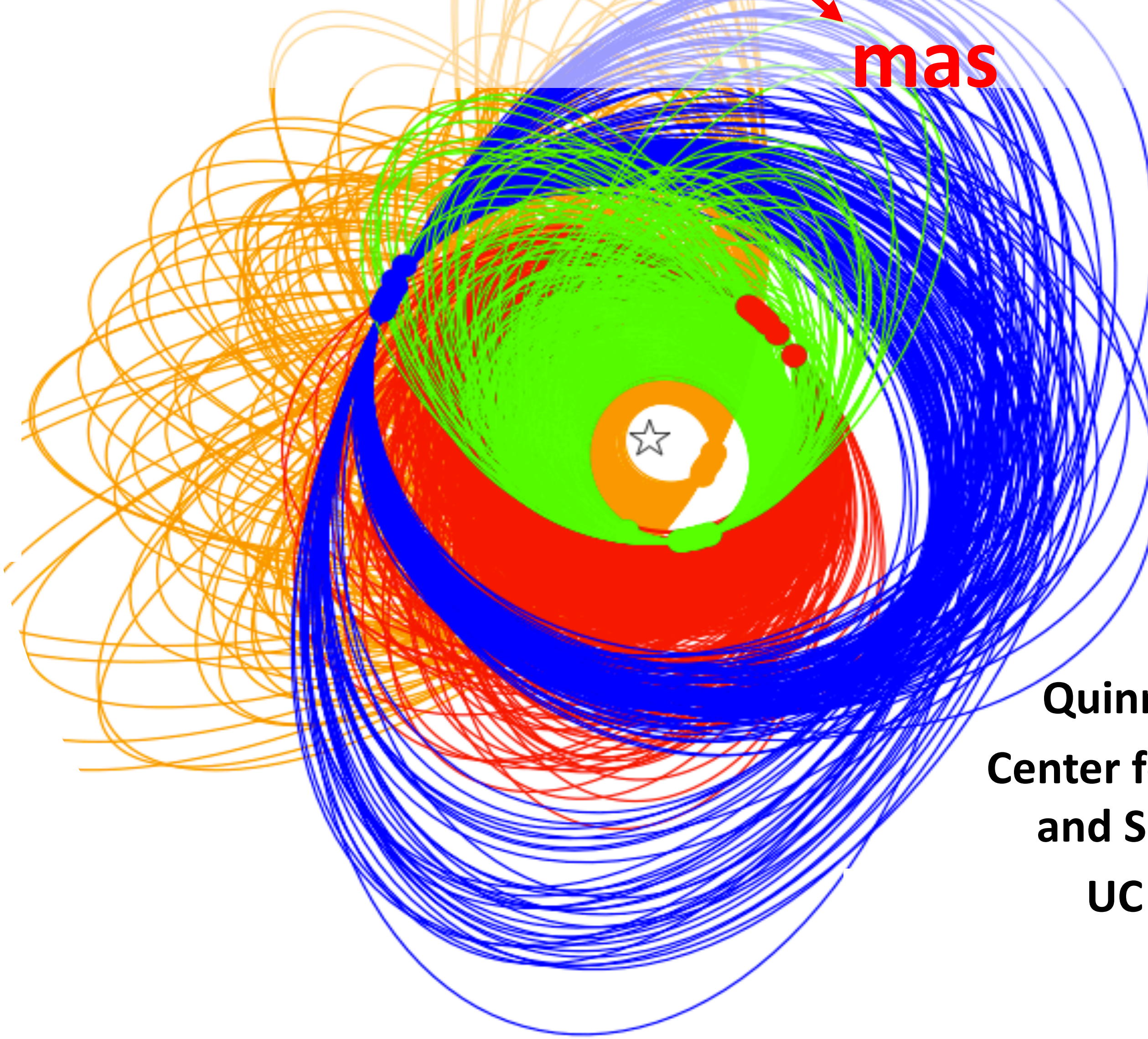
Combining Astrometry and Direct Imaging: Breaking the 1 uas barrier

mas



Quinn Konopacky

Center for Astrophysics and Space Science

UC San Diego

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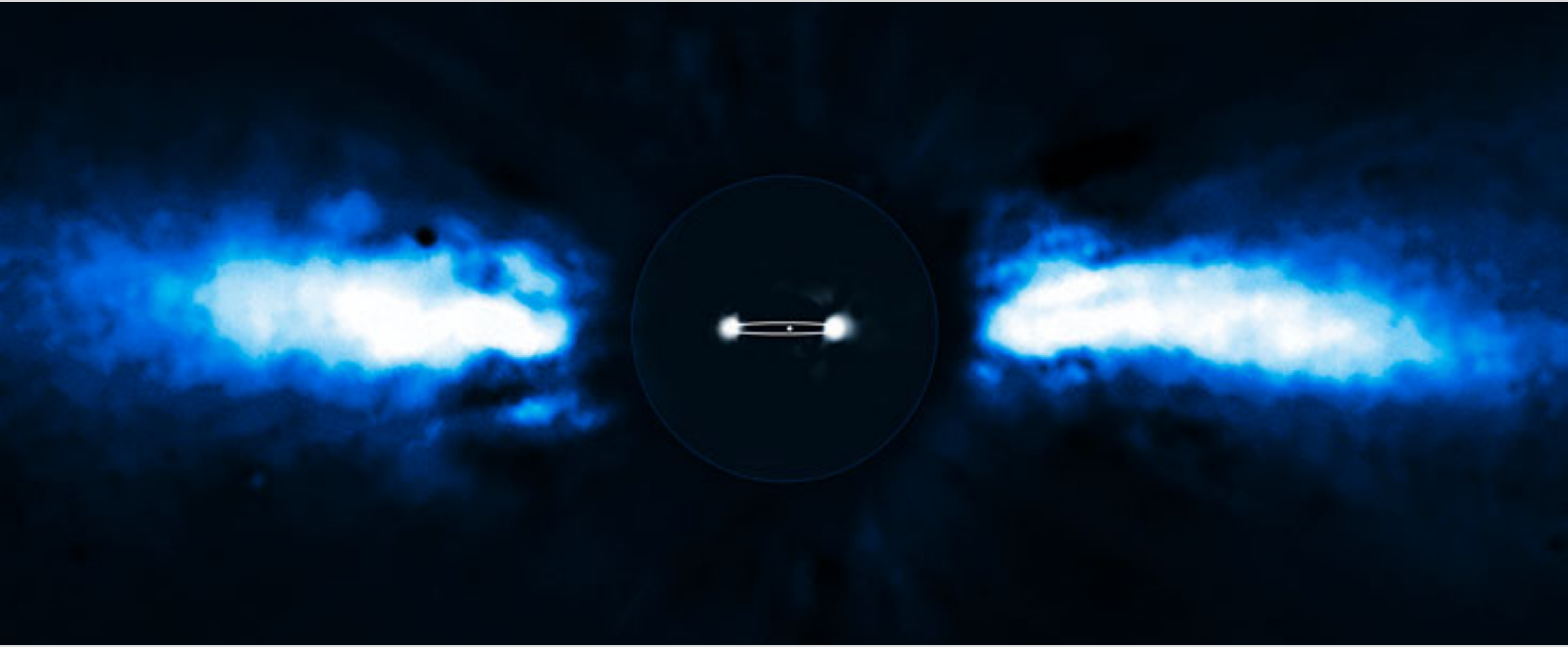
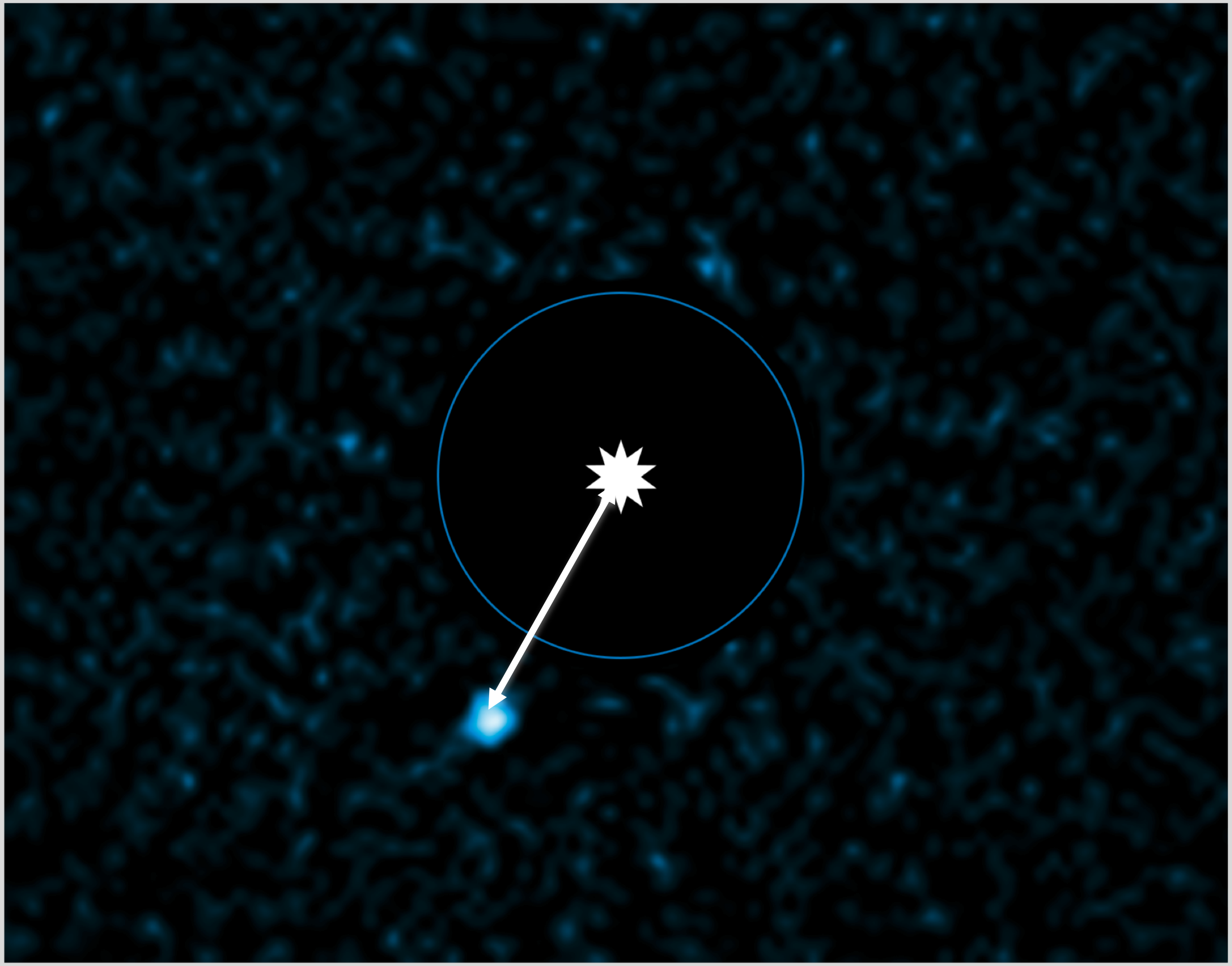
Understanding the orbital properties of directly imaged planets can provide powerful constraints on their evolution.



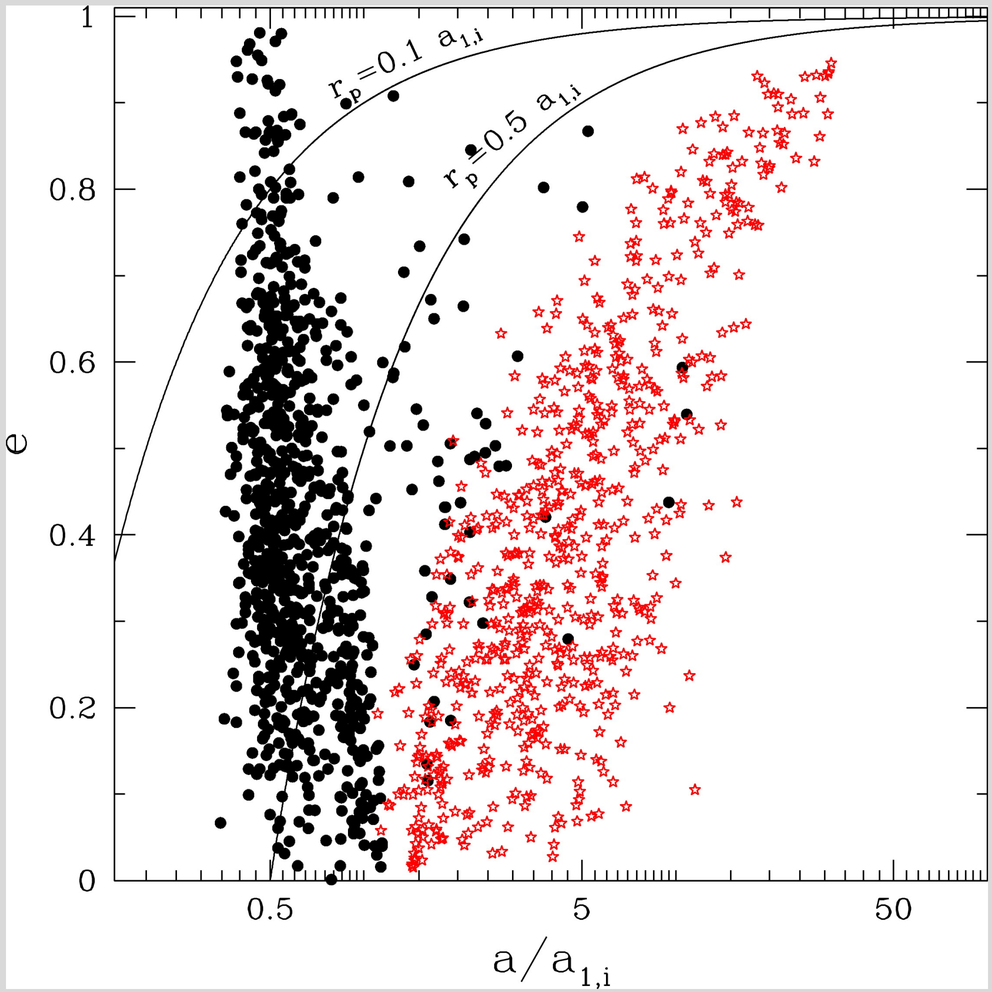
ESO

Astrometric (positional) measurements of directly imaged planets are used to confirm their association with the star and to learn about their orbits.



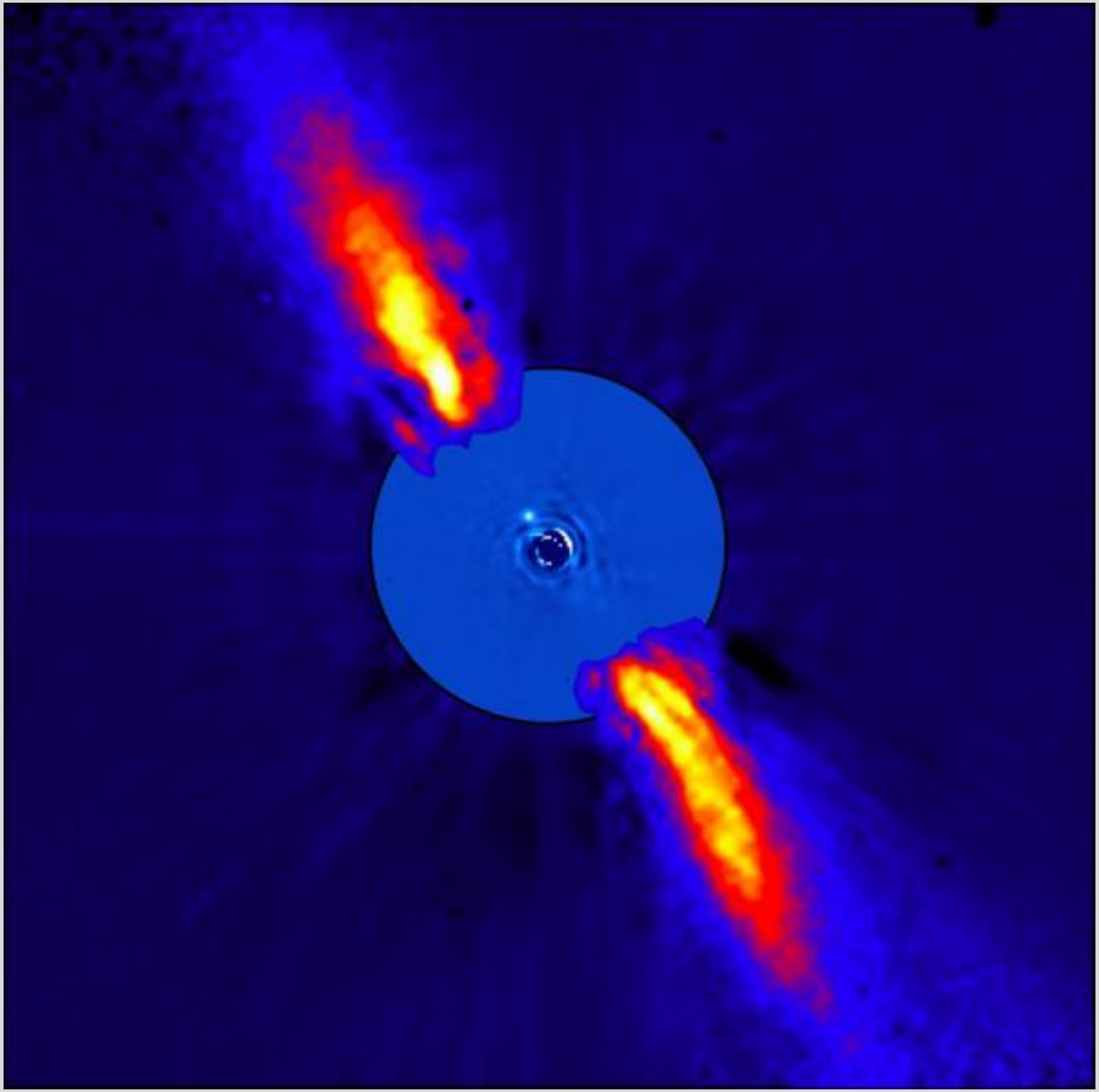
HD 95086b (VLT/NACO)
Rameau et al. 2013

Orbital eccentricities can be used as a tracer of formation or subsequent dynamical processes.



Chatterjee et al. 2008

Orbital information can highlight when interesting events may occur in a system – e.g., the β Pic transit.



