How Do We Get Astrometric Measurements? (+ a little about spectra).

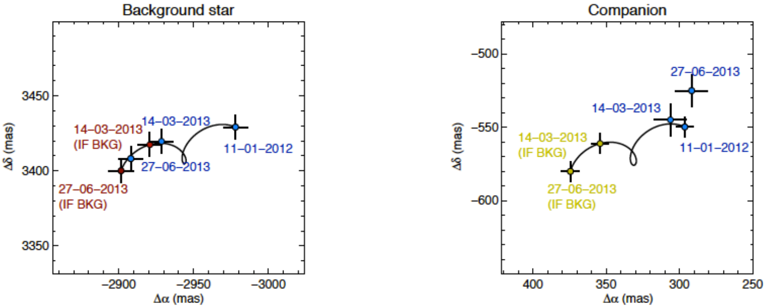
Laurent Pueyo, Space Telescope Science Institute

Sagan summer workshop 2014

July 23, 2014

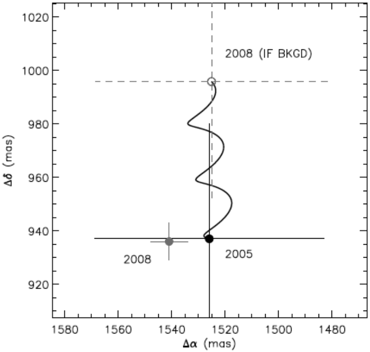
Astrometry to confirm candidates

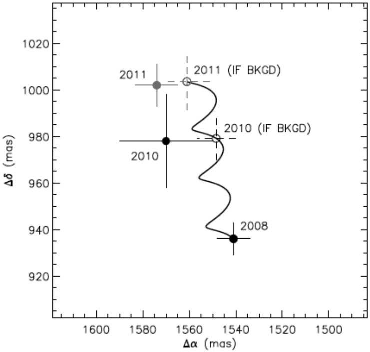
Combine proper motion and parallactic motion to establish physical association. Rameau et al. (2013), Mawet et al. (2012)



Astrometry to confirm candidates

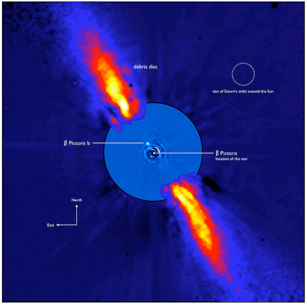
Combine proper motion and parallactic motion to establish physical association. Rameau et al. (2013), Mawet et al. (2012)

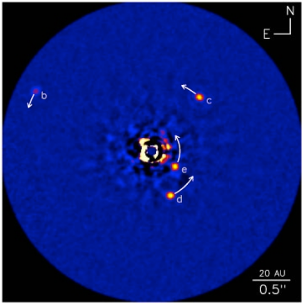




Limitation of direct imaging: uncertainty in the mass luminosity relationship

Lagrange et al. (2010), Marois et al. (2009)



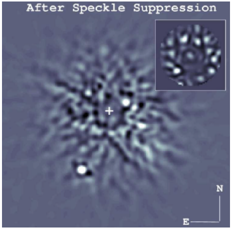


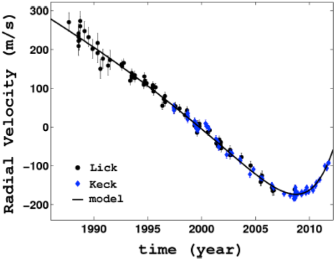
Direct imaging does not measure the dynamical mass

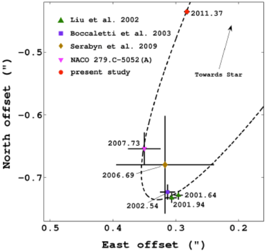
- Mass can be inferred based on the estimated age of the star and evolutionary tracks at young ages.
- Orbital motion is necessary to measure the true dynamical mass.
- **Large separation = Long temporal baselines are required in order to constrain orbital motion...or small error bars!**

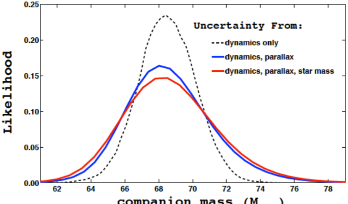
Planet-Star gravitational interaction

Find a object around a star that has been monitored for over 20 years with Radial velocity.



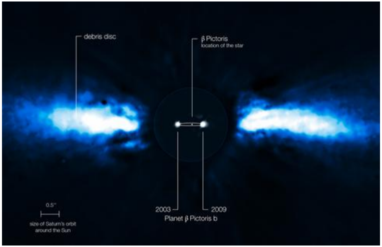


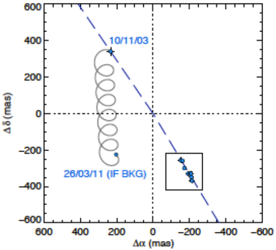




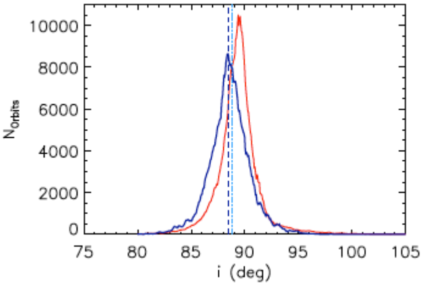
Planet-Disk gravitational interaction

Find a planet around a star with a disk that has been monitored for over 20 years with direct imaging.





Chauvin et al. (2012), Macintosh et al. (2014)



- Strong constraint on the orbital inclination of Beta Pictoris b.
- Dynamical mass bound from RV.

