Kernel-Phase Interferometry for Super-Resolution Detection of Faint Companions

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Kernel-phases are self calibrating observables used for high contrast imaging **at or even below λ/D**. We are currently using this technique to search for companions to nearby brown dwarfs in archival HST images. The pipeline will be particularly **applicable to JWST** and the future 30m class telescopes and will soon be available as a **python package**.

Background

The detection of companions to stars – both planets and stellar binaries – has traditionally relied on three methods: radial velocities (RVs), transits/eclipses, and direct imaging.

- Transit and RV surveys are insensitive to companions at large semimajor axes. While direct-imaging surveys are more sensitive to such objects, **there is often a gap between these two regimes, inside the inner working angle of direct imaging and outside the regime where transits and RVs can efficiently survey.**
- Imperfections in the optical path (and AO correction) introduce "speckles" which can be misinterpreted as companions. Speckles can be corrected using many different techniques but all tend to fail near λ/D.
- Interferometric analysis takes advantage of the wave nature of light and can be used to reject speckle noise and detect companions with high contrast *at or even below* the diffraction limit. **Rather than subtracting off the PSF, these techniques uses the information contained in it to infer the geometry of the source.** The discovery of the newly forming giant planet LkCa15b by Kraus & Ireland (2012) demonstrates the power of such techniques.

Filling the gap between RV and transit surveys and classical direct imaging surveys would offer a crucial new view of both stellar multiplicity and exoplanetary systems.

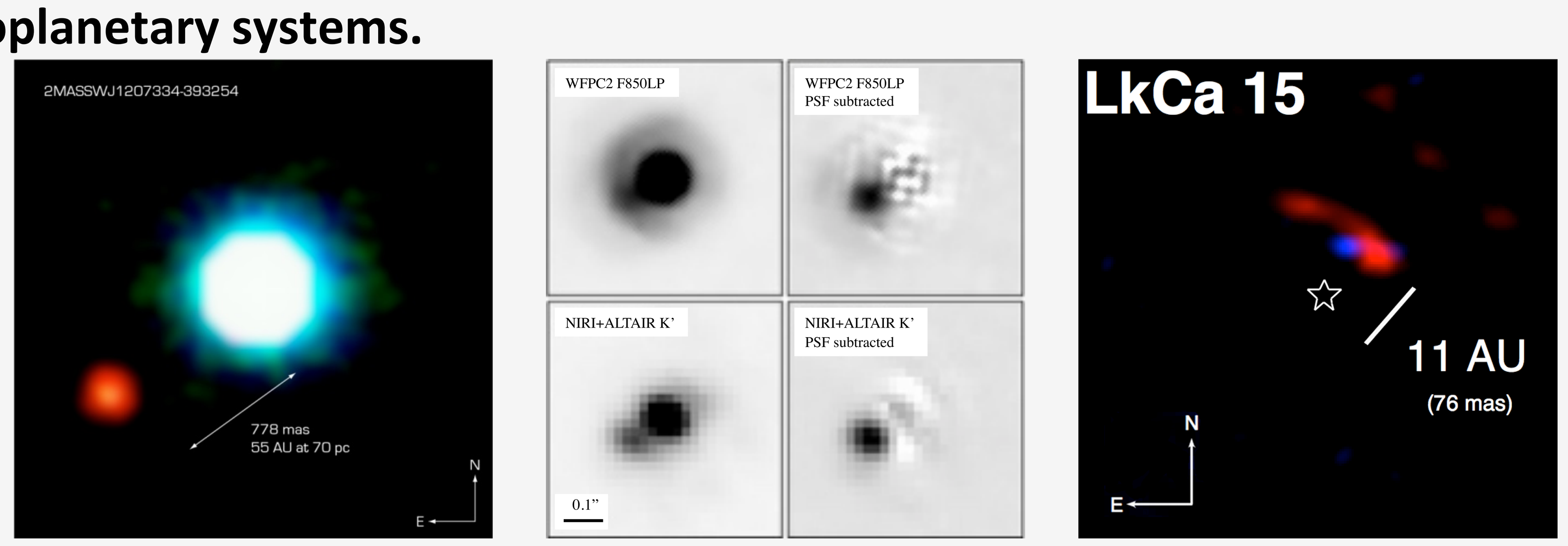

Figure 1: Examples of previously imaged low-mass companions. *Left*: VLT NACO image of 2MASS 1207AB, a brown dwarf with a ~7 M_{Jup} companion at ~55 AU (Chauvin et al. 2004). *Center*: WFPC2 and NIRI+ALTAIR raw and PSF subtracted images of the young brown dwarf 2MASS J044144 with a 5-10 M_{Jup} companion at 15 AU (Todorov et al. 2010). *Right*: Keck NRM K' (blue) and L' (red) band reconstructed images of LkCa 15b, a ~6 M_{Jup} companion at ~20 AU inside the gap of a transitional disk around a ~2 Myr old solar analogue (Kraus & Ireland 2012).

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S. Factor is P.I. of HST Cycle 24 Archival project 14561 which is supporting this work.