Lagrange et al. 2009

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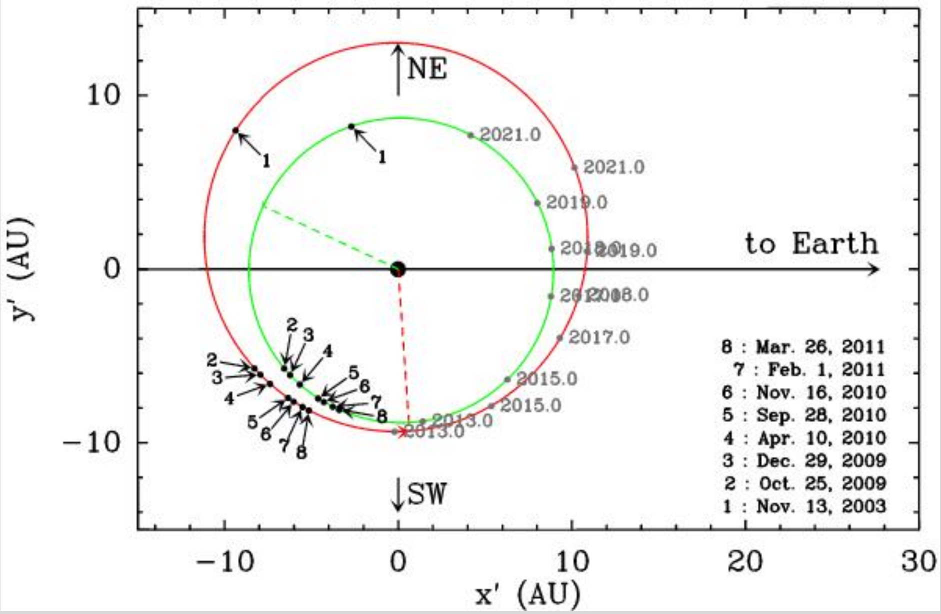

Chauvin et al. 2012 – Allowed with 1 σ

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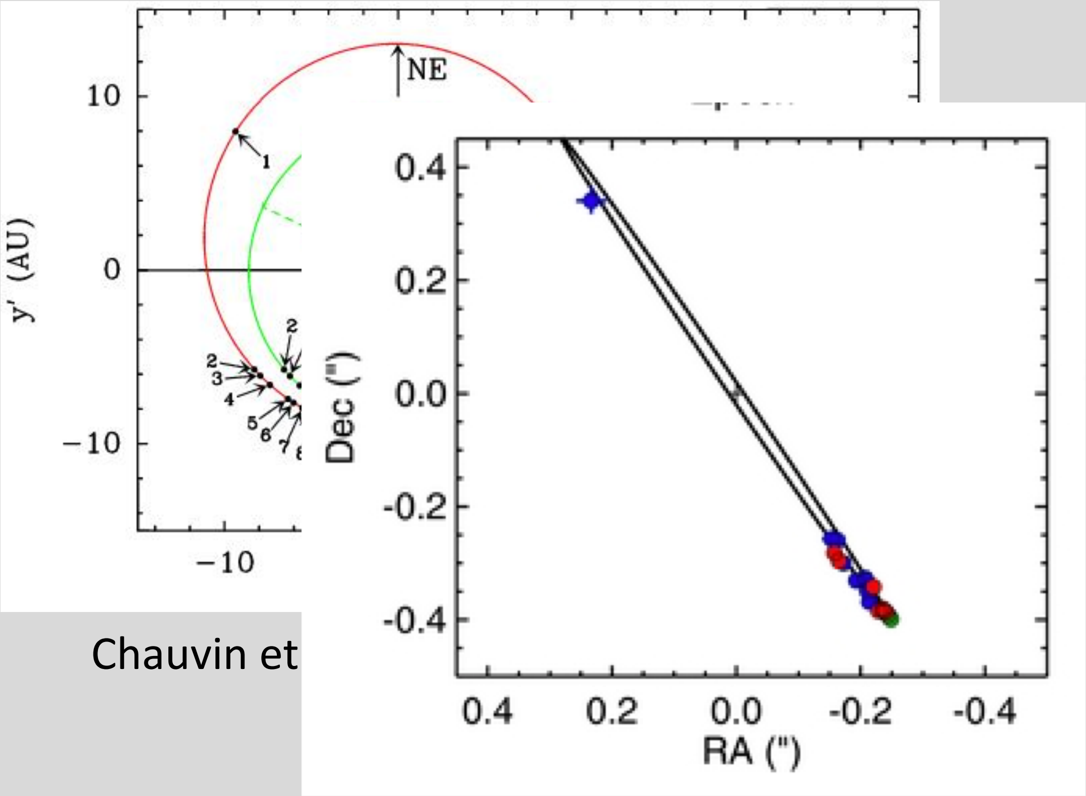

Chauvin et

Nielsen et al. 2014 – Allowed with 1 σ

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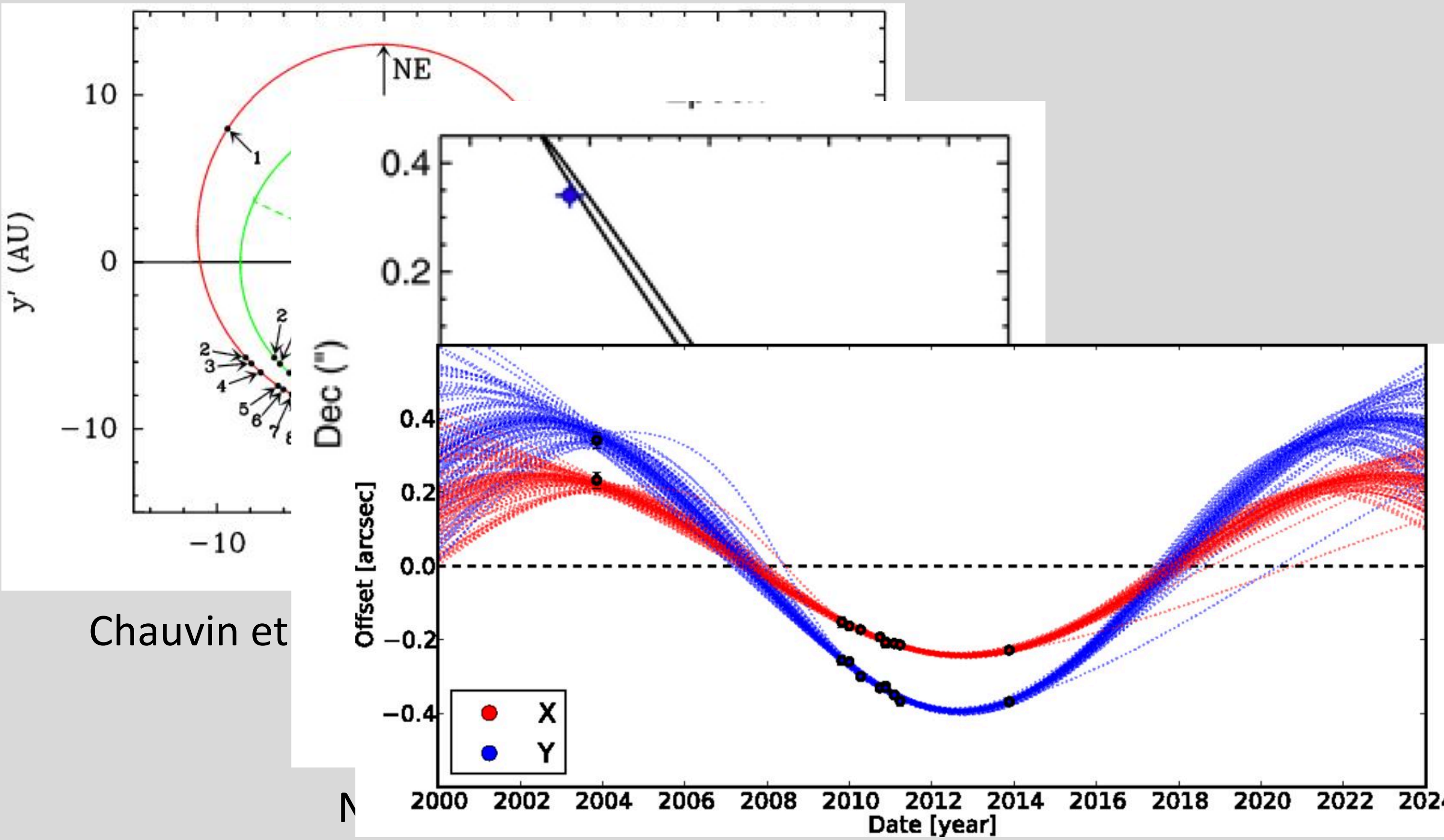
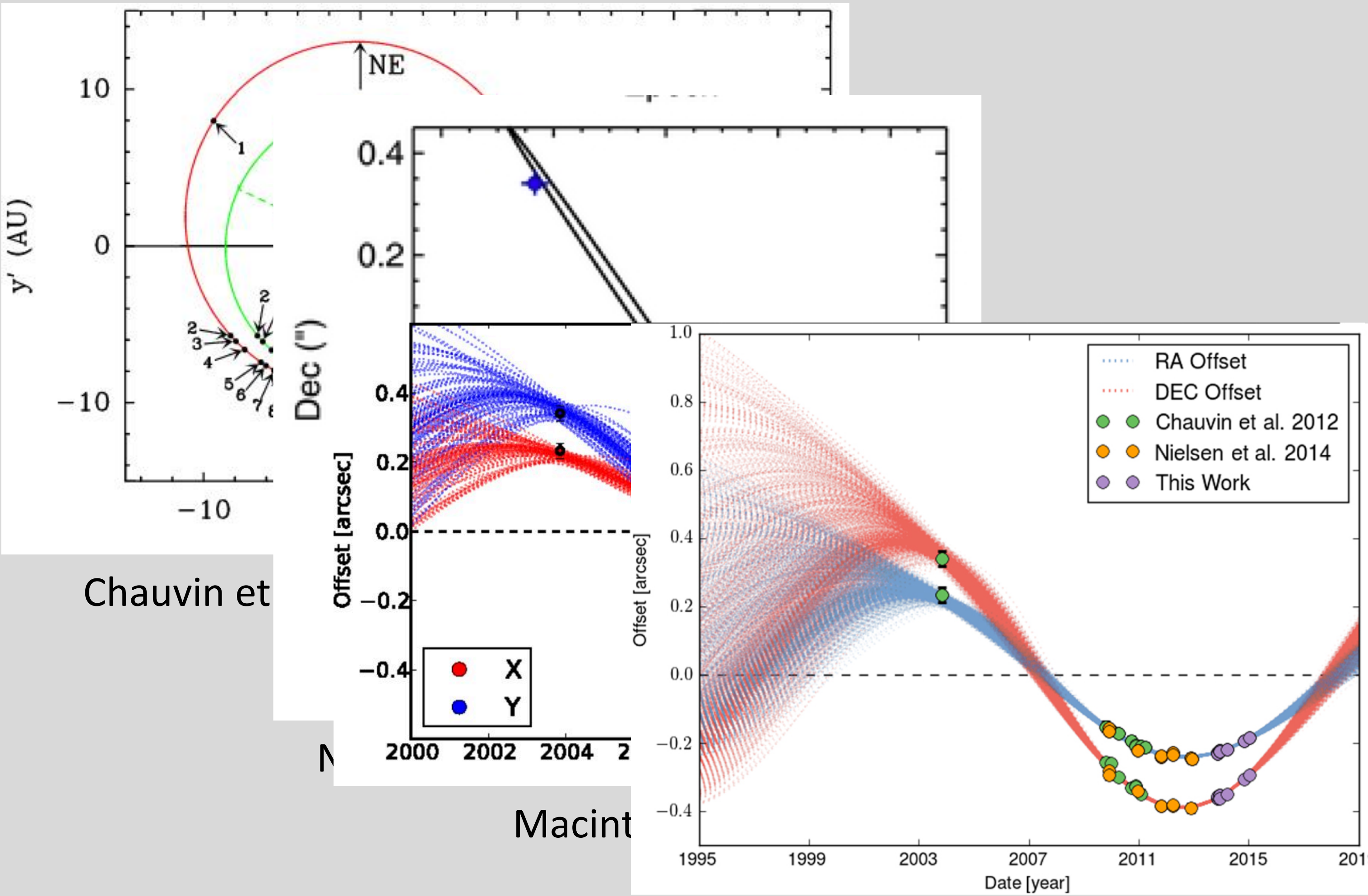


Chauvin et

N

Macintosh et al. 2014 – 4% transit probability

Orbital information can highlight when interesting events may occur in a system – e.g., the β Pic transit.



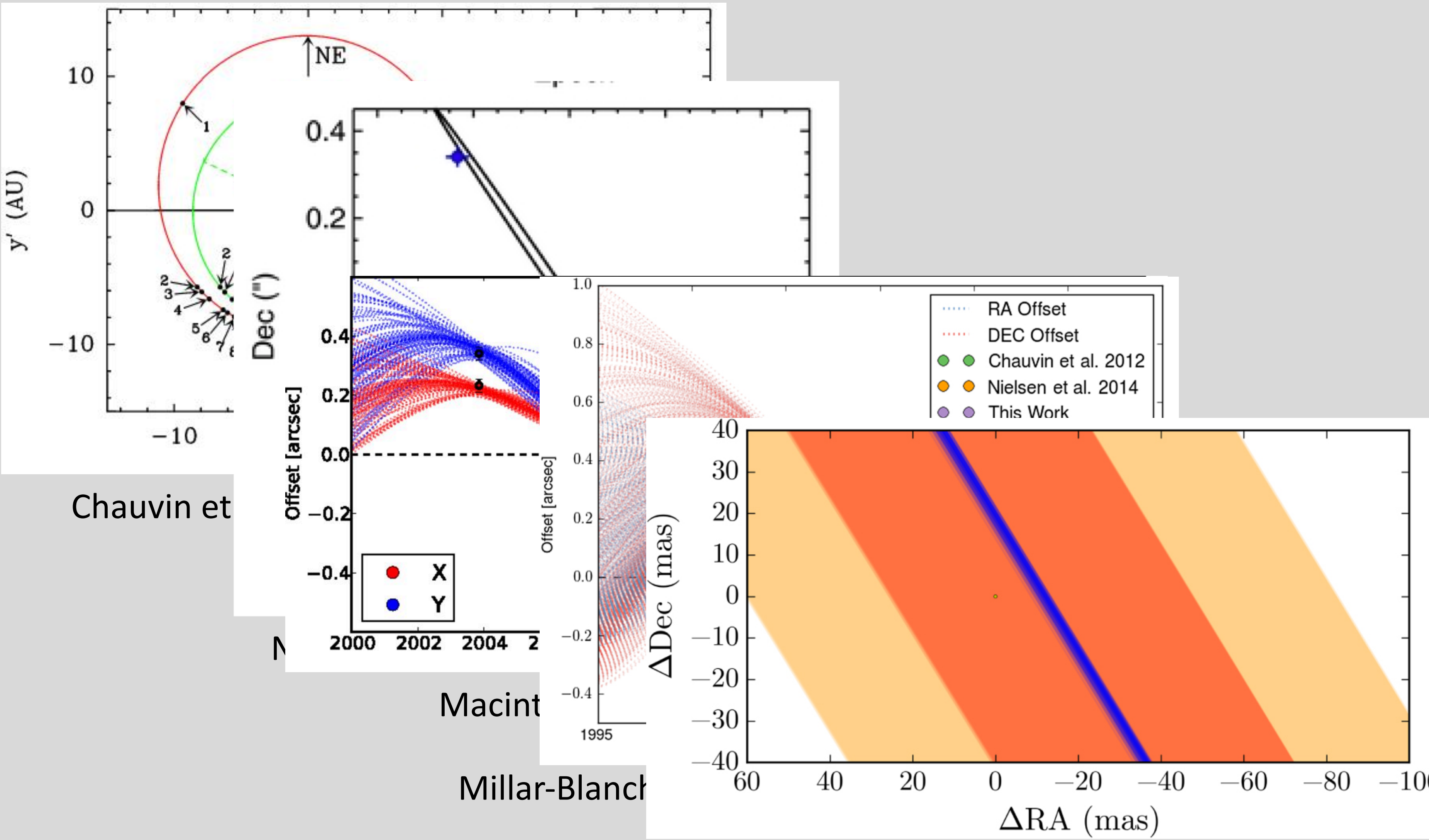
Chauvin et

N

Macint

Millar-Blanchaer et al. 2015 – 0.06% transit probability

Orbital information can highlight when interesting events may occur in a system – e.g., the β Pic transit.



Chauvin et

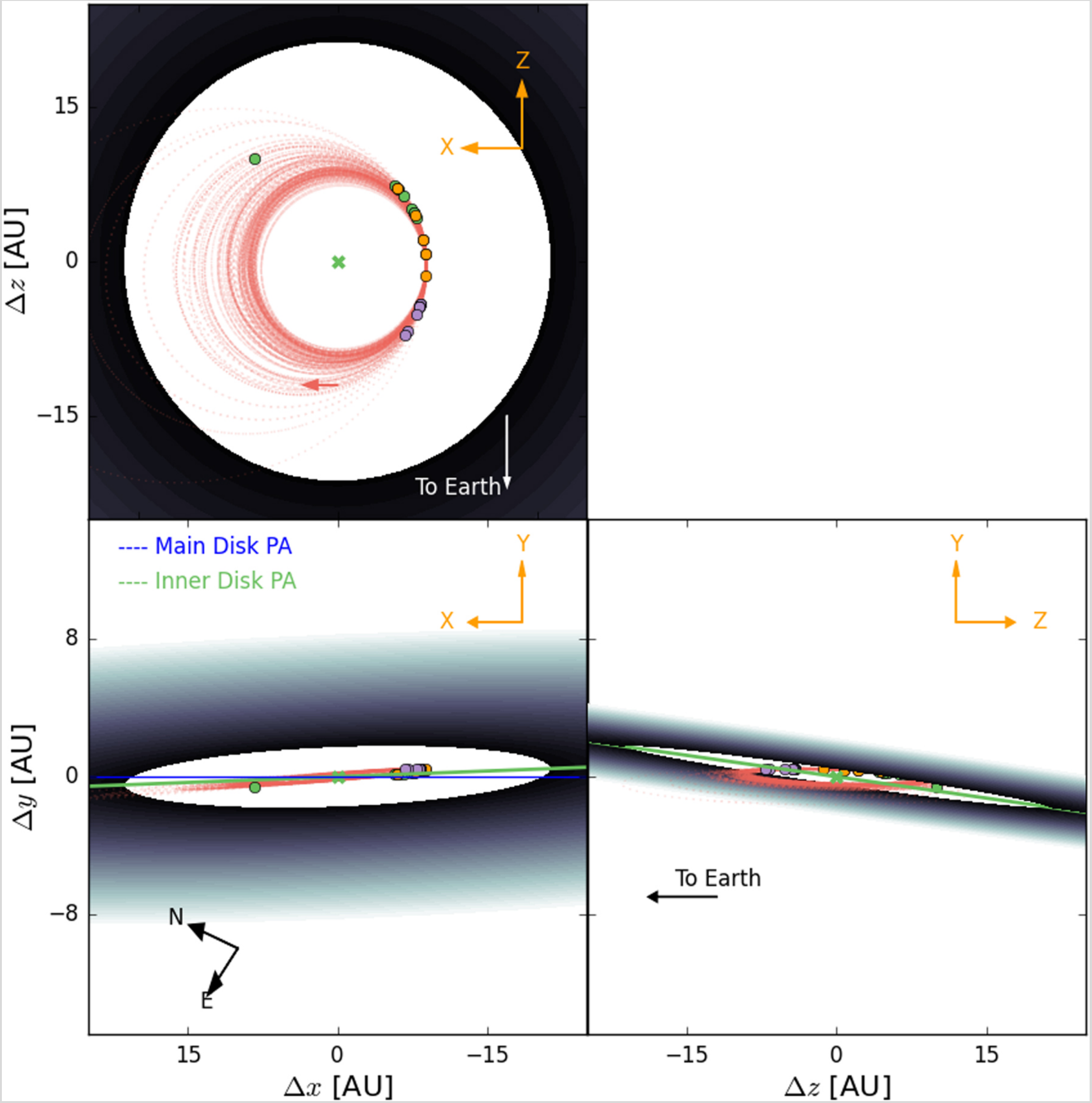
N

Macint

Millar-Blanch

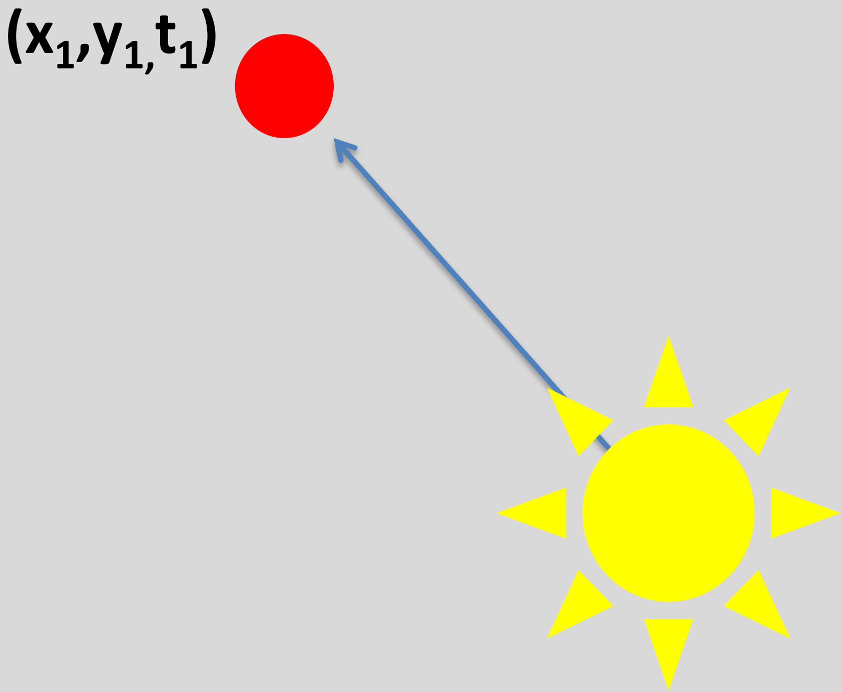
Wang et al. 2016 – Ruled out to 10 σ

Orbits can be compared with disk structure to illuminate the cause of the structure and probe formation outcomes.