Planet-Planet gravitational interaction

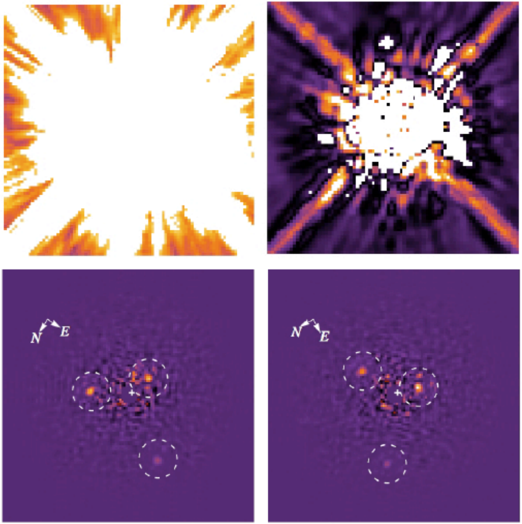
Observe orbital motion in a multiple planetary system.
1998 observations of HR8799

Telescope

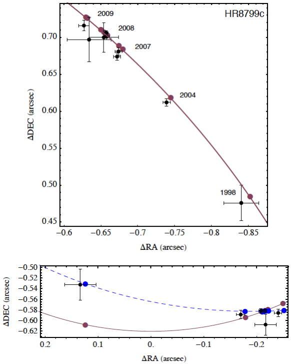
Path of the light

Coronagraph

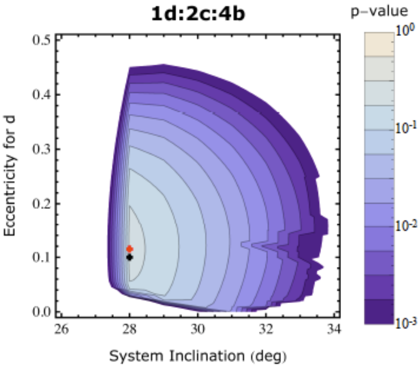
Near-IR detector



Orbital motion and dynamical mass



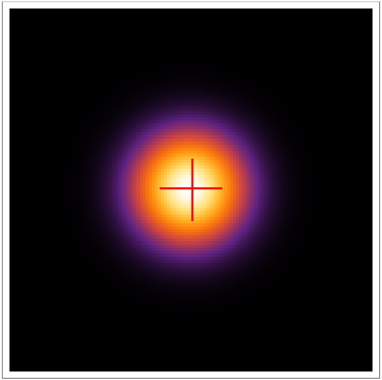
Soummer et al. (2011)



Upper bound for dynamical mass

Esposito et al. (2012): dynamical analysis which including HR8799e. In order for the system to be stable at for at least as long as the estimated age of the primary: mass upper limit $\sim 5\ M_{Jup}$.

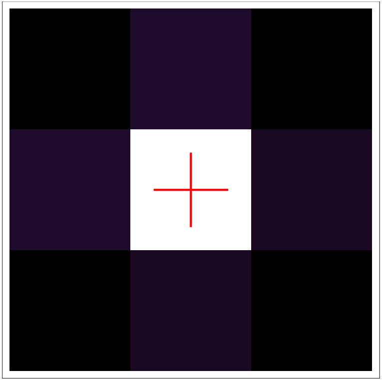
Challenges of astrometry in the presence of speckles



1 pixel $\sim$ 70 mas.

- Reduction corrupts the signal at the pixel level and biases the astrometry.
- This is critical for orbital motion.
- Once can refine the geometric parametrization of LOCI to find the least biased reduction.
- The error is then the distribution of bias over $\sim 10^5$ reductions of PSFs with synthetic planets.

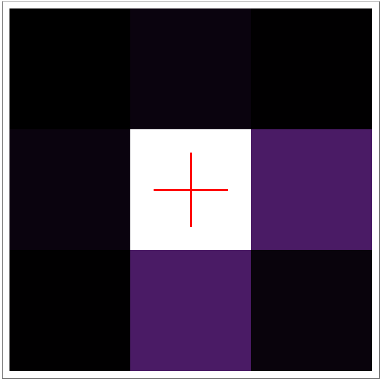
Challenges of astrometry in the presence of speckles



1 pixel $\sim$ 70 mas.

- Reduction corrupts the signal at the pixel level and biases the astrometry.
- This is critical for orbital motion.
- Once can refine the geometric parametrization of LOCI to find the least biased reduction.
- The error is then the distribution of bias over $\sim 10^5$ reductions of PSFs with synthetic planets.

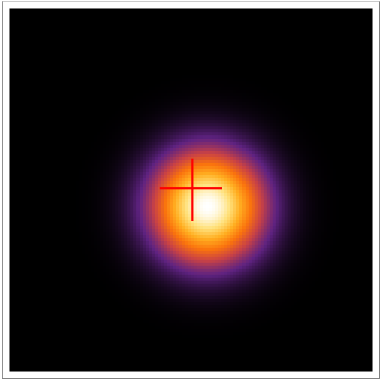
Challenges of astrometry in the presence of speckles



1 pixel ~ 70 mas.

- Reduction corrupts the signal at the pixel level and biases the astrometry.
- This is critical for orbital motion.
- Once can refine the geometric parametrization of LOCI to find the least biased reduction.
- The error is then the distribution of bias over $\sim 10^5$ reductions of PSFs with synthetic planets.

