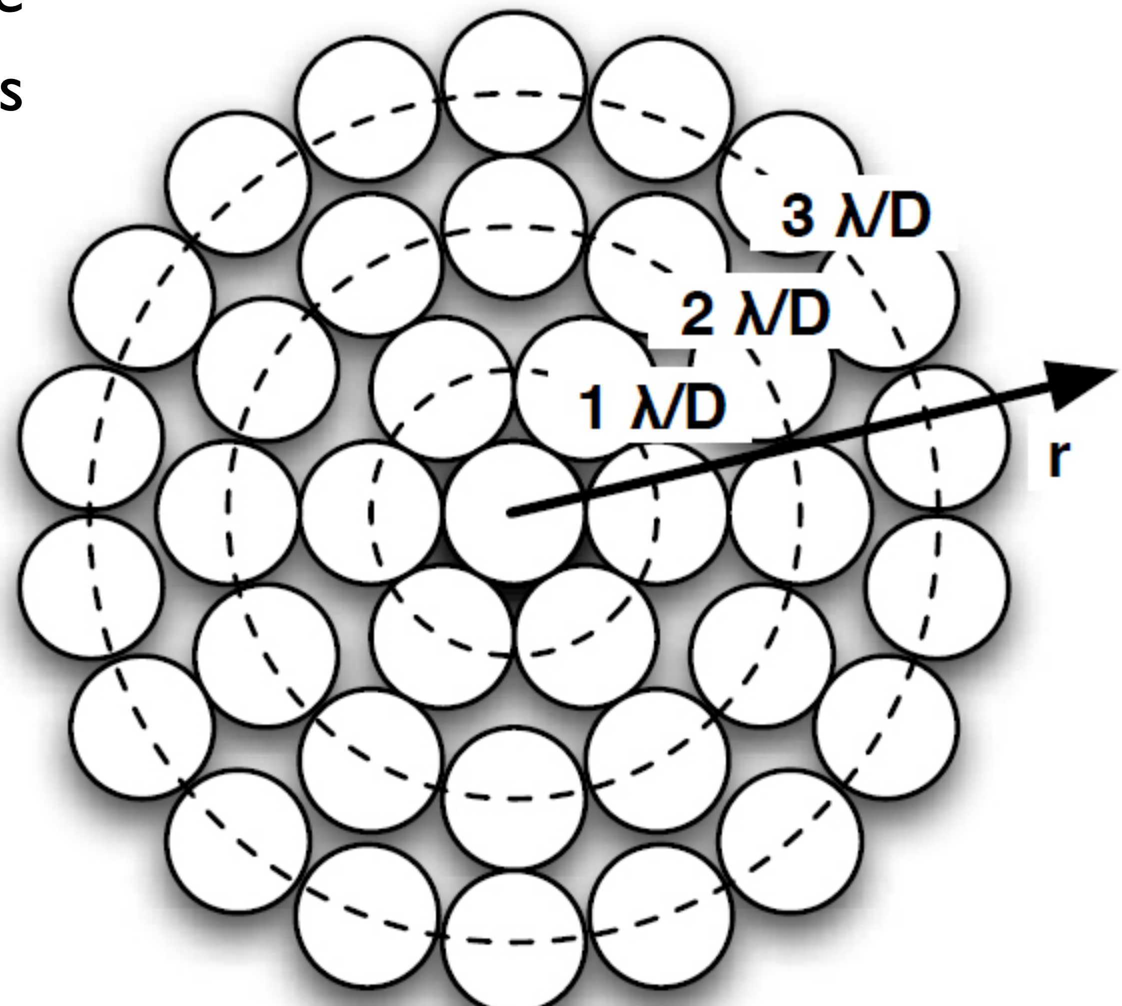
Principal Component Analysis



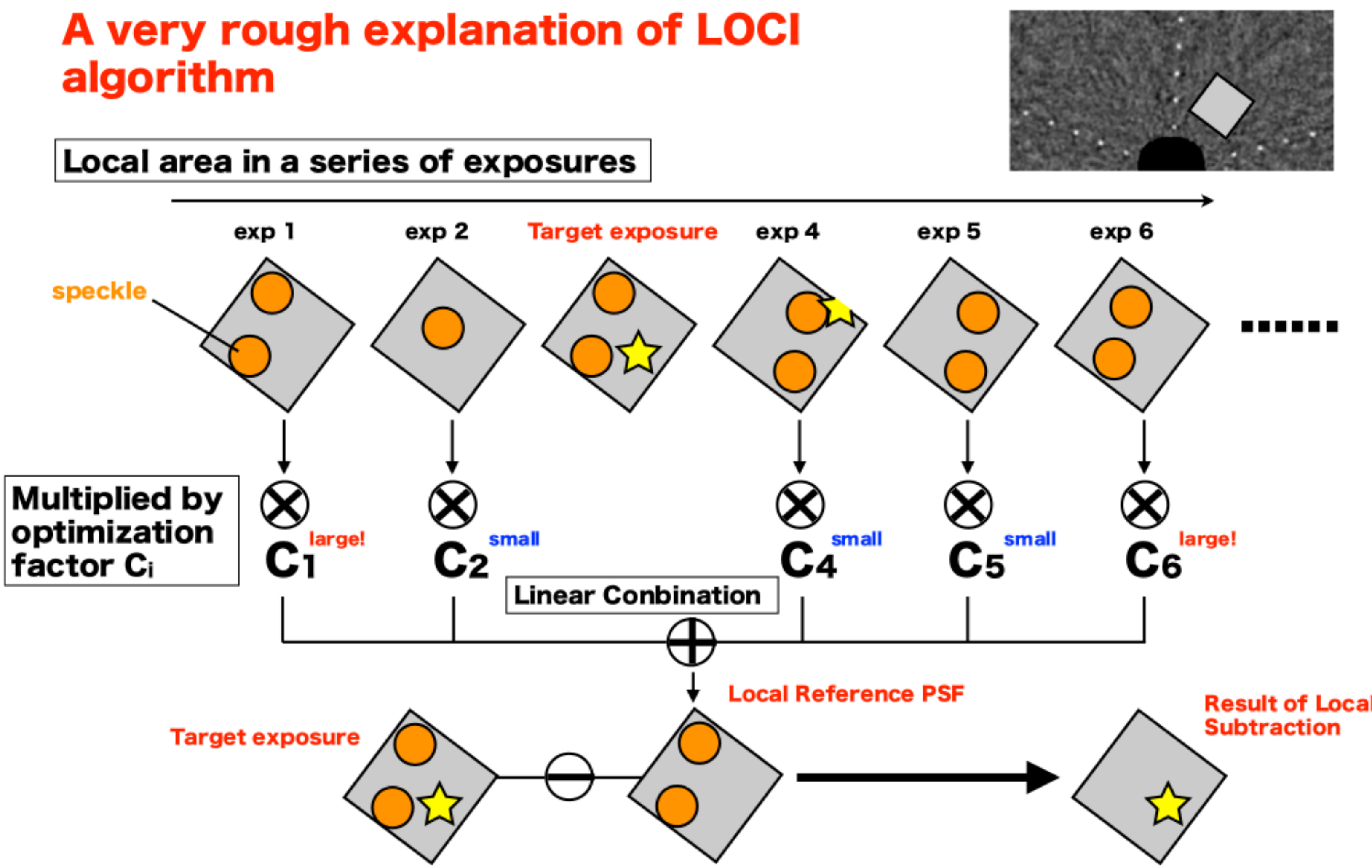


Small-number statistics….

- All things conspire to make small angles difficult…



Locally Optimized Combination of Images
- LOCI



Source: Kandori 's slides