Millar-Blanchaer et al. 2015

With direct imaging, what do we actually want to measure?



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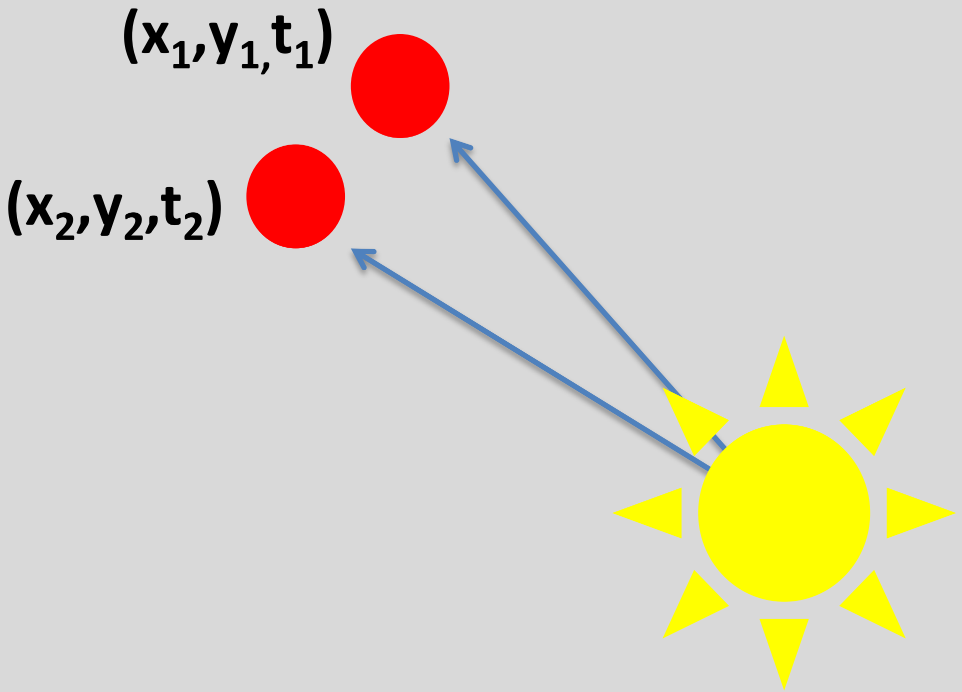

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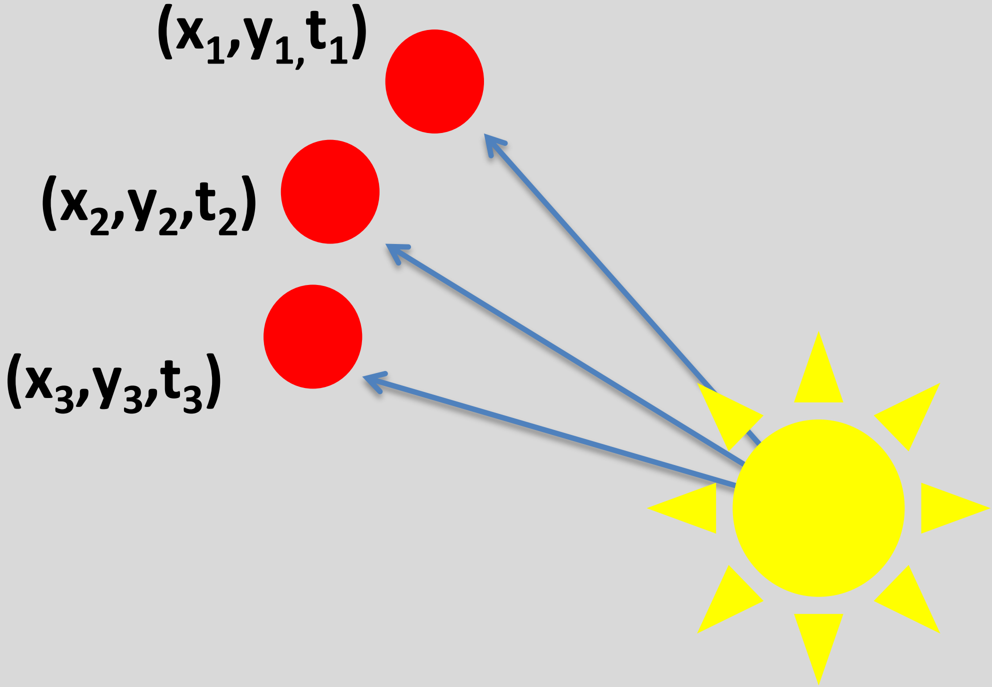
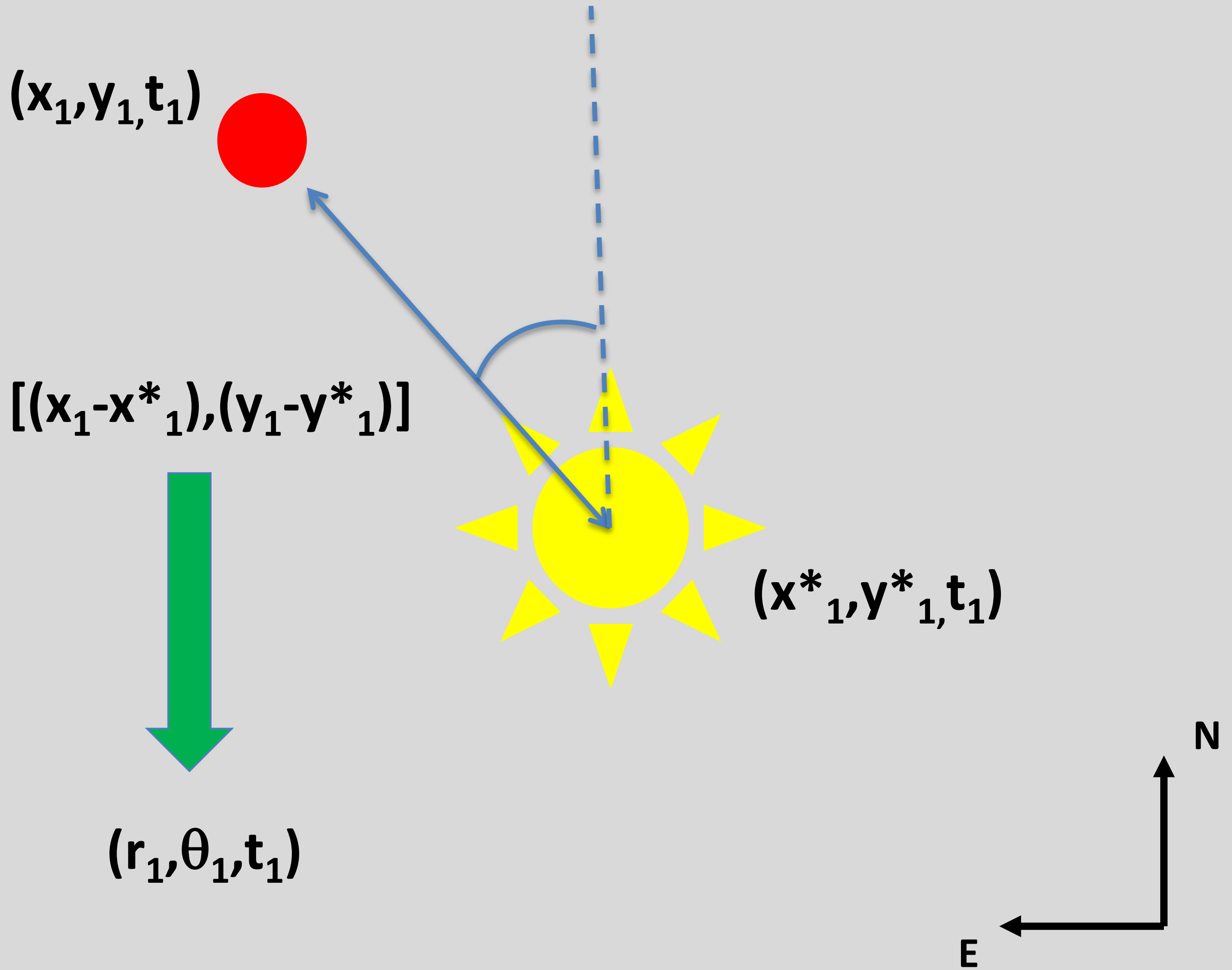
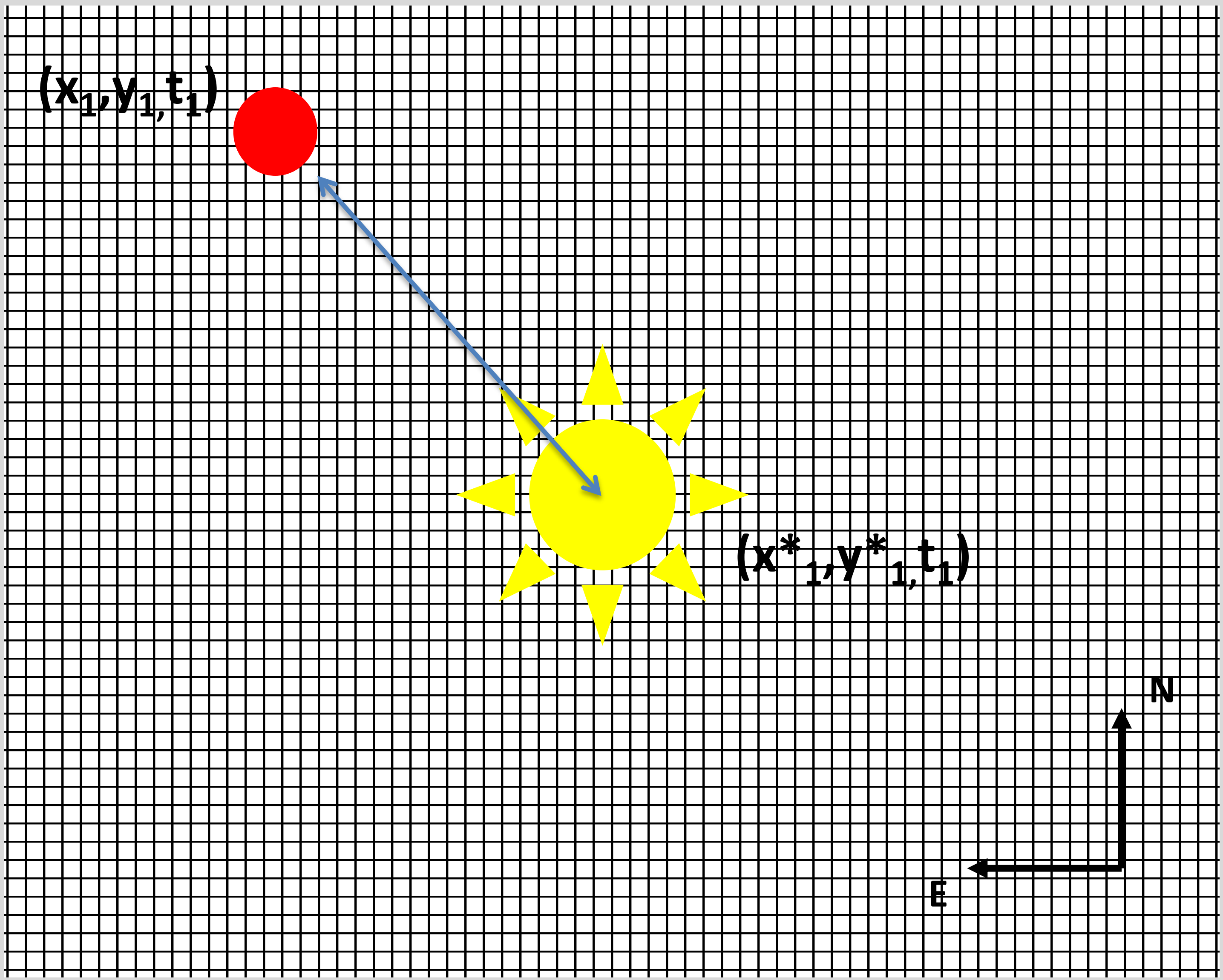


What are the challenges/limitations of performing these measurements?

As with visual binaries, we avoid reference frame requirements by performing *relative* astrometry.



Positional measurements require accurate estimation of the exact center of the two objects.



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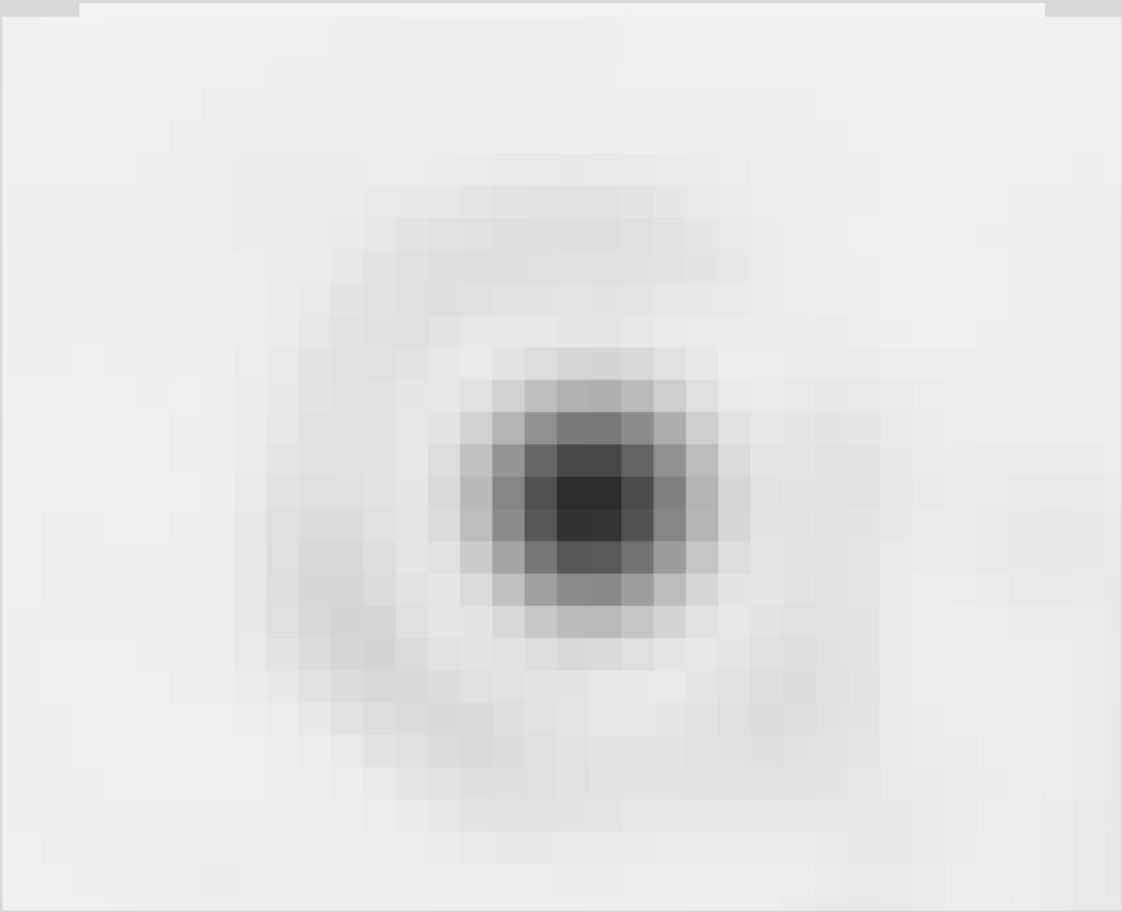
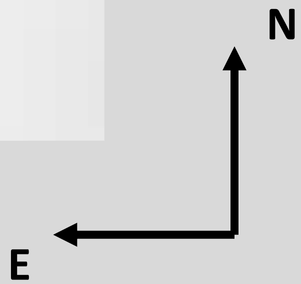


Triple system HD 205545, Keck NIRC2



There are theoretical predictions for astrometric precision.

$$\sigma \sim \frac{Full\ Width\ Half\ Max}{Signal\ to\ Noise\ Ratio}$$

e.g., Lindegren (1978), King (1983), Kaiser et al. (2000)

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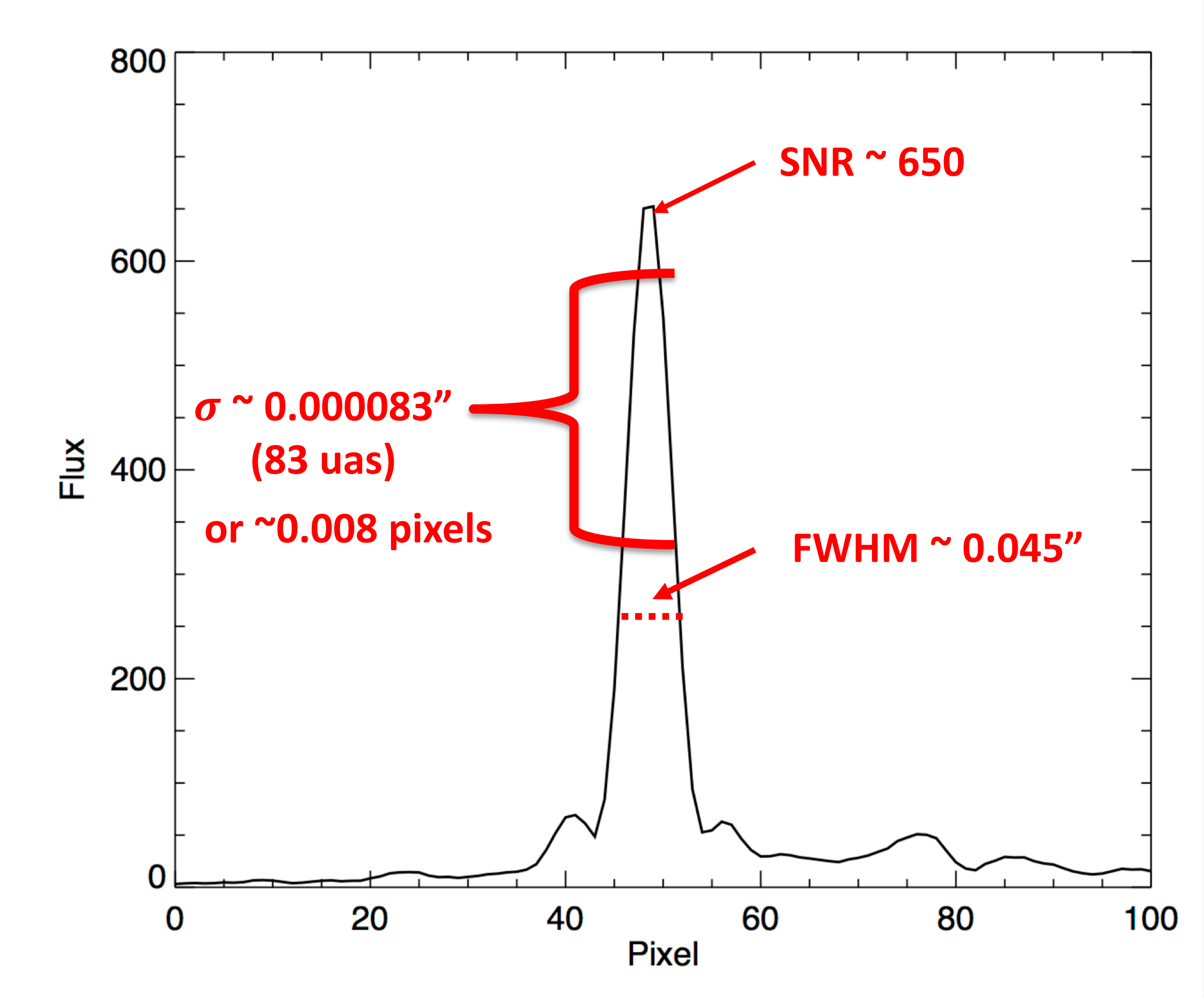