Challenges of astrometry in the presence of speckles

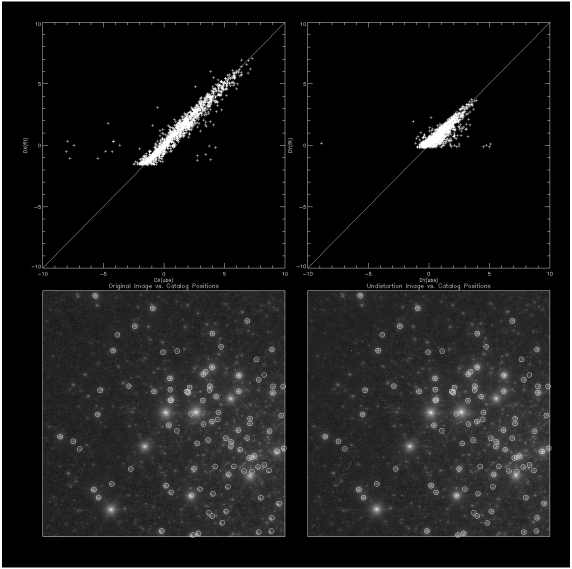


1 pixel ~ 70 mas.

- Reduction corrupts the signal at the pixel level and biases the astrometry.
- This is critical for orbital motion.
- Once can refine the geometric parametrization of LOCI to find the least biased reduction.
- The error is then the distribution of bias over $\sim 10^5$ reductions of PSFs with synthetic planets.

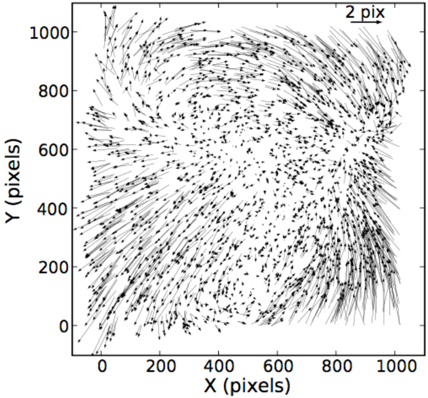
Distortion

Yelda et al. (2010), Konopacky et al. (2014)



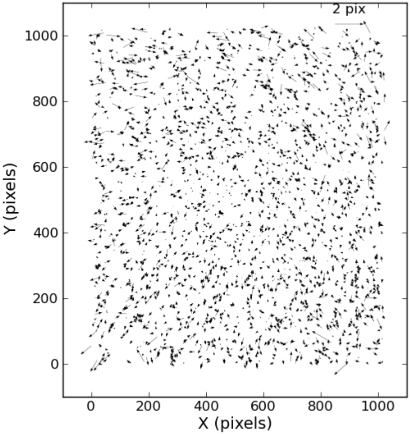
Distortion

Yelda et al. (2010), Konopacky et al. (2014)



Distortion

Yelda et al. (2010), Konopacky et al. (2014)



Distortion

Yelda et al. (2010), Konopacky et al. (2014)

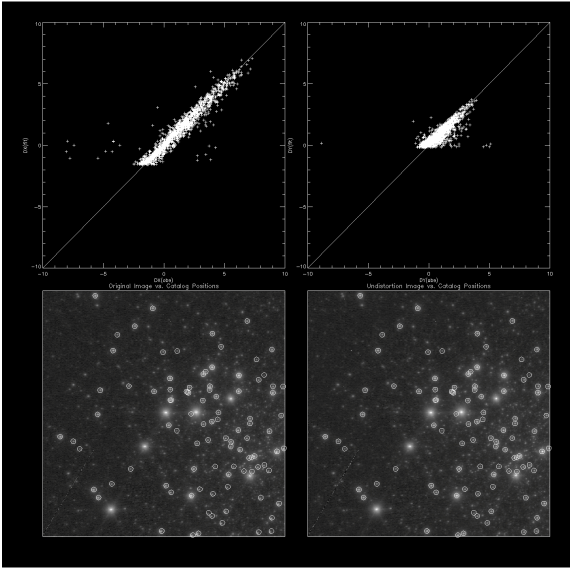


Plate Scale and PA offset

Observe binaries with either:

- Well constrained orbital elements.
- Simultaneous epochs obtained with a well calibrated instrument.

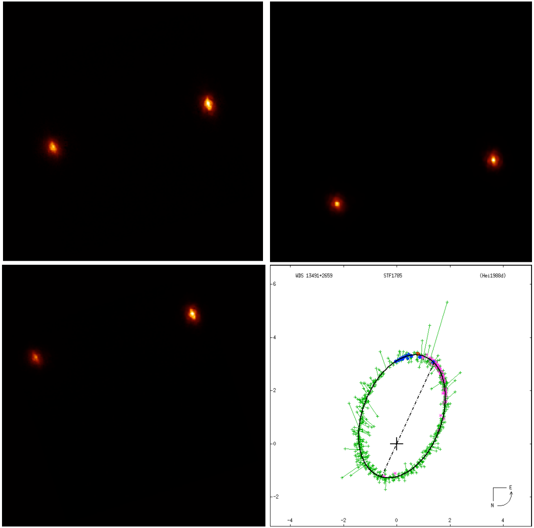
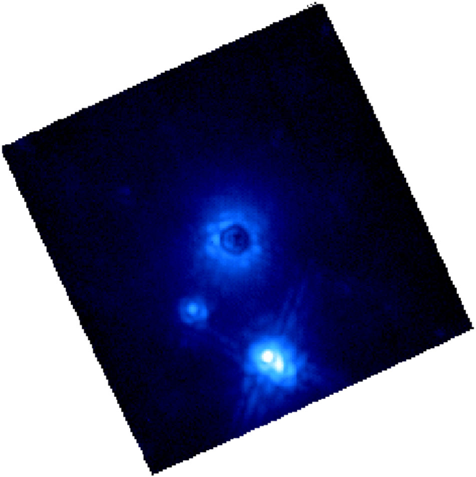


Plate Scale and PA offset

Observe binaries with either:

- Well constrained orbital elements.
- Simultaneous epochs obtained with a well calibrated instrument.