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Results: A widely applicable pipeline for high contrast imaging at λ/D

Below is a test case showing a binary brown dwarf observed by Pravdo et al. 2004 (and reanalyzed by Martinache 2010). We are currently analyzing a large set of HST NICMOS/NIC1 observations to search for close in binary and possibly triple brown dwarf systems. **We fit and statistically compare single and double point models using Bayesian model comparison** (using `PyMultiNest`; Buchner et al. 2014). Previous estimates of the detection limits (Martinache 2010, Pope et al. 2013) show a detection with **50:1 contrast at 80 mas (0.5λ/d at 1.9 μm) or 3:1 contrast at 35 mas** is possible with 99% confidence. In Taurus, these respectively correspond to a ~few M_{Jup} mass planet around a late M or brown dwarf at 10 AU or a similar mass binary at 5 AU. We are currently working to measure the detection limits of this pipeline.

Figure 3: *Top left*: HST NICMOS1 image of GL164 (F190N, up is at a PA of −152°). *Bottom row*: Fourier amplitude (left) and phase (right). Grey circles show the sampled points. *Top right*: kernel-phases calculated from the sampled phases. A single point would have kernel-phases of 0° (with some small spread). This is clearly not the case, indicating the presence of a binary.

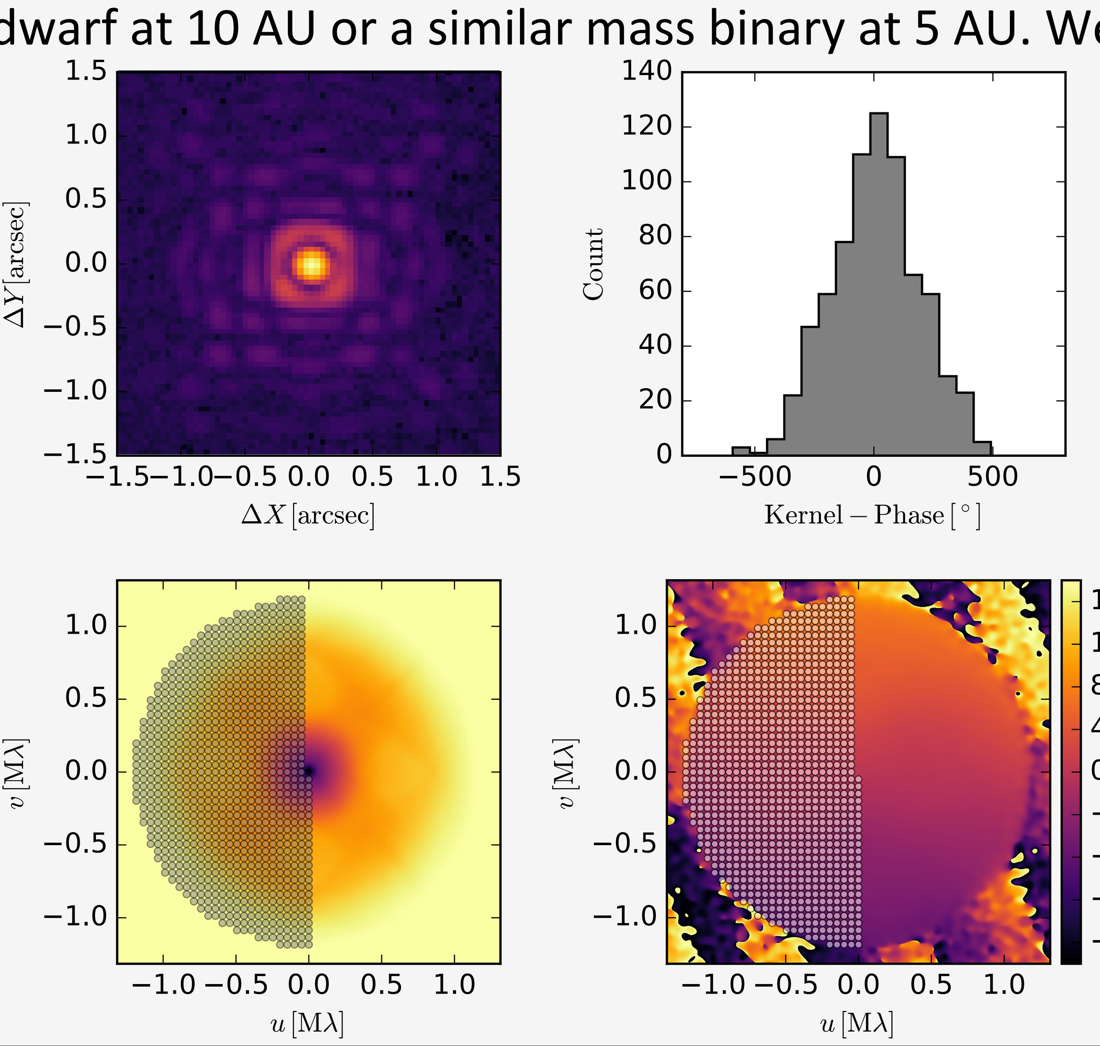