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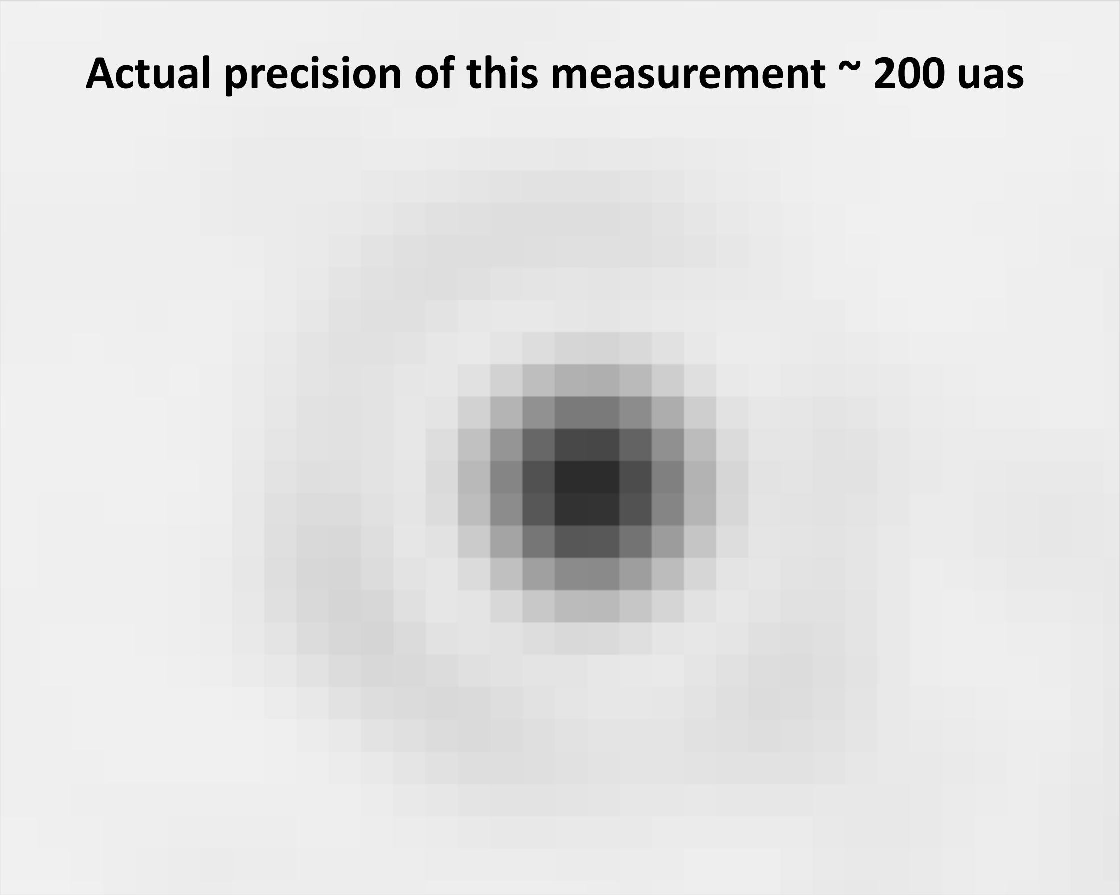
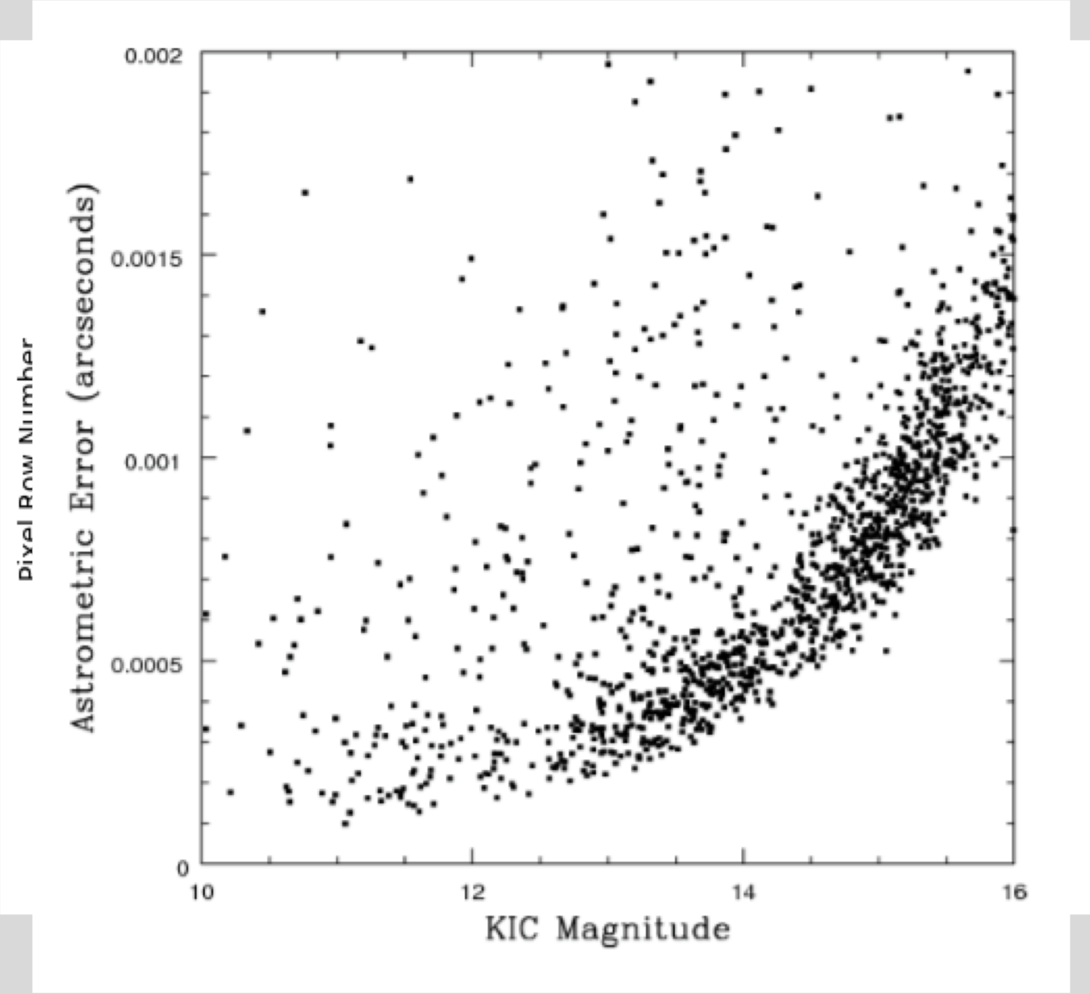


In practice, the theoretical limit is challenging to reach.

Side note – the dependence of precision on SNR generated some excitement about using Kepler data for astrometry.

lightkurve.keplerscience.org

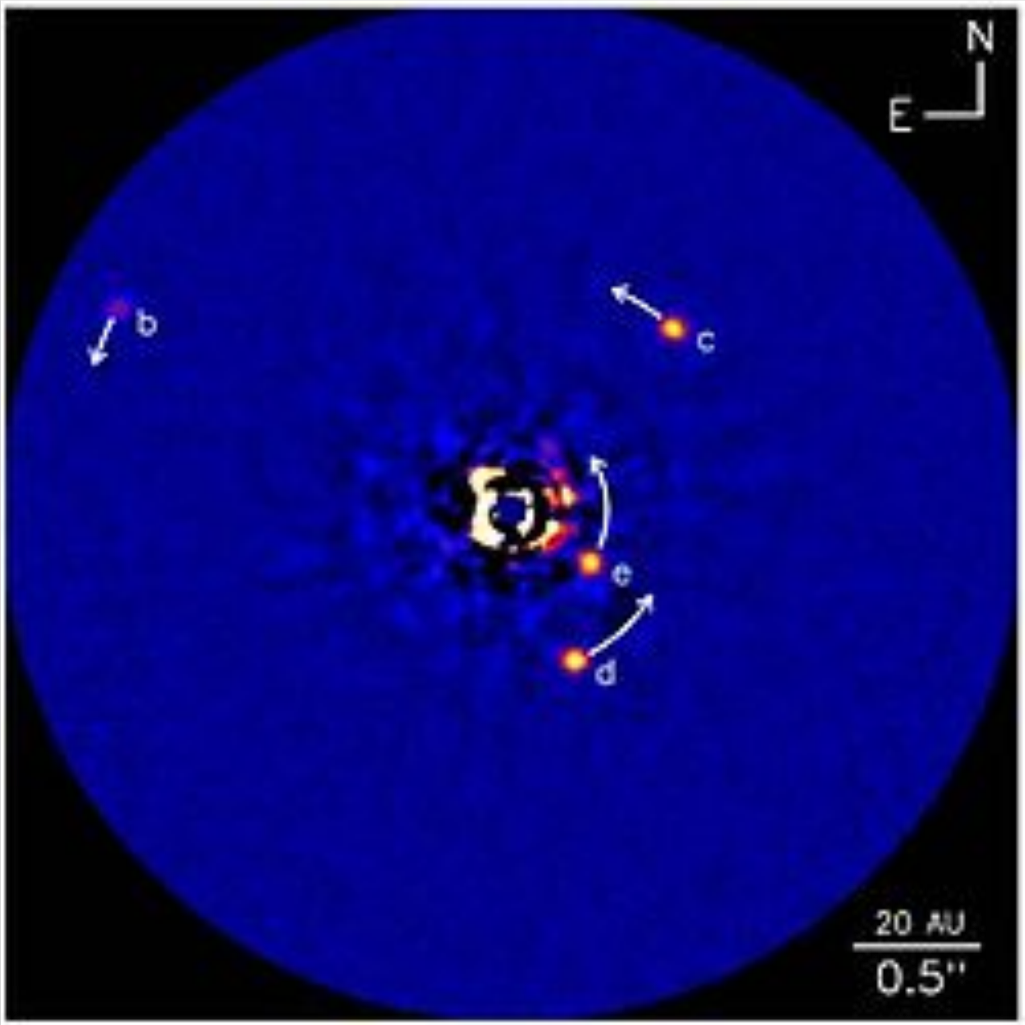


Monet et al. 2010

Undersampled pixels (3.98”), large FWHM (5-6”) but very high SNR (>10,000)

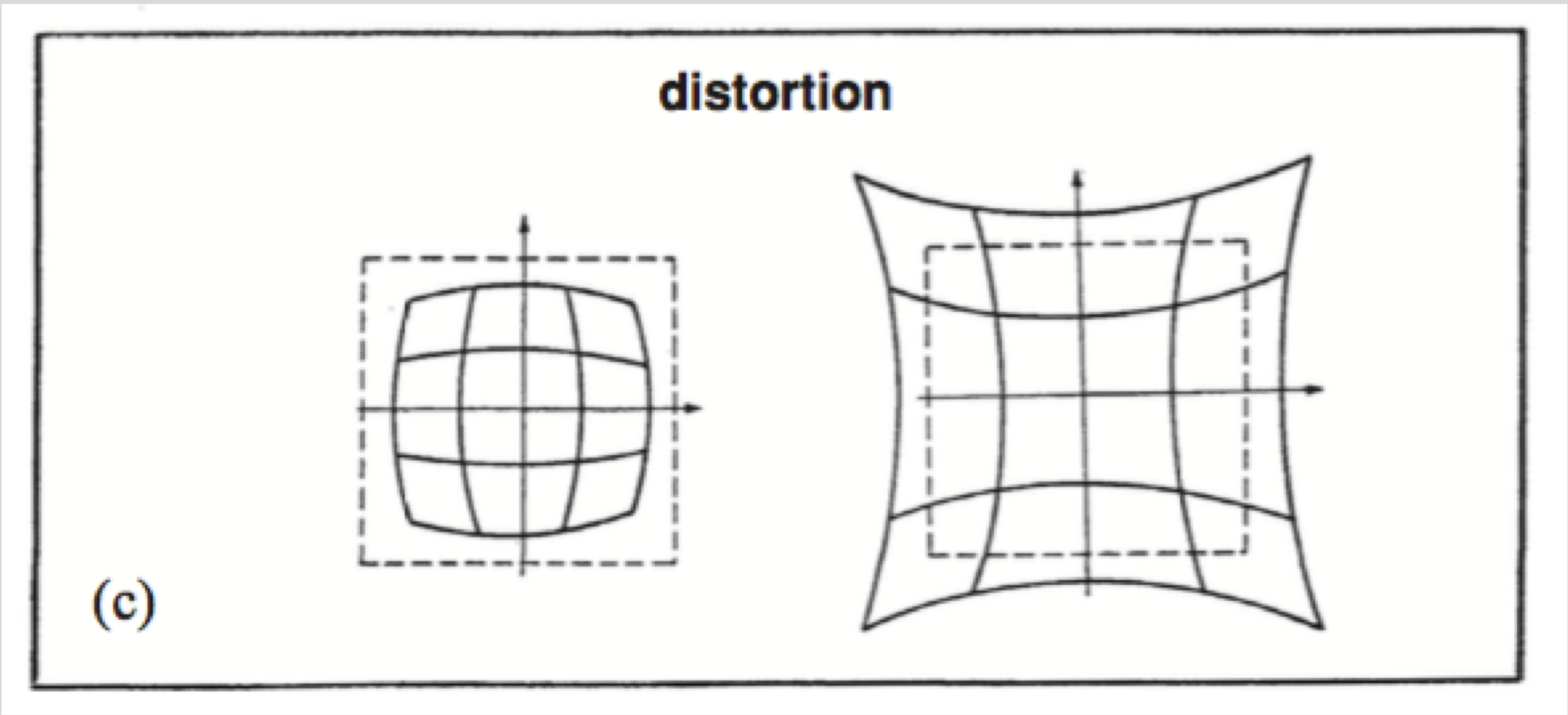
Precision as good as 0.0001 pixels implied

Let's go through some of the sources of astrometric error for direct imaging.



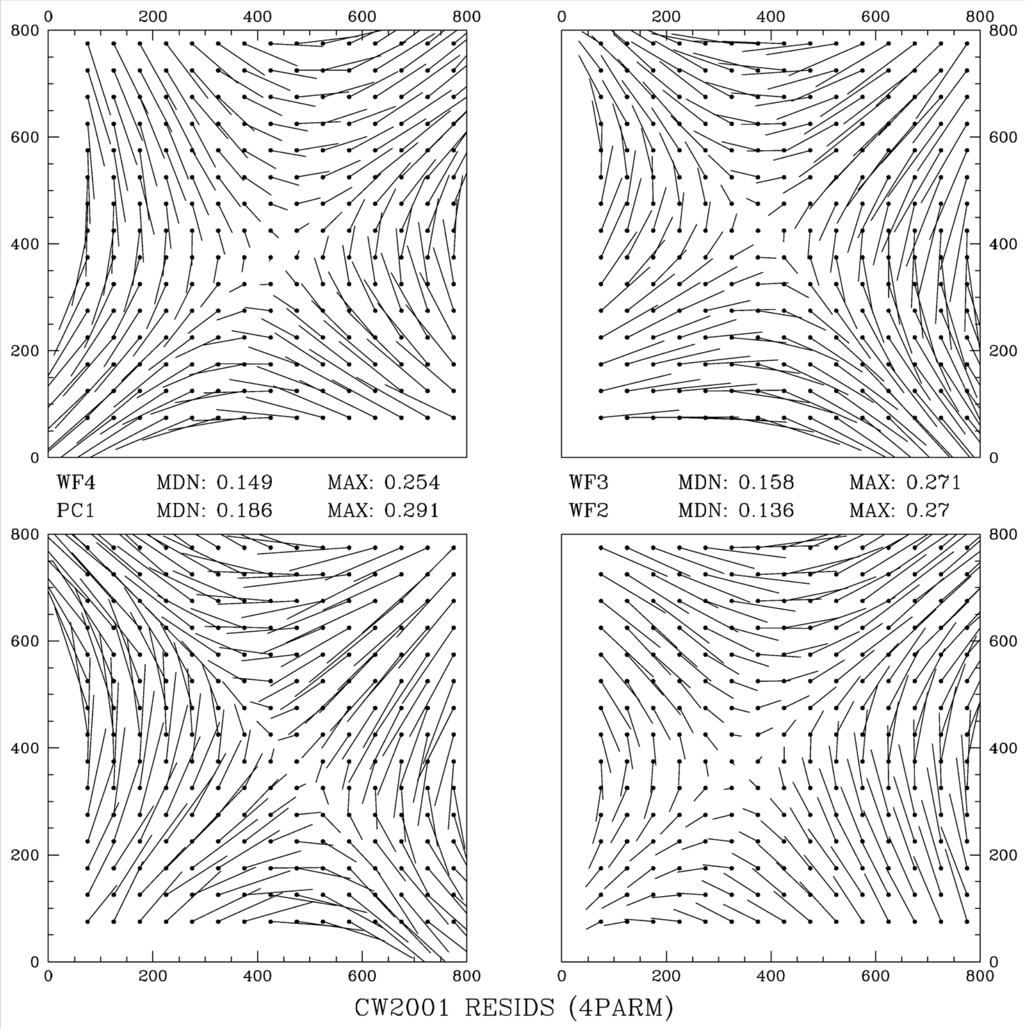
HR 8799
Marois et al. 2010

One of the first sources of uncertainty to deal with is distortion.



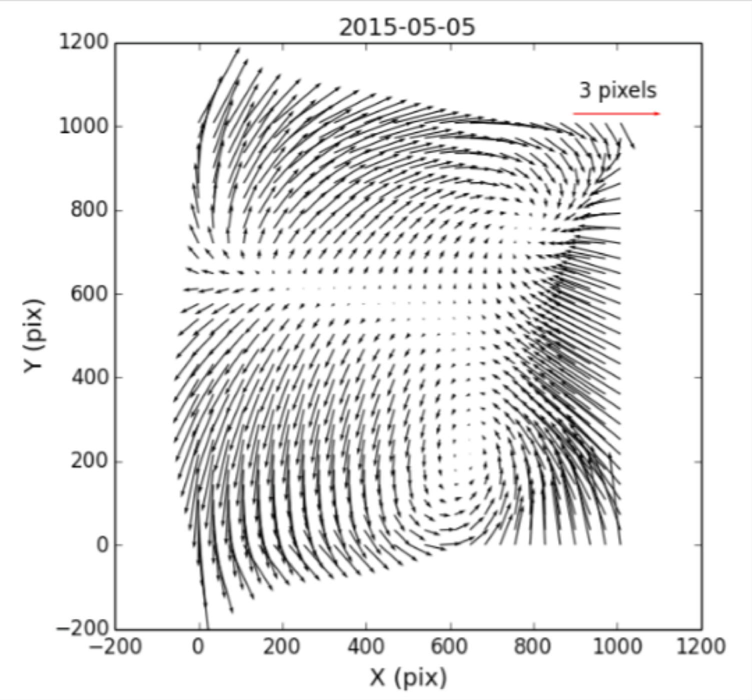
Resource: Astronomical Optics by Schroeder

Optical aberrations in a telescope/camera can "move" the centroid of a star by a small amount up to 10s of milliarcseconds.

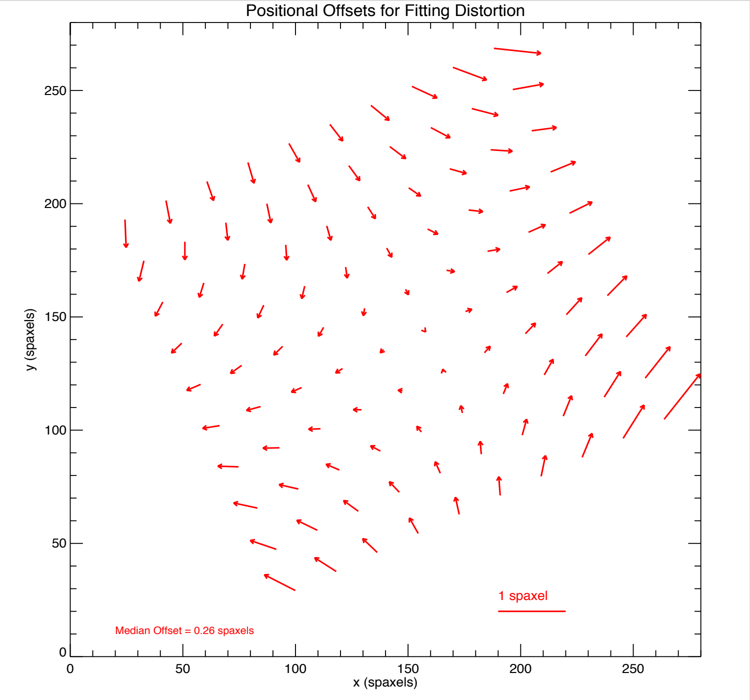


HST WFPC2, Anderson & King 2003

Optical aberrations in a telescope/camera can "move" the centroid of a star by a small amount up to 10s of milliarcseconds.