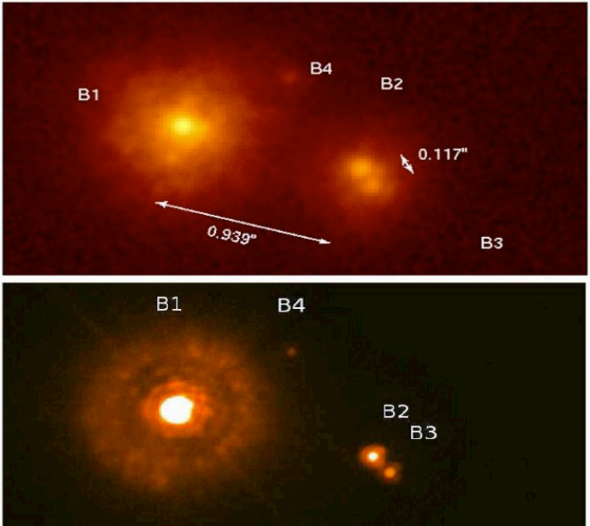


Close et al. (2013), Konopacky et al. (2014)

Plate Scale and PA offset

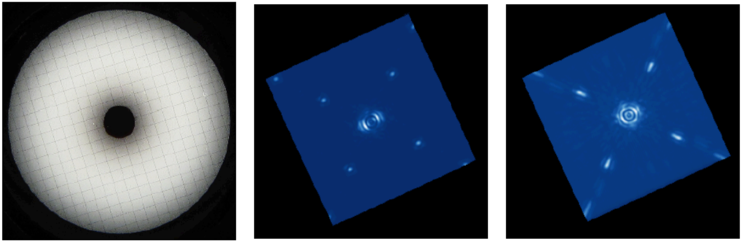
Observe binaries with either:

- Well constrained orbital elements.
- Simultaneous epochs obtained with a well calibrated instrument.



Raw data

Step 1a: Image registration, with nice satellite spots.



Algorithm

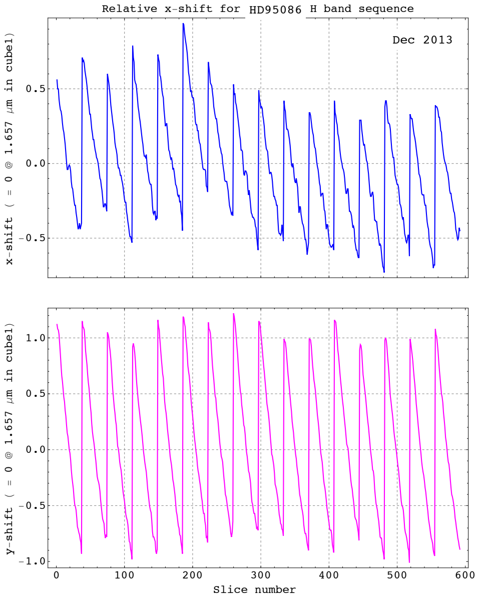
- Find the location of each spot in each slice.
- Fit each spot to a model in order to retrieve its location and its brightness.
- From the location of the four spots derive the scaling law and the stellar location in each slice.
- Shift and rescale each image.

Step 1b: Image registration, with crummy satellite spots.

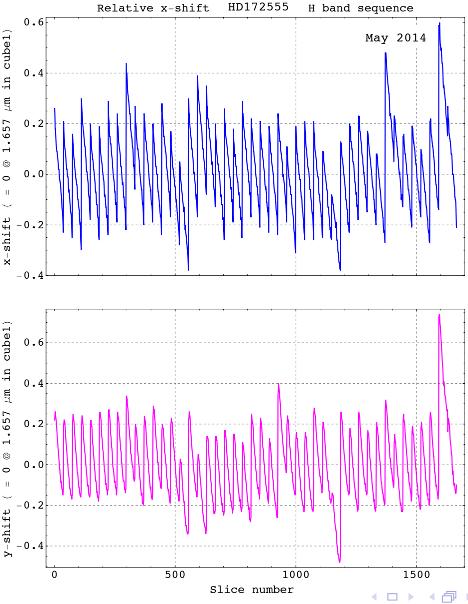
Algorithm

- Pick a reference slice.
- Fourier transform each slice and vary the scale of the u-v plane (zero padding if FFT, u-v sampling if MFT).
- For each slice find the u-v plane scaling that maximizes the cross correlation between the *modulus* of the Fourier transformed images. This decouples the problem of calculating relative scaling and centering.
- Stretch/squash all slices at the wavelength of interest.
- Use a MFT based sub-pixel image registration algorithm (Guizar and Fienup 2009).

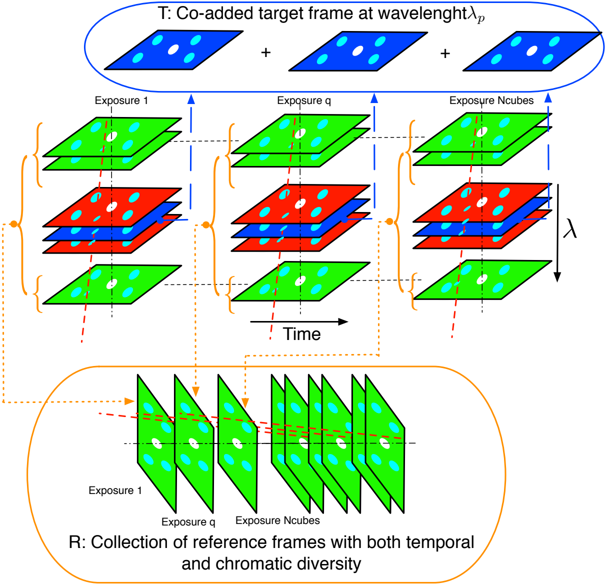
Step 1: Image registration, typical results