NIRC2, Service et al. 2016



GPI, Konopacky et al. 2014

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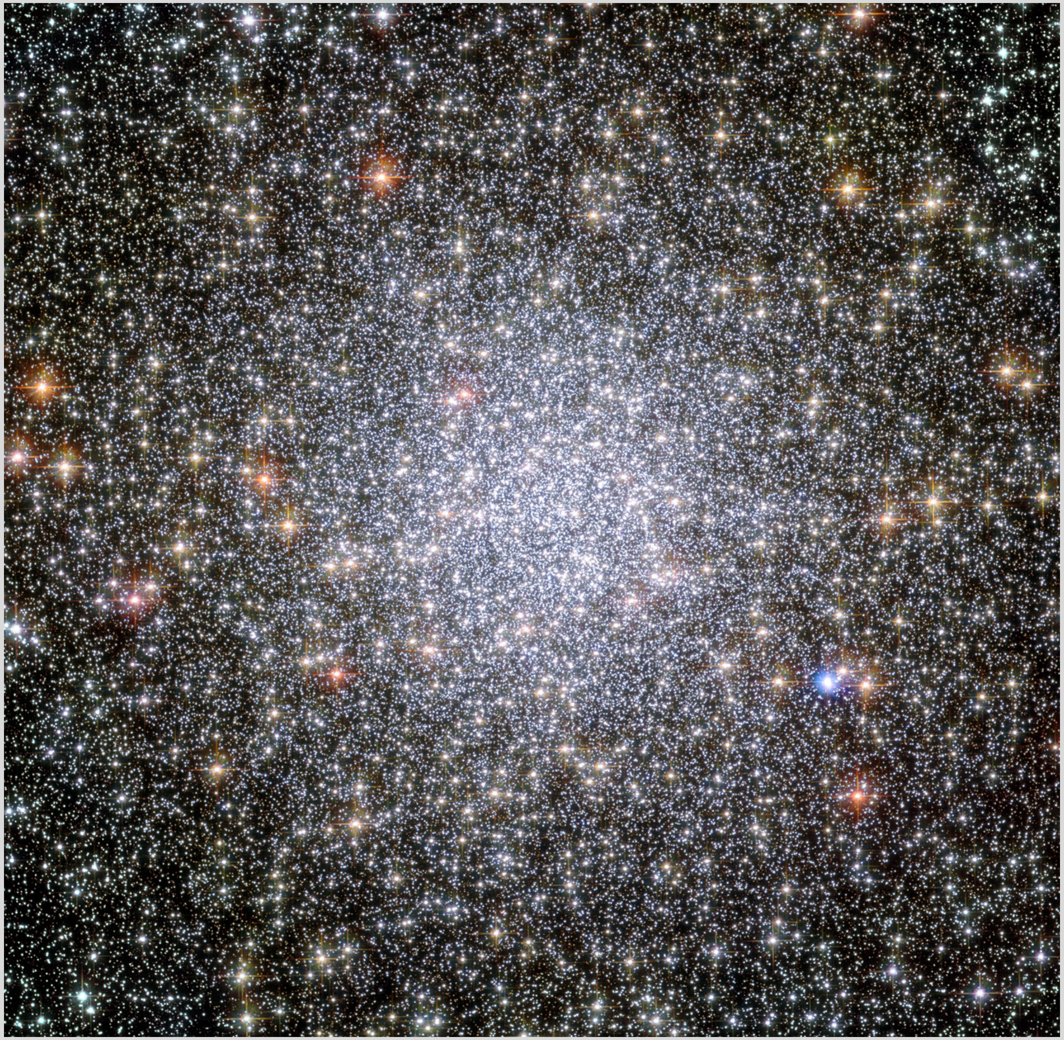
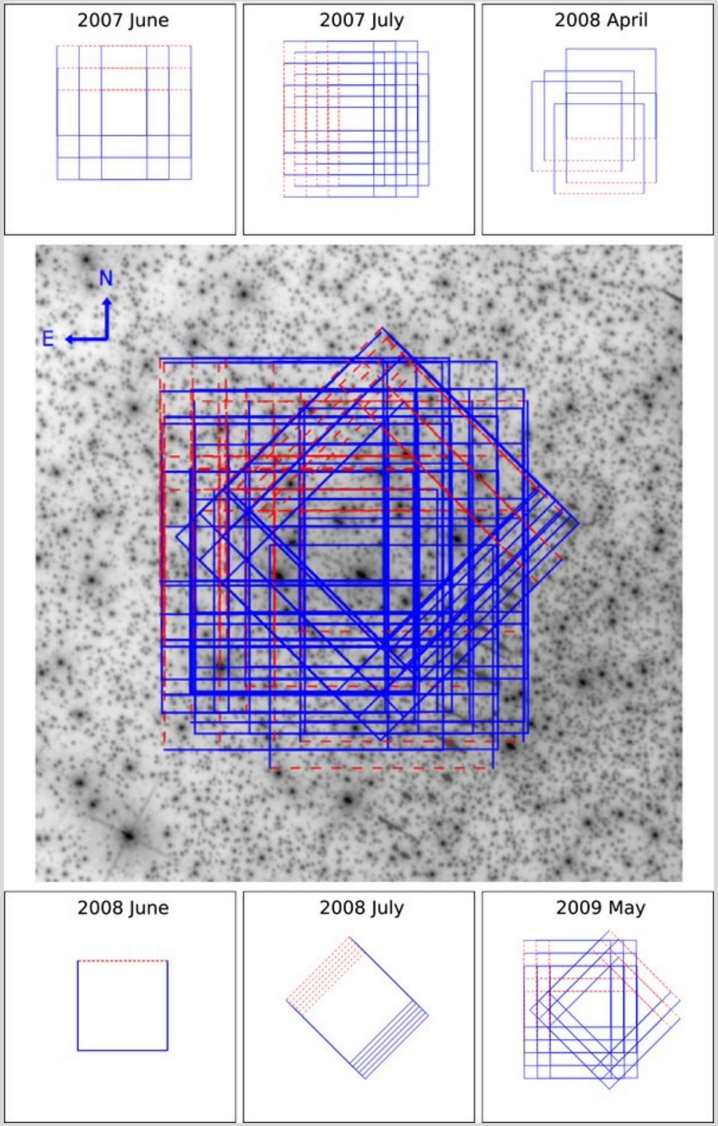
Distortion pattern is typically measured using a dense field of stars (or simulated stars).



For HST solutions, use a globular cluster like 47 Tucanae (Anderson & King 2003)

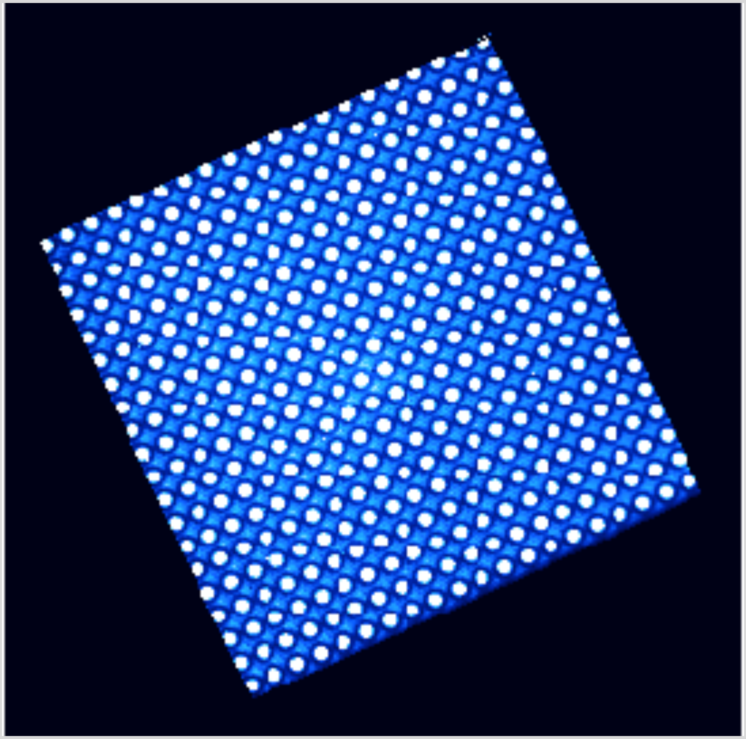
Credit: NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration
Acknowledgment: J. Mack (STScI) and G. Piotto (University of Padova, Italy)

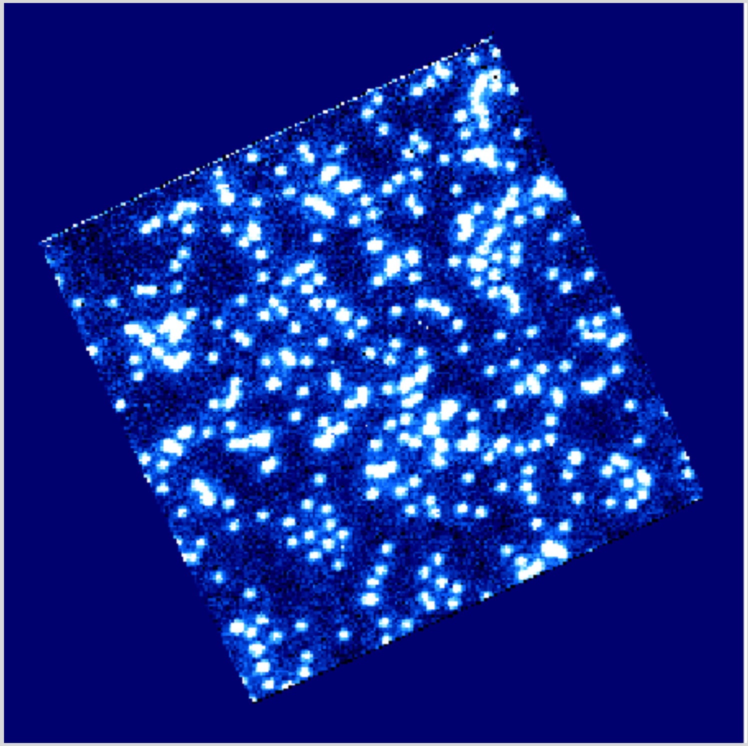
Distortion pattern is typically measured using a dense field of stars (or simulated stars).



For NIRC2 solutions, use a globular cluster M92 (Yelda et al. 2010)

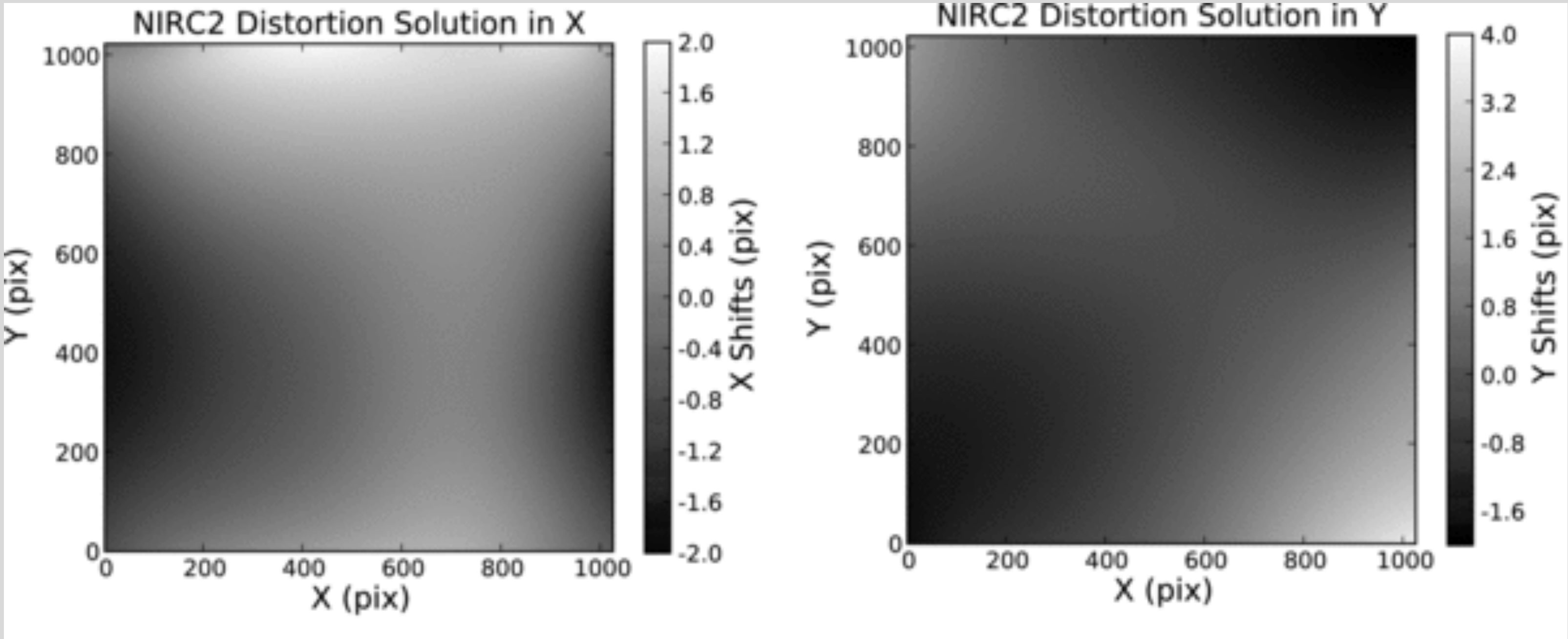
Distortion pattern is typically measured using a dense field of stars (or simulated stars).





For GPI solutions, use a pinhole mask (Konopacky et al. 2014)

Fitting residual maps with polynomial or spline surfaces allow you to correct for shifted pixels.



Bivariate B-spline, NIRC2, Yelda et al. 2010

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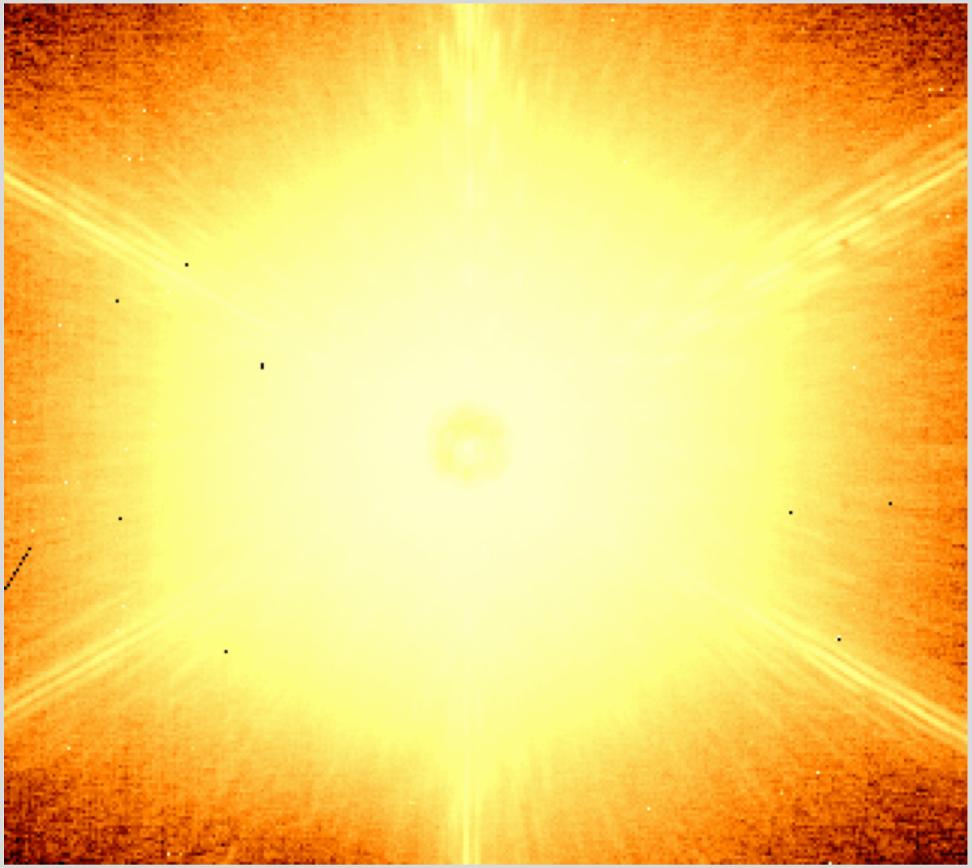
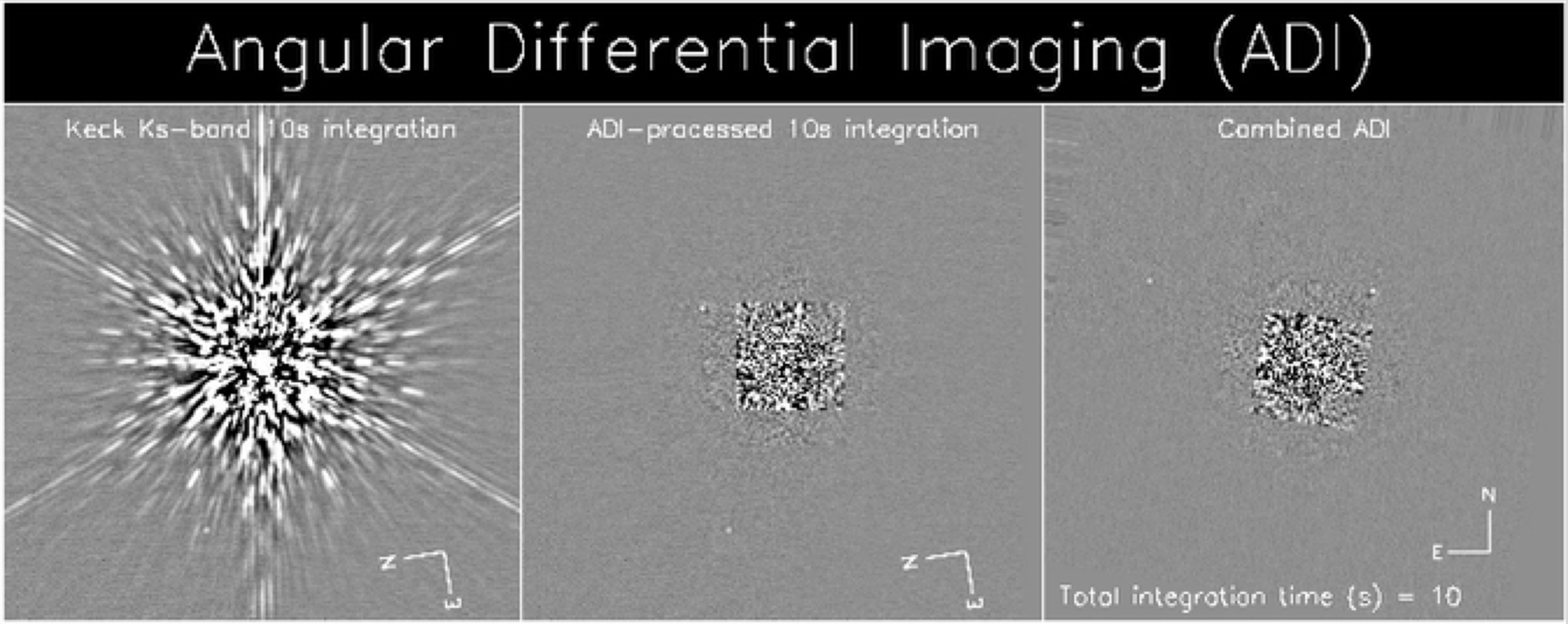
So now your data is reduced and corrected for distortion – next comes starlight removal (PSF subtraction).