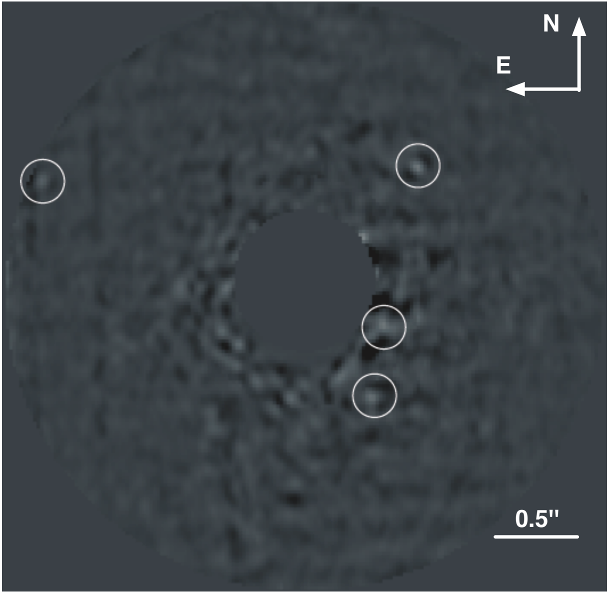
Step 1: Image registration, typical results



Step 2: partition the image in zones and apply your favorite algorithm.



Step 2: partition the image in zones and apply your favorite algorithm.



Step 3: estimate the location of the planets in detector coordinate and their flux.

Multiple solutions for the problem of signal recovery

- Solution 1: inject fakes sources.
- Solution 2: inject a "negative fake" in the raw data.
- Solution 3: perturbation methods.
- Solution 4: use priors on spectrum to select references.
- Solution 5: hope that the companion flux is in the high order PCA modes.
- Solution 6: ask a different PCA question.

For the detection problem there is a magic recipe: pick your favorite algorithm and tweak the parameters until your false positive and/or your false negative probabilities are low enough

For the characterization problem there no magic recipe yet: for each problem there is a preferred solution. During the hand on session try to make your own opinion about where the trade offs are.

Step 3: estimate the location of the planets in detector coordinate and their flux.

Multiple solutions for the problem of signal recovery

- Solution 1: inject fakes sources.
- Solution 2: inject a "negative fake" in the raw data.
- Solution 3: perturbation methods.
- Solution 4: use priors on spectrum to select references.
- **Solution 5: hope that the companion flux is in the high order PCA modes.... or something else.**
- Solution 6: ask a different PCA question.

For the detection problem there is a magic recipe: pick your favorite algorithm and tweak the parameters until your false positive and/or your false negative probabilities are low enough

For the characterization problem there no magic recipe yet: for each problem there is a preferred solution. During the hand on session try to make your own opinion about where the trade offs are.

Step 3 [PCA only]: planet pixel coordinates and flux

Calibrated image calculated using a projection on the Principal Components.

$$F(n) = \left(I_{\psi_0}(n) - \sum_{k=1}^{K_{klip}} < I_{\psi_0}, Z_k^{KL} >_{\mathscr{S}} Z_k^{KL}(n) \right) + \varepsilon \left(A(n) - \sum_{k=1}^{K_{klip}} < A, Z_k^{KL} >_{\mathscr{S}} Z_k^{KL}(n) \right)$$

Pueyo et al. (2014)

Step 3 [PCA only]: planet pixel coordinates and flux

We find the location $\overrightarrow{n_0}$ and brightness β of the planet using forward modeling.
We minimize:

$$\min_{(\overrightarrow{n_0},\beta)} \left\{ \sum_{n=1}^{N_{\mathscr{S}}} \left(F(\overrightarrow{n}) - \beta \left[A(\overrightarrow{n} - \overrightarrow{n_0}) + \sum_{k=1}^{K_{klip}} < A(\overrightarrow{n} - \overrightarrow{n_0}), Z_k^{KL}(\overrightarrow{n}) >_{\mathscr{S}} Z_k^{KL}(\overrightarrow{n}) \right] \right)^2 \right\}.$$

Pueyo et al. (2014)

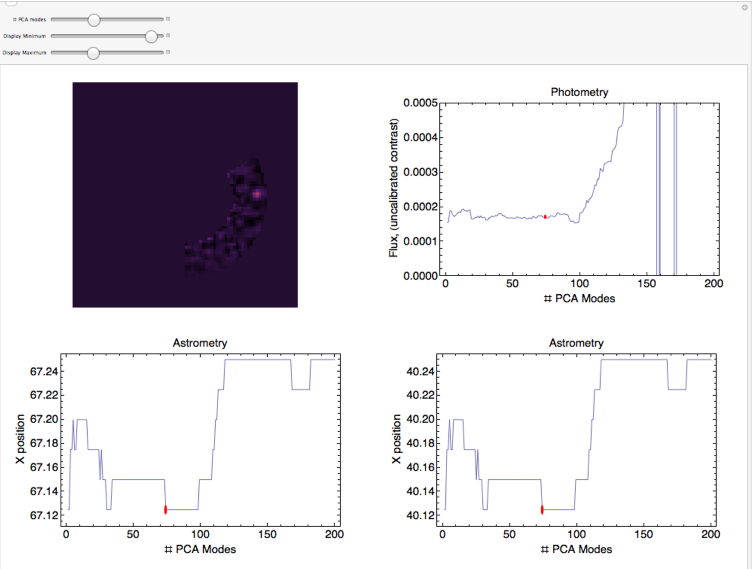
Step 3 [PCA only]: planet pixel coordinates and flux

Provided that the statistics of the noise *after* PSF subtraction is gaussian and zero mean then the unbiased astrometry and photometry are given by:

$$\begin{aligned}
\overrightarrow{n_{Astro}} &= \arg\max_{(\vec{n_0})}\{C(\vec{n_0})\} = \arg\max_{(\vec{n_0})}\Bigg\{ < F(\vec{n}), A(\vec{n}-\vec{n_0}) >_{\mathscr{S}} \\
&- \sum_{k=1}^{K_{klip}} < A(\vec{n}-\vec{n_0}), Z_k^{KL}(\vec{n}) >_{\mathscr{S}} < F(\vec{n}), Z_k^{KL}(\vec{n}) >_{\mathscr{S}} \Bigg\} \\
\beta_{Photo} &= \frac{C(\overrightarrow{n_{Astro}})}{||A(\vec{n}-\overrightarrow{n_{Astro}})||_{\mathscr{S}}^2 - \sum_{k=1}^{K_{klip}} < A(\vec{n}-\vec{n_0}), Z_k^{KL}(\vec{n}) >_{\mathscr{S}}^2}
\end{aligned}$$

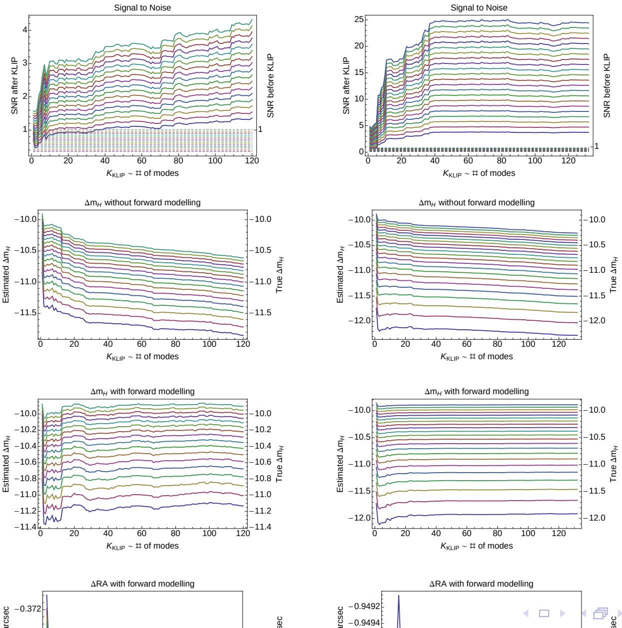
Pueyo et al. (2014)

Step 3 [PCA only]: planet pixel coordinates and flux

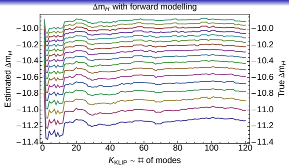


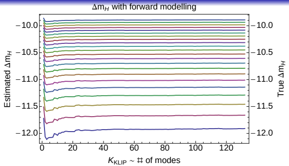
Astrometry and photometry after point source forward modelling

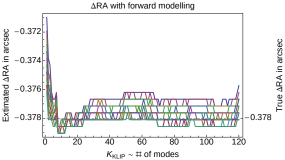
Step 3 [PCA only]: planet pixel coordinates and flux

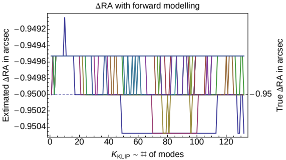


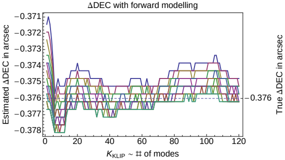
Step 3 [PCA only]: planet pixel coordinates and flux

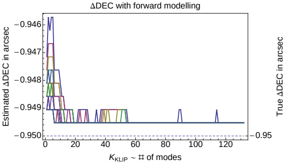












Step 3 [PCA only]: planet pixel coordinates and flux

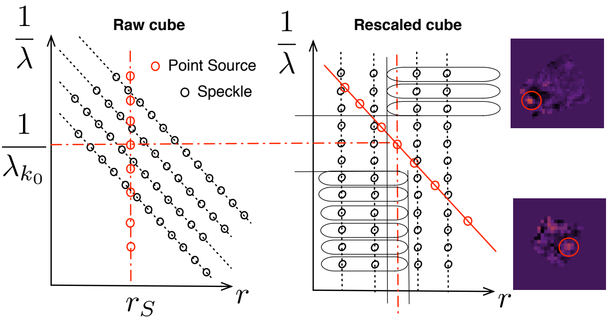
Provided that the statistics of the noise *after* PSF subtraction is gaussian and zero mean then the unbiased astrometry and photometry are given by:

$$\begin{aligned}
\overrightarrow{n_{Astro}} &= \arg\max_{(\vec{n_0})}\{C(\vec{n_0})\} = \arg\max_{(\vec{n_0})}\Bigg\{ < F(\vec{n}), A(\vec{n}-\vec{n_0}) >_{\mathscr{S}} \\
&- \sum_{k=1}^{K_{klip}} < A(\vec{n}-\vec{n_0}), Z_k^{KL}(\vec{n}) >_{\mathscr{S}} < F(\vec{n}), Z_k^{KL}(\vec{n}) >_{\mathscr{S}} \Bigg\} \\
\beta_{Photo} &= \frac{C(\overrightarrow{n_{Astro}})}{||A(\vec{n}-\overrightarrow{n_{Astro}})||^2_{\mathscr{S}} - \sum_{k=1}^{K_{klip}} < A(\vec{n}-\vec{n_0}), Z_k^{KL}(\vec{n}) >^2_{\mathscr{S}}}
\end{aligned}$$

This is only true when there is no signal from the companion in the reference library. NOT ALWAYS TRUE with IFU data!

Step 3 [PCA only]: planet pixel coordinates and flux

Before Step 3: Make sure to have a "companion free" PSF library.



The remaining parameters are the extend of the "radial inclusion zone", the extend of the "wavelength inclusion zone", and the actual geometry of the zone $\Delta r, \Delta\theta$.