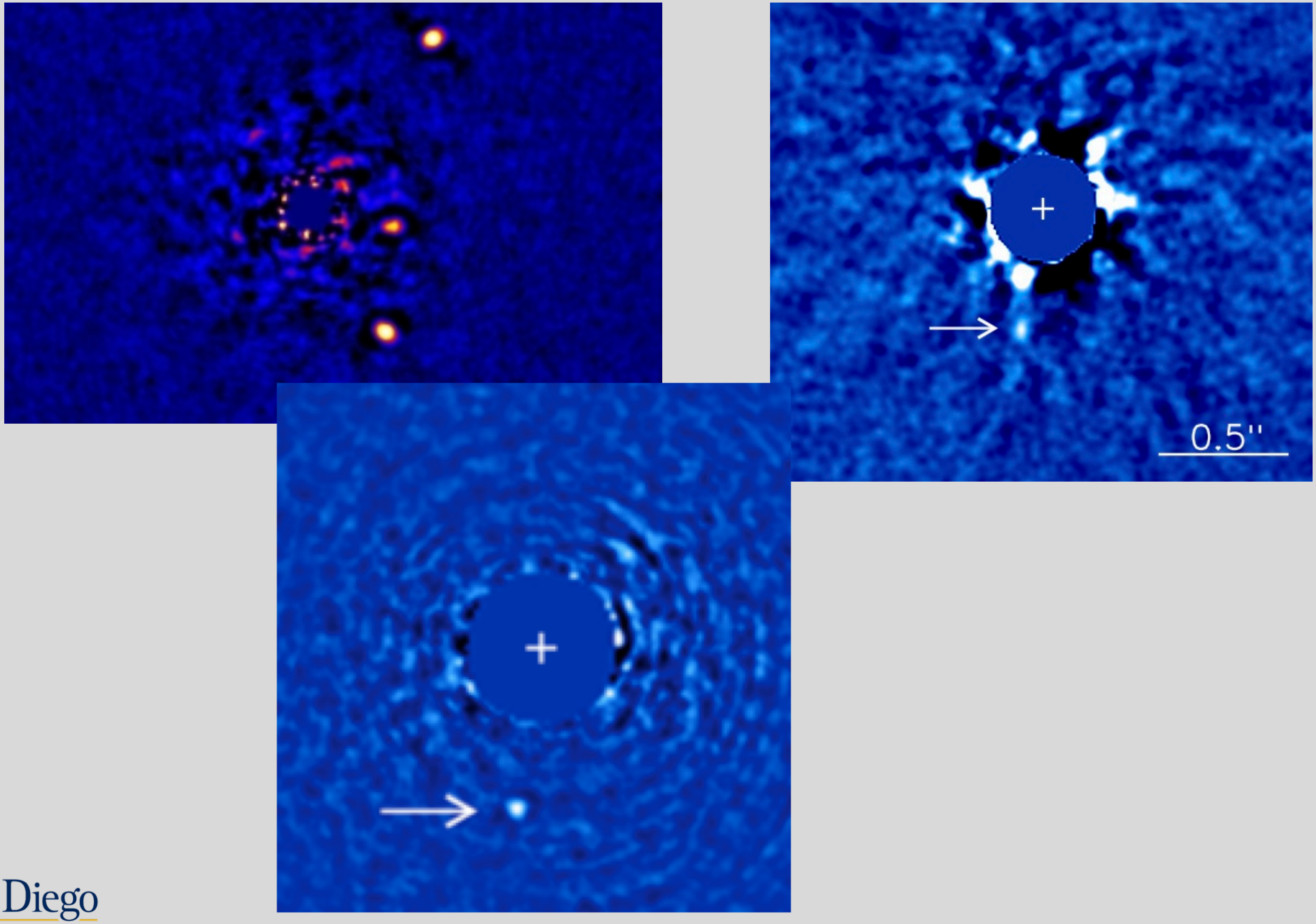


Unprocessed data on HR 8799 from NIRC2 – 600 mas coronagraphic spot used

Angular differential imaging and LOCI/KLIP PSF subtraction are powerful techniques, but can introduce astrometric biases.



Depending on choice of subtraction techniques, the planet PSF can be strongly impacted.



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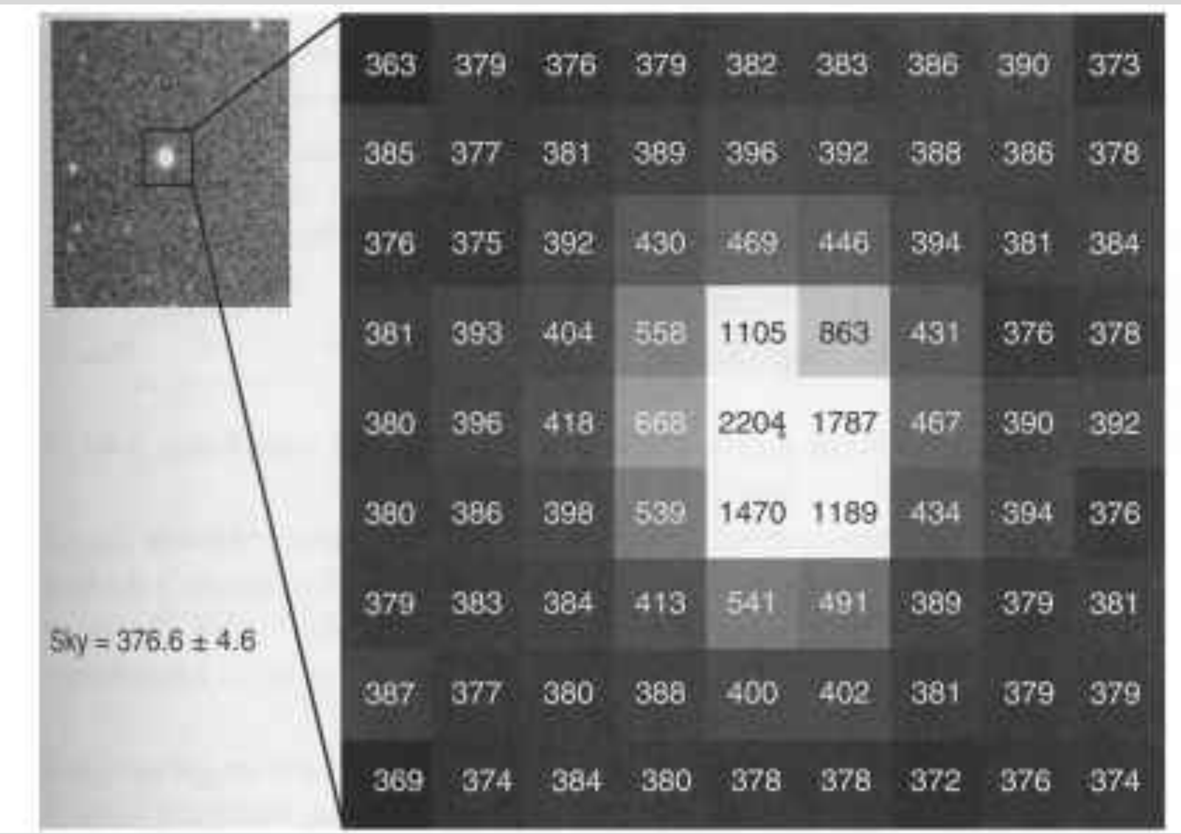
Straightforward centroid calculations can be biased by PSF structure.

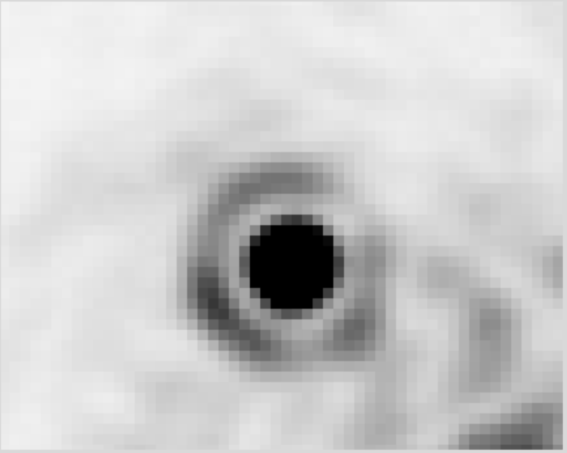


astronomyclub.xyz

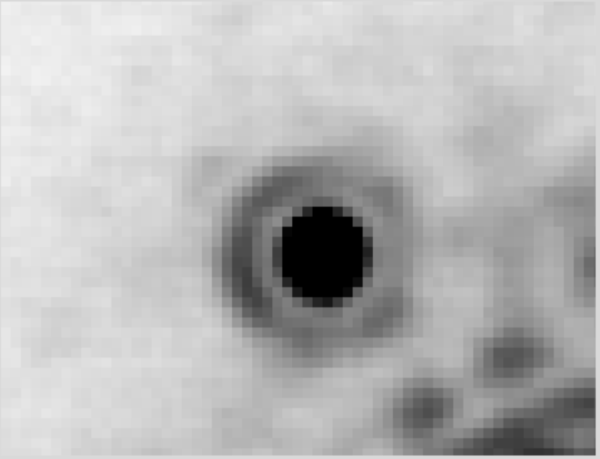
$$\hat{x} = \frac{\sum x I_{x,y}}{\sum I_{x,y}}$$

$$\hat{y} = \frac{\sum y I_{x,y}}{\sum I_{x,y}}$$

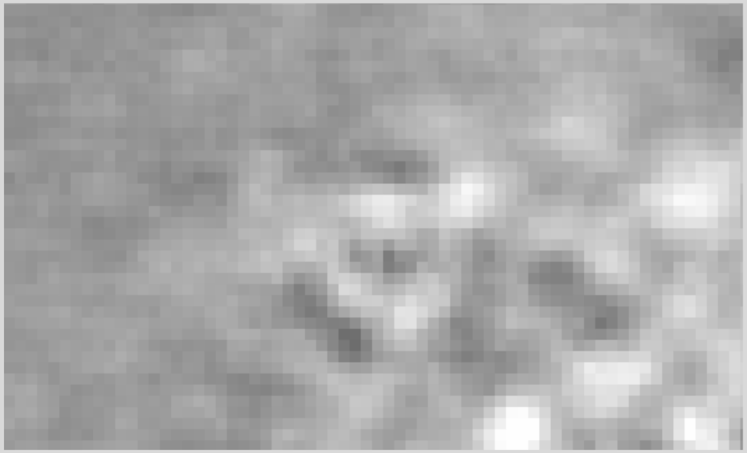
PSF fitting tends to give the most precise results.



Data



Model (measured PSF)



Data – Model (residuals)

Keck NIRC2

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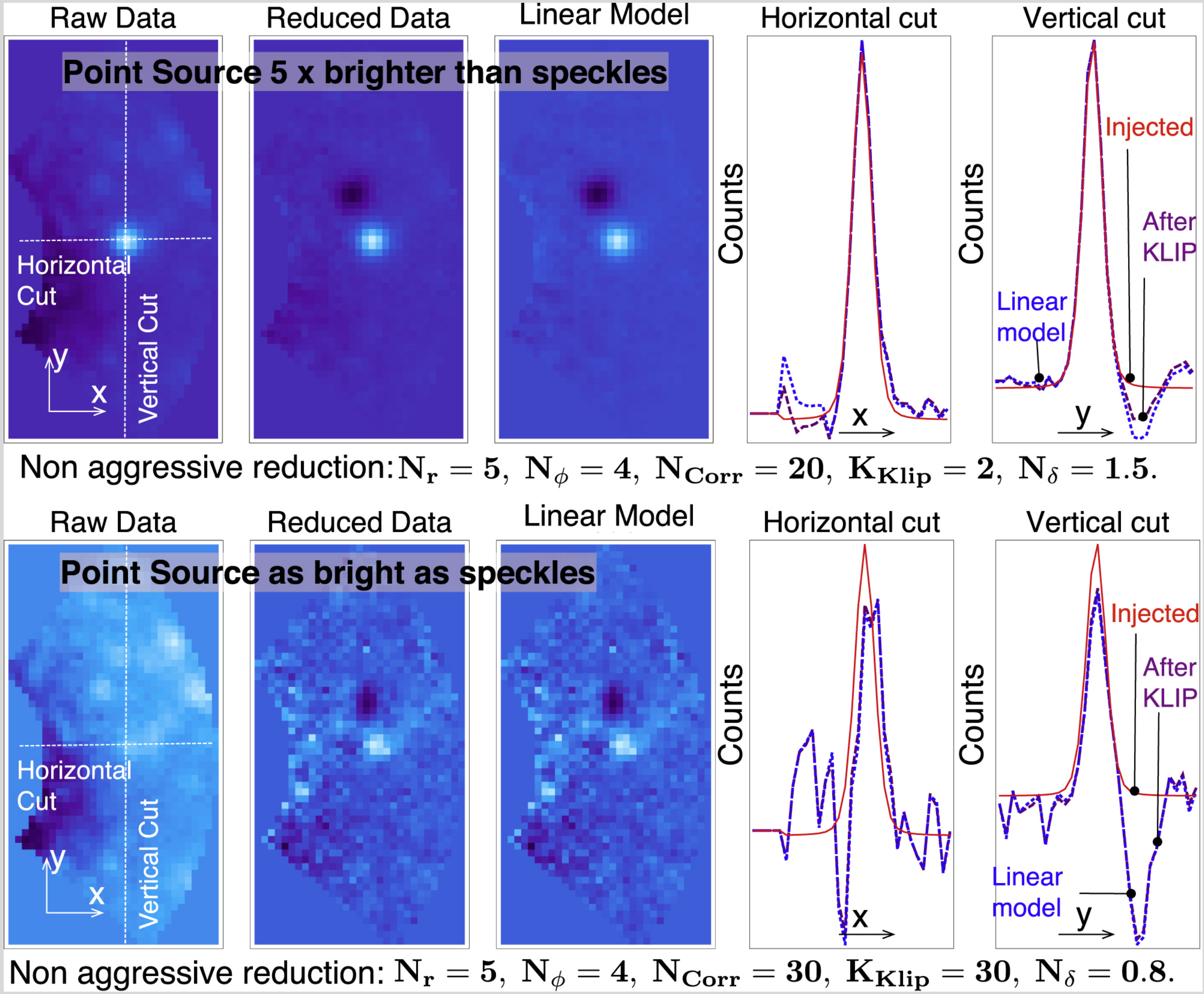
Providing an accurate PSF model for a "speckle subtracted" image is yielding excellent results.



Pueyo 2016

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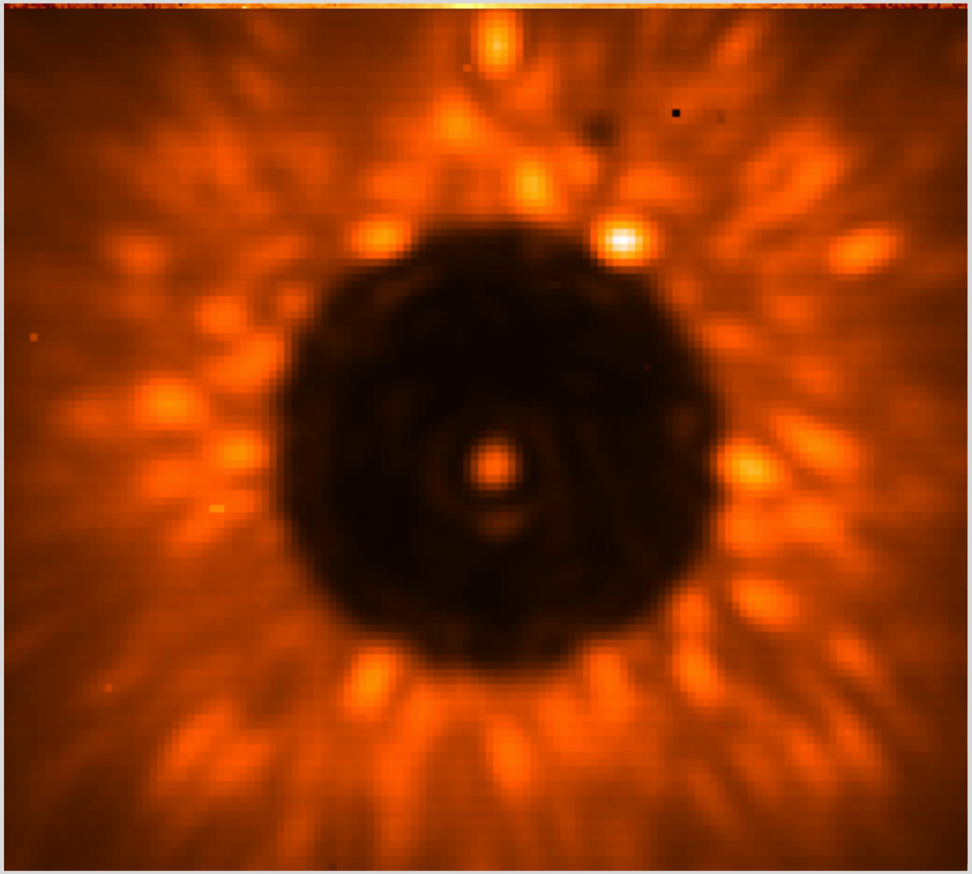
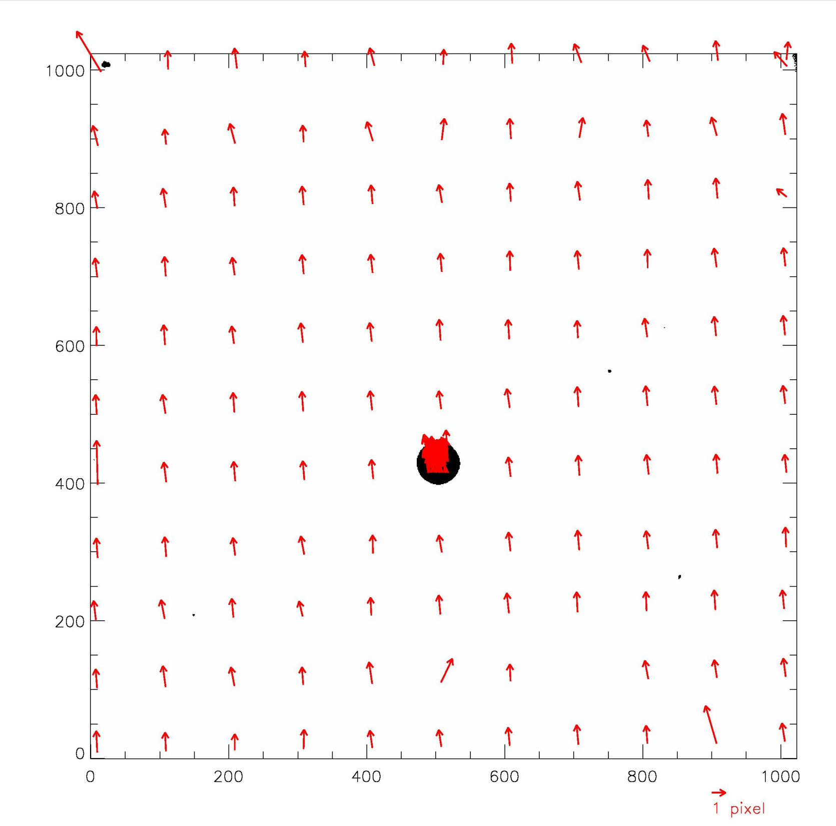
So now we can find the positions of our planets – but what about the star??

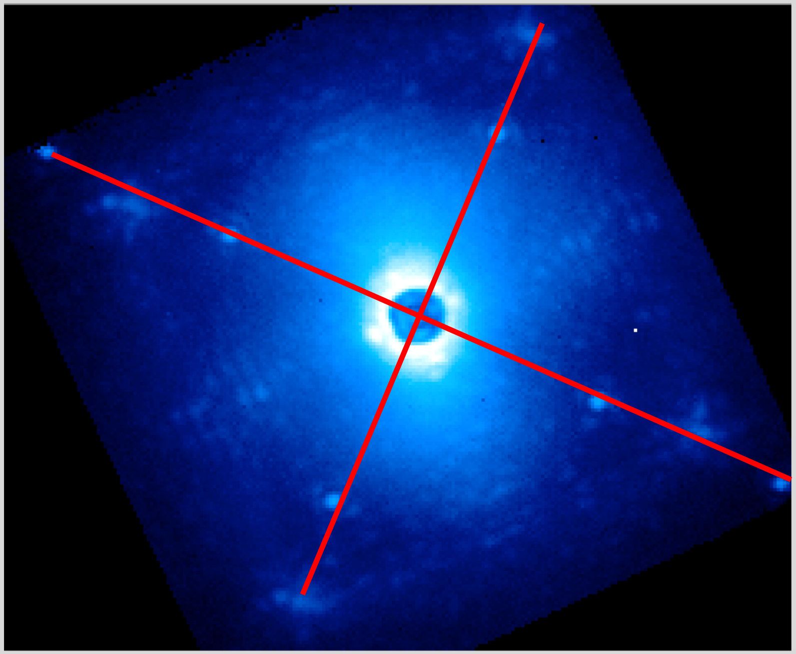


Sometimes your good fortune isn't as good as you thought it was…

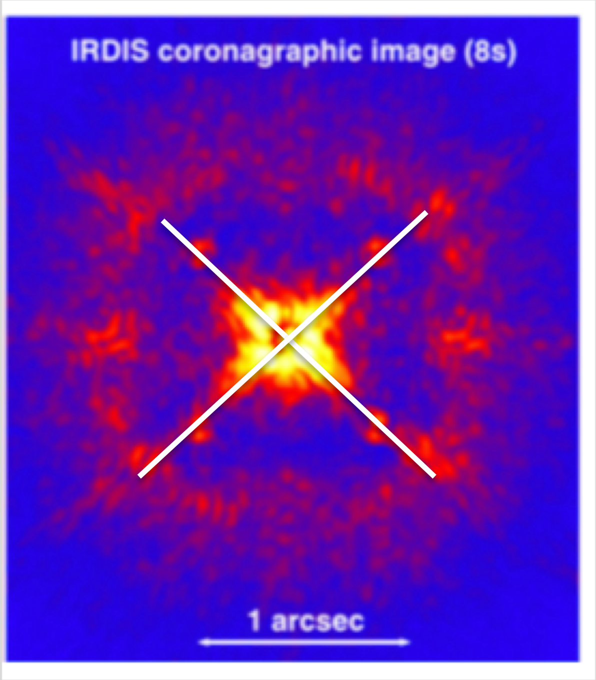


Calibration map showing the direction of the "flow" caused by the NIRC2 focal plane mask. Arrow size is different under the spot.