Step 3 [PCA only]: planet pixel coordinates and flux

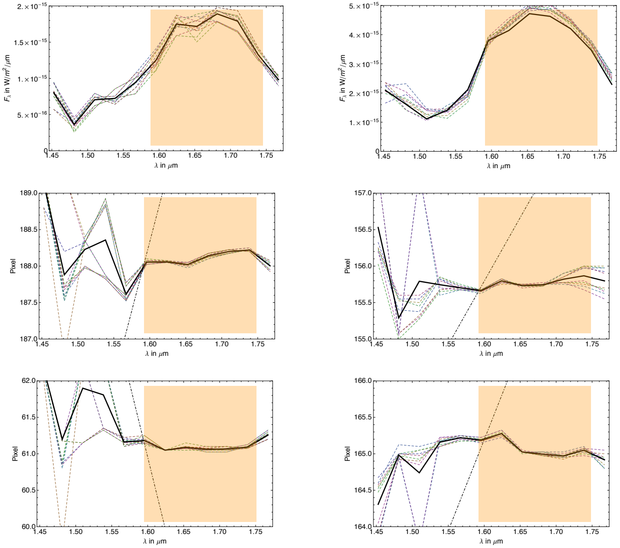
Reduction for an ensemble of zone geometries and exclusion parameters.

We use the planet location as a function of wavelength and the planet flux as a function of PCA modes to test the of the validity of the gaussinaity and companion free hypothesis for each configuration.

Step 3 [PCA only]: planet pixel coordinates and flux

Reduction for an ensemble of zone geometries and exclusion parameters.

HR9799b HR9799c



Step 3 [PCA only]: planet pixel coordinates and flux.

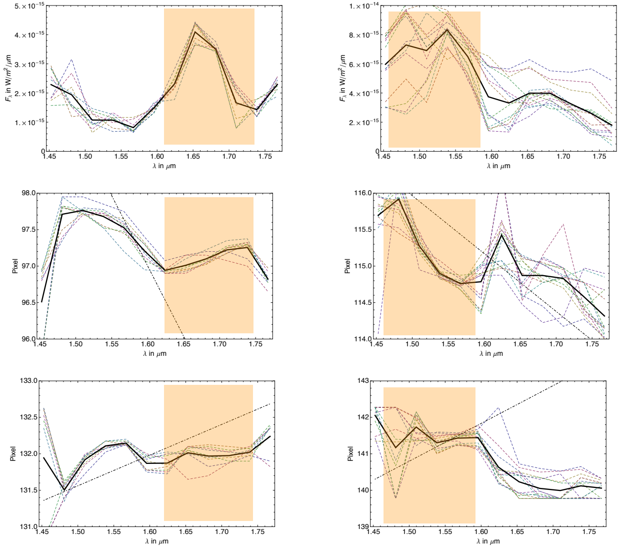
Reduction for an ensemble of zone geometries and exclusion parameters.

We use the planet location as a function of wavelength and the planet flux as a function of PCA modes to test the of the validity of the gaussinaity and companion free hypothesis for each configuration.

Step 3 [PCA only]: planet pixel coordinates and flux.

Reduction for an ensemble of zone geometries and exclusion parameters.

HR9799d HR9799e



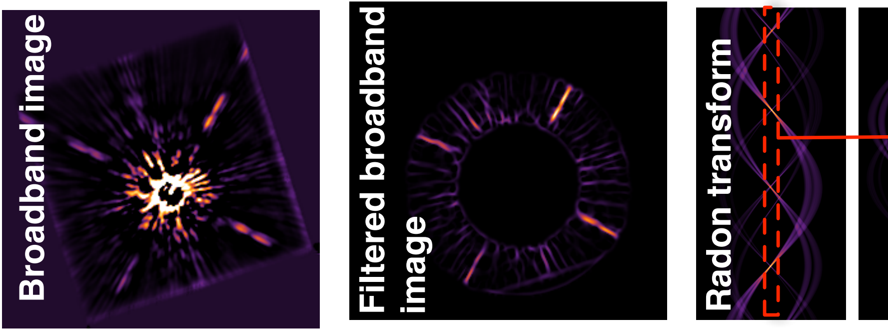
Step 4: stellar location.

Optional step

- When the satellite spots feature no asymmetries and are high SNR then the location of the star is known from the image registration step.
- When the satellite spots are "crummy", or gone, then the image registration step only yield relative alignment.
- When looking at broadband images, the satellite spots are elongated, then the image registration step only yield relative alignment.

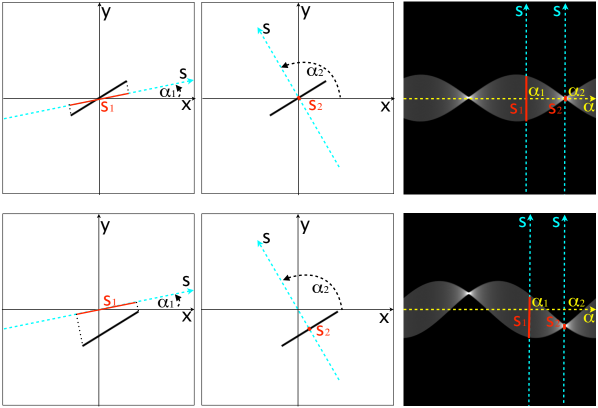
Step 4: stellar location.

We use a Radon transform of broadband images.