Newer instruments have other methods for locating the star.



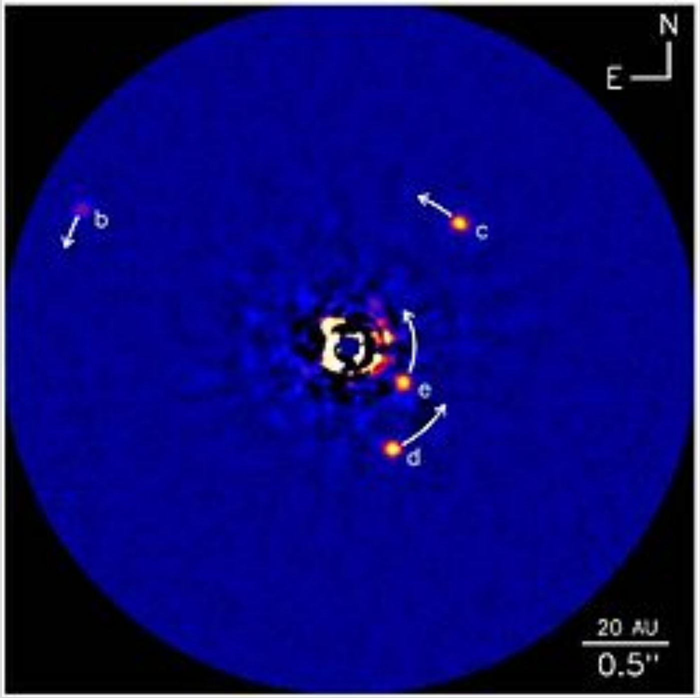
GPI “Satellite Spots” from apodizer grid
Macintosh et al. 2014



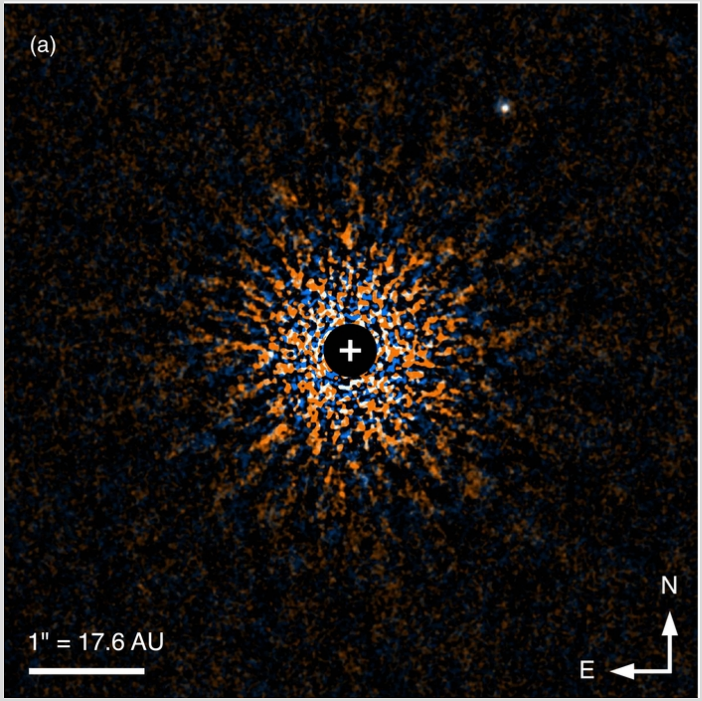
SPHERE DM Waffle Pattern
Milli et al. 2018

So what is the current astrometric precision for directly imaged planets?

Direct imaging precision is still at the milliarcsecond level.



HR8799 with NIRC2, ~3 – 20 mas,
Marois et al. 2010,
Konopacky et al. 2016



GJ 504b with Subaru/HiCIAO, ~8 – 20 mas,
Kuzuhara et al. 2013

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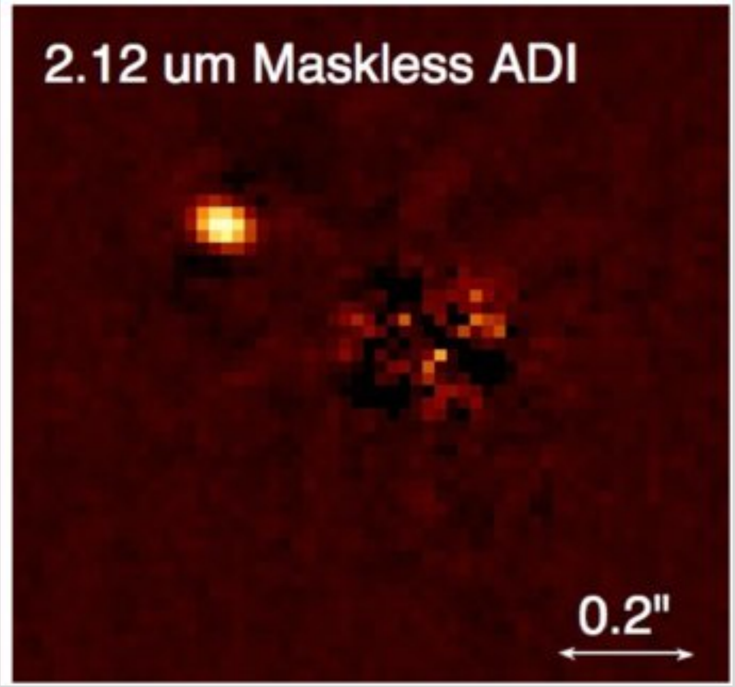
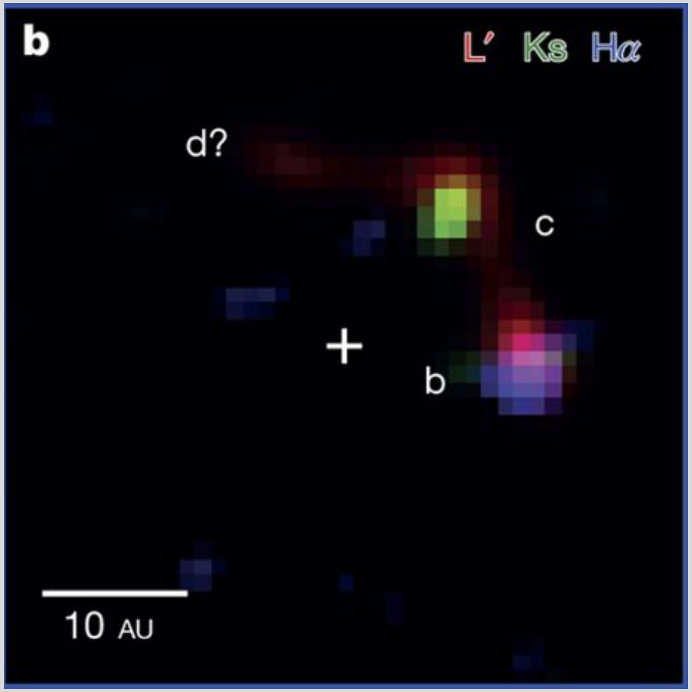
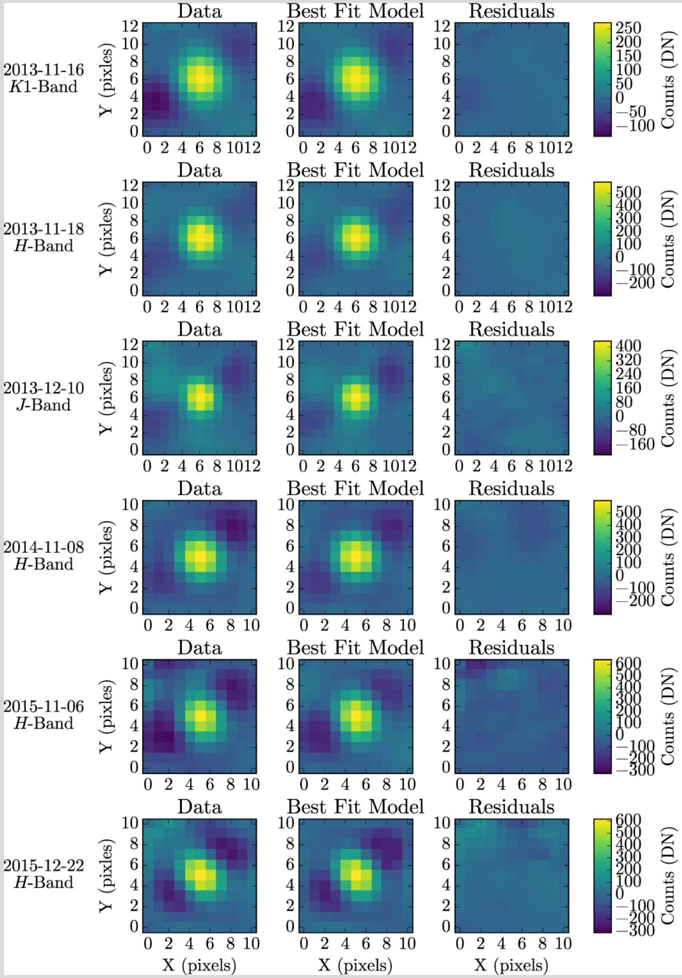


PZ Tel with NICI, 3-10 mas,
Biller et al. 2010

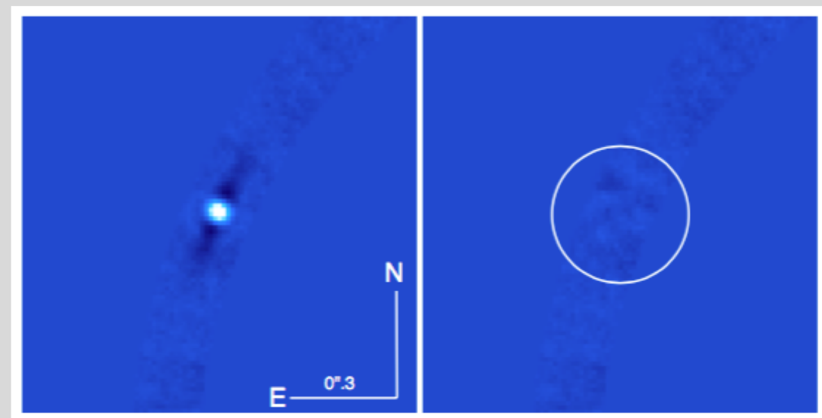


LkCA 15 with MagAO, 8mas,
Sallum et al. 2015

Some studies have approached the 1 mas precision mark.

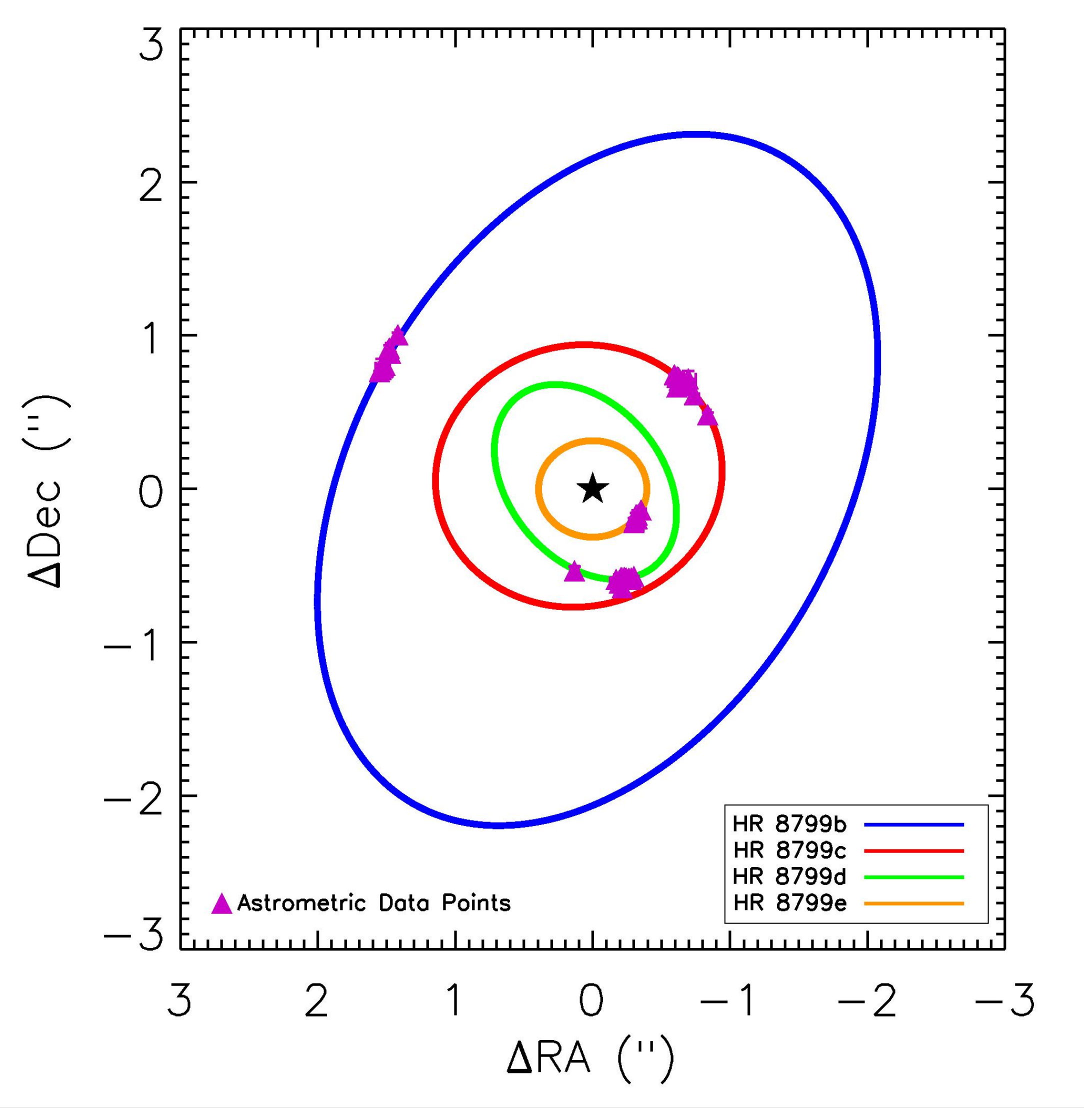


βPic b with GPI, ~1 mas
Wang et al. 2016



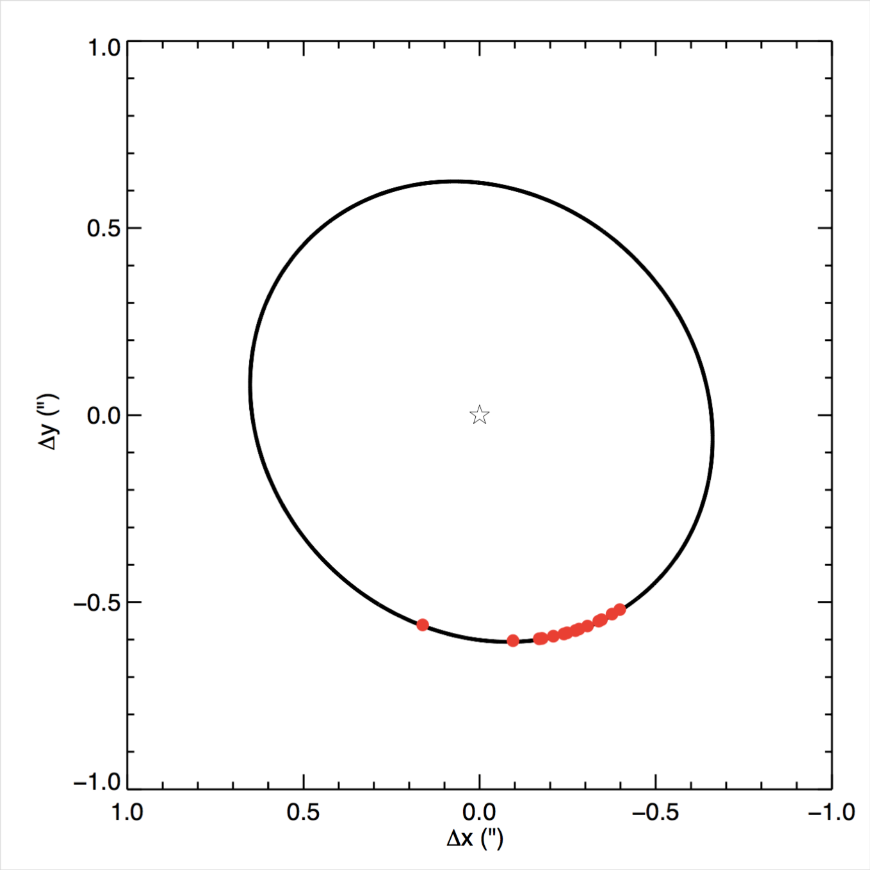
HR 8799bcde with SPHERE, ~2 mas
Wertz et al. 2016

Once we get better precision on our astrometry, we need to think carefully about how we combine datasets.



Zurlo et al. 2016

Fitting undersampled orbits with systematics in astrometry can lead to biased results.



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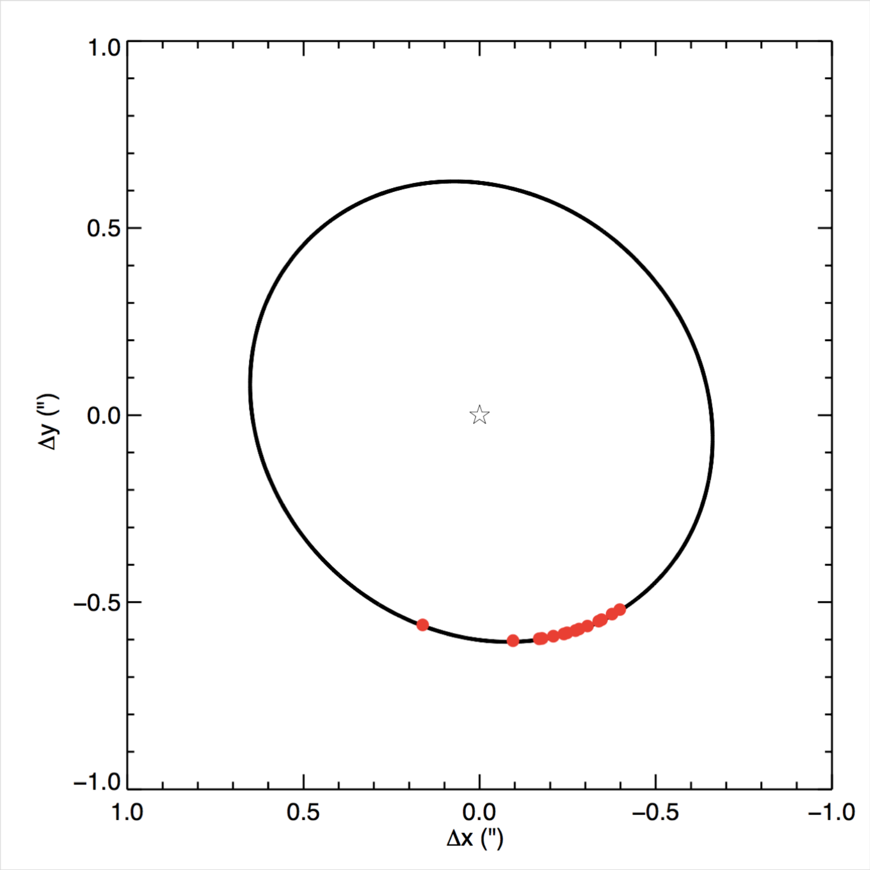

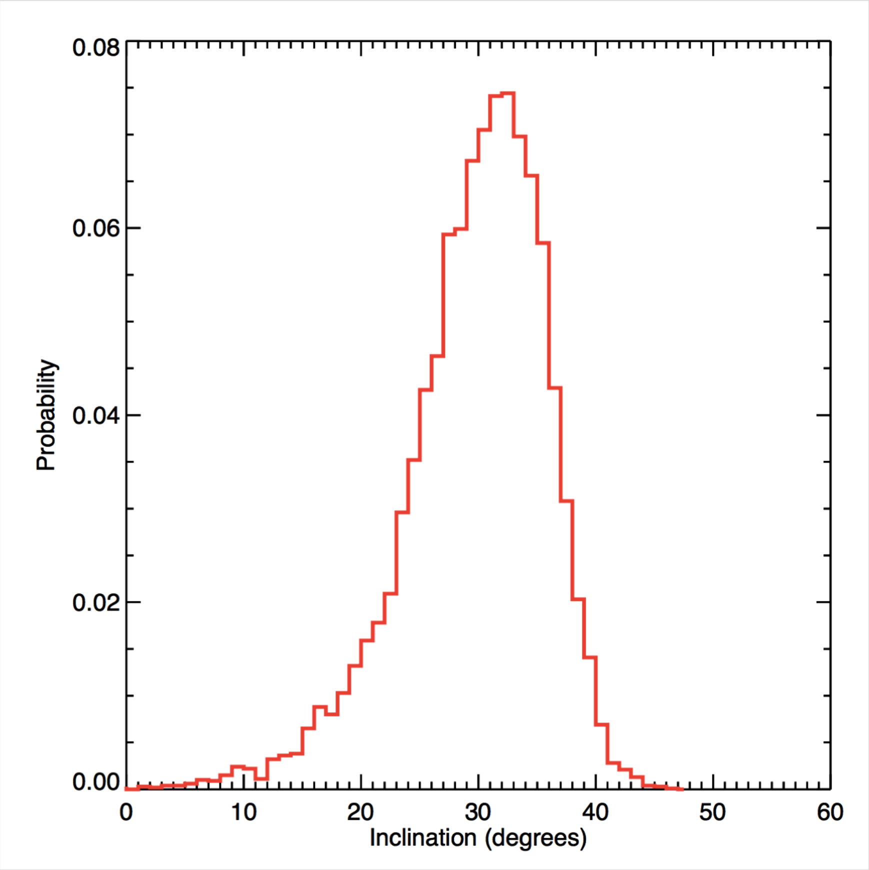

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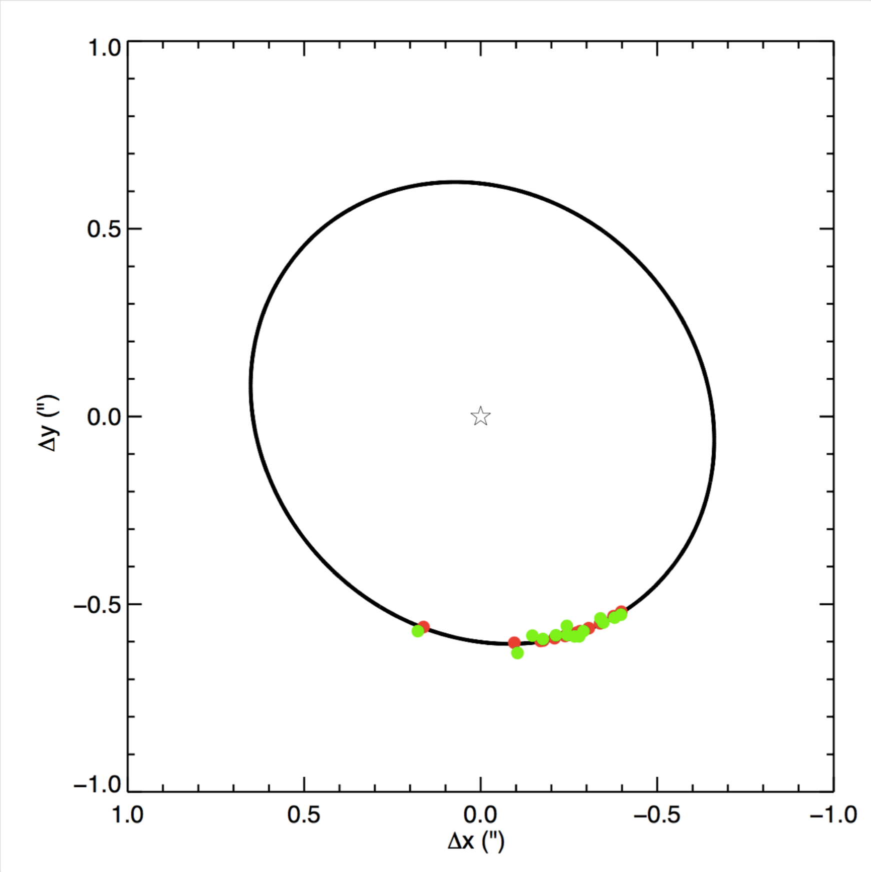

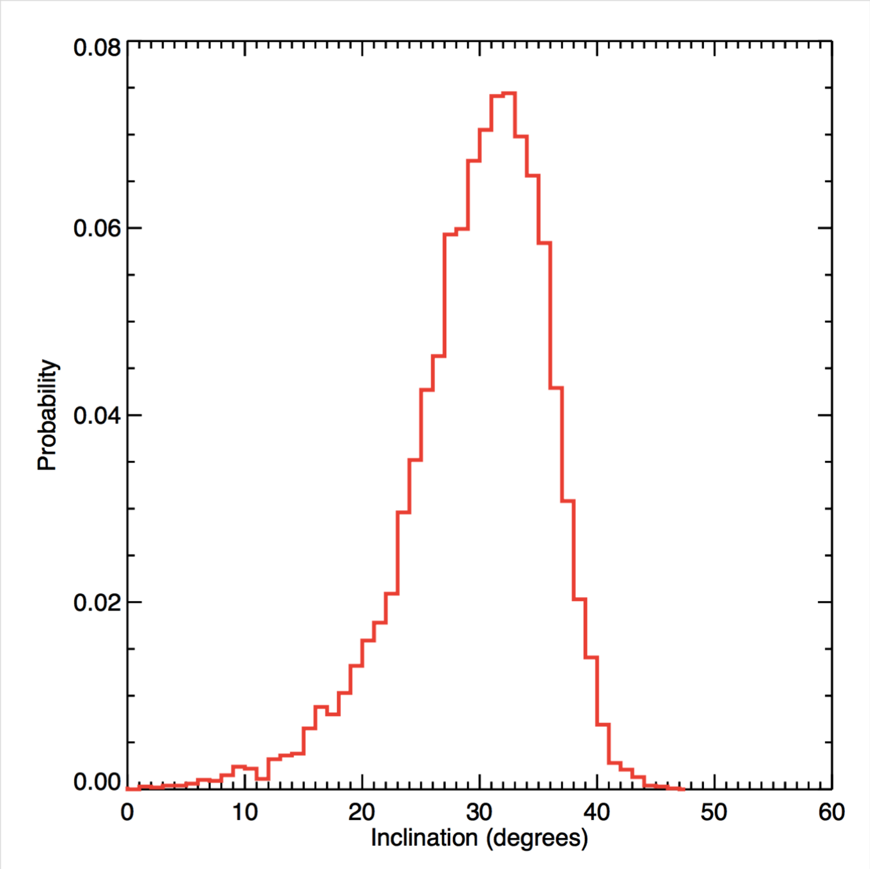

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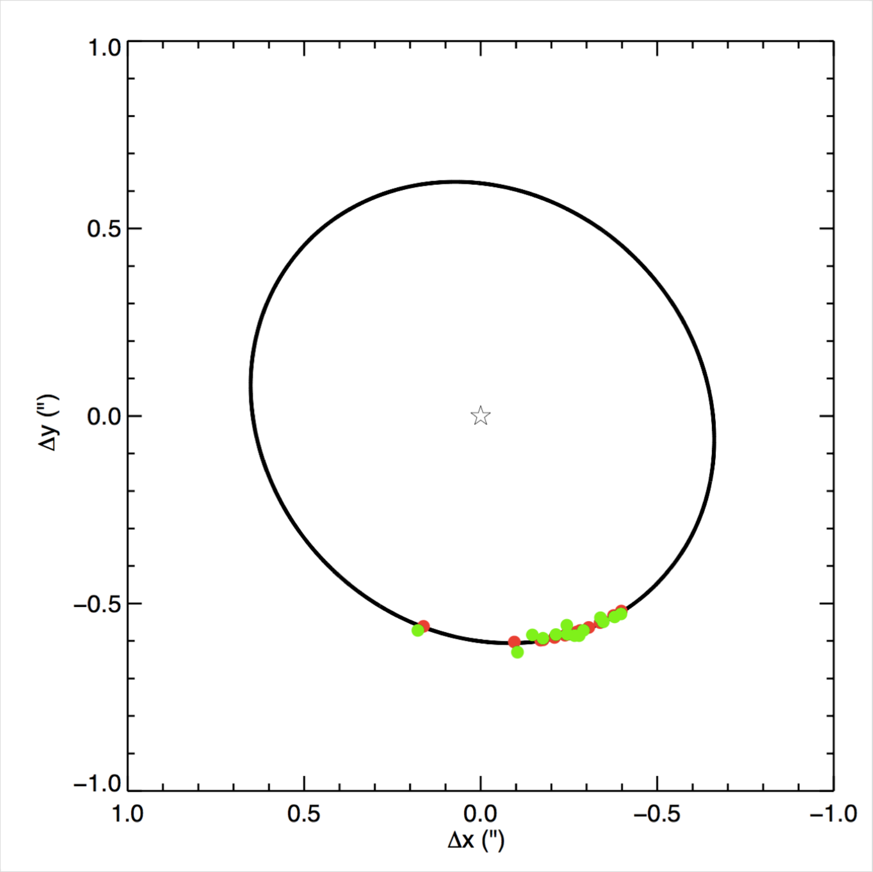
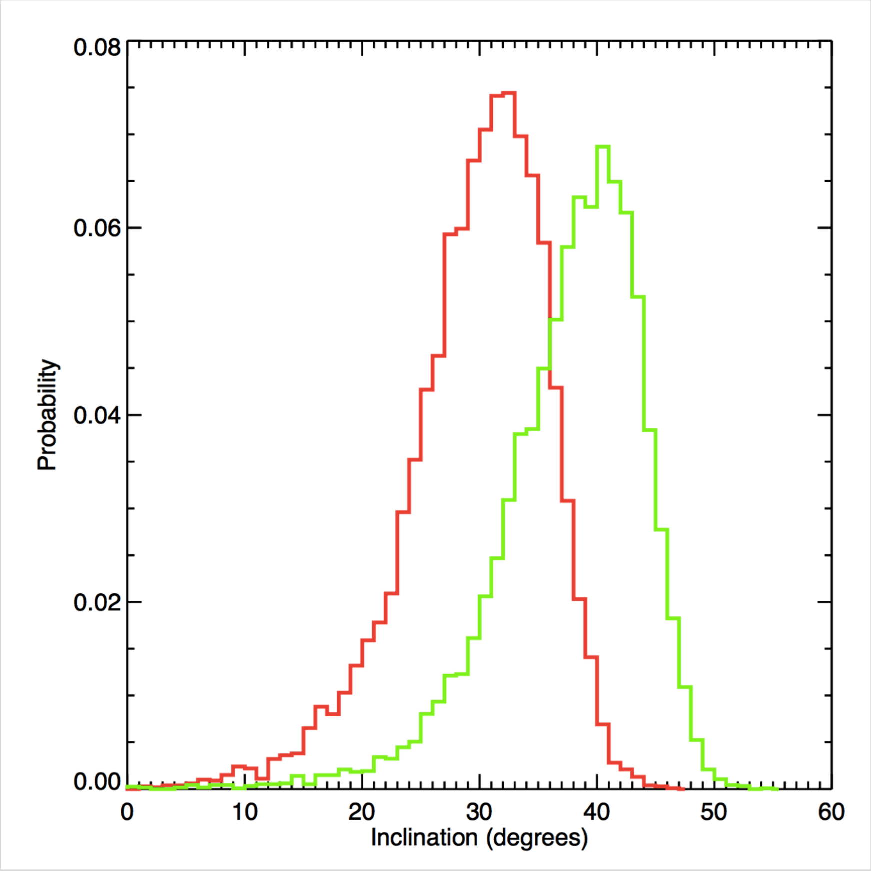
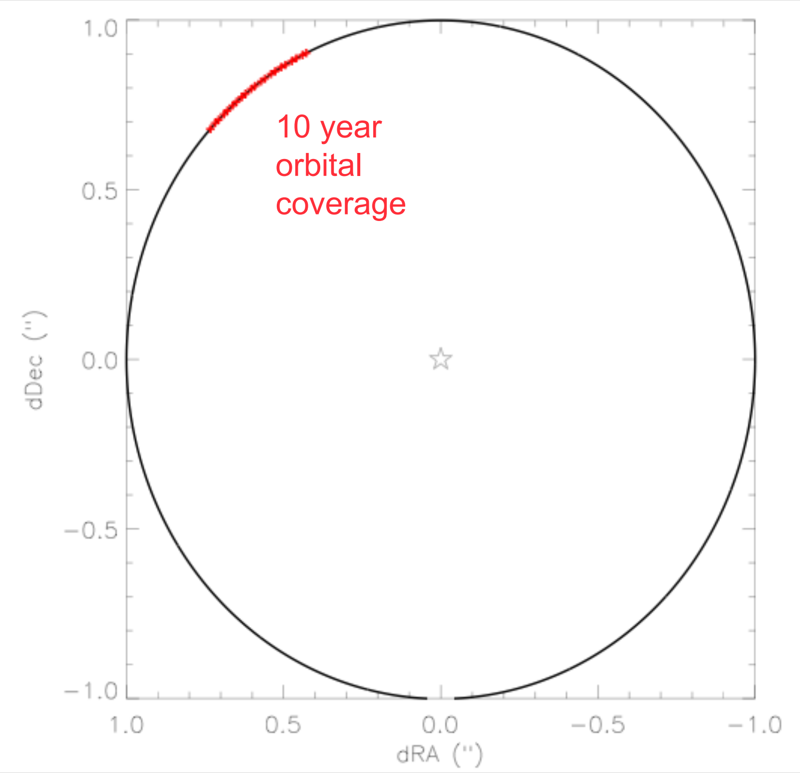




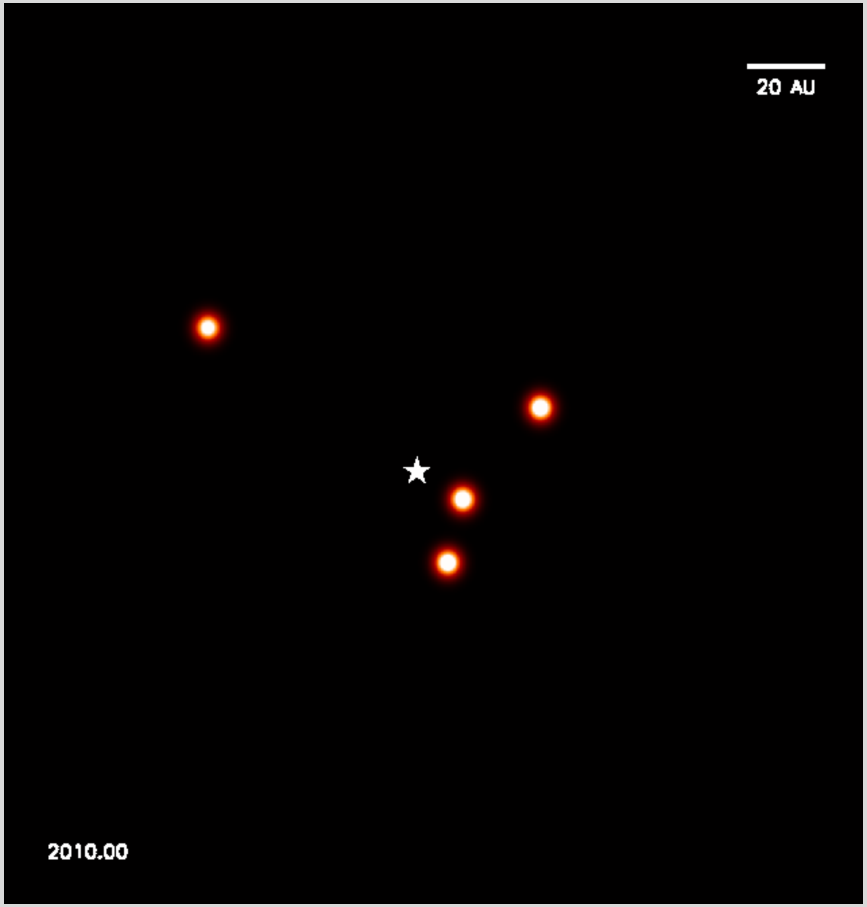
Konopacky et al. 2016a

But if we can control systematics and continue to push our precision, the results will be very rewarding!

- Over 10 years of monitoring, improving precision by a factor of ~2 results in:
  - 30% better constraints on eccentricity
  - 60% better constraints on period
  - 40% better constraints on semimajor axis
  - 20% better constraints on inclination



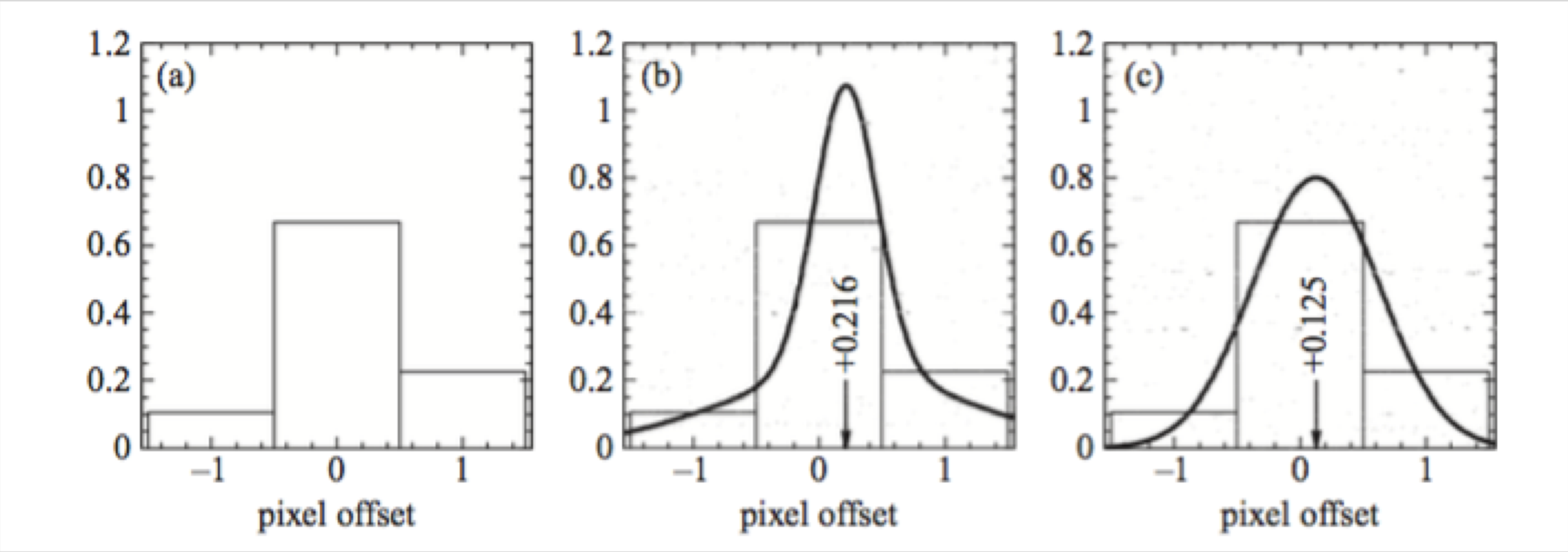
Circular, face on orbit with a=30 AU and distance=30 pc



Thanks! Hope everyone learned a lot this week!

Good Reference Text: Astrometry for Astrophysics: Methods, Models, and Applications, Ed. William van Altena

Obtaining the exact center of light can be a challenging problem with an impacted PSF.



Anderson 2012 (undersampled PSF)