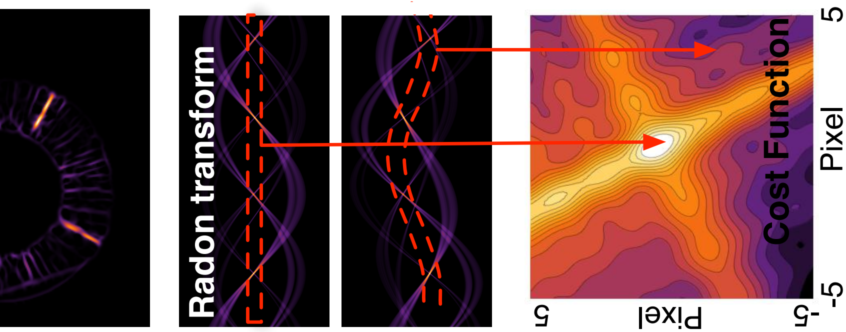
Step 4: stellar location.

We use a Radon transform of broadband images.



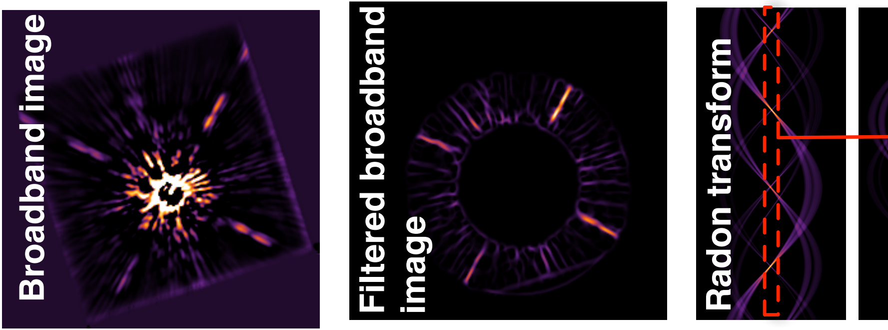
Step 4: stellar location.

We use a Radon transform of broadband images.



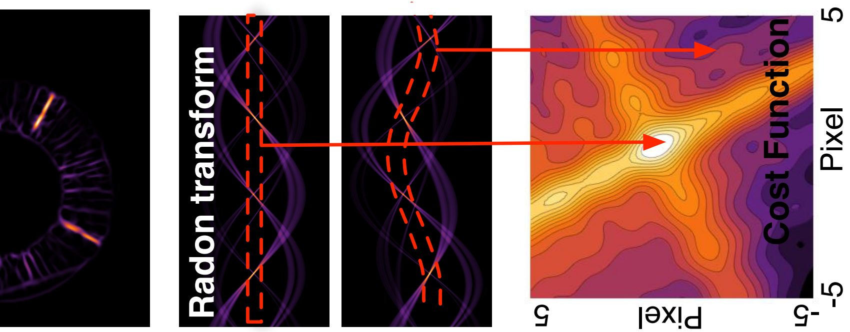
Step 4: stellar location.

We use a Radon transform of broadband images.



Step 4: stellar location.

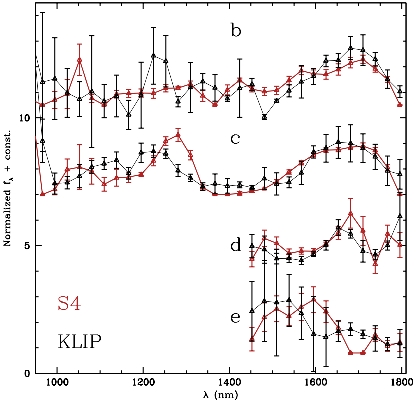
We use a Radon transform of broadband images.



Spectrum with an IFU

While spectro-photometry is what makes directly imaged exo-planets most interesting, astrometry is essential to their full characterization.

Spectro-photometry and Astrometry ought to be estimated jointly when using IFU data. (when possible)



Oppenheimer at al. (2013)

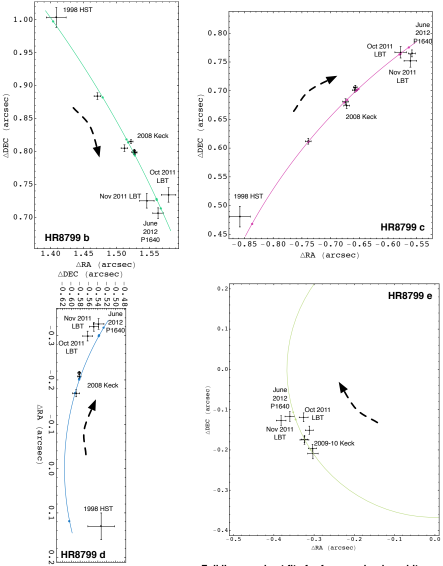
Putting the astrometry together

Recap

- Distortion was measured and included in at the data cube level.
- We have estimated the relative location of the planet wrt star.
- We know the plate scale and the PA offset.

We have all we need to get astrometric estimates and uncertainties.

Next step: fit orbits



Full lines are best fits for face-on circular orbits

Bibliography

- Rameau et al. (2013), http://arxiv.org/abs/1310.7483
- Mawet et al. (2012), http://arxiv.org/abs/1207.6017
- Marois et al. (2010), http://arxiv.org/abs/1011.4918
- Lagrange et al. (2010), http://arxiv.org/abs/1006.3314
- Crepp et al. (2011), http://arxiv.org/abs/1112.1725
- Chauvin et al. (2012), http://arxiv.org/abs/1202.2655
- Macintosh et al. (2014), http://arxiv.org/abs/1403.7520
- Yelda et al. (2010), http://arxiv.org/abs/1010.0064
- Konopacky et al. (2014) http://arxiv.org/abs/1407.2305
- Close et al. (2013), http://arxiv.org/abs/1308.4155
- Gizar et al. (2008), http://www.opticsinfobase.org/ol/abstract.cfm?uri=ol-33-2-156
- Pueyo et al. (2014), in revision.
- Oppenheimer at al. (2013), http://arxiv.org/abs/1303.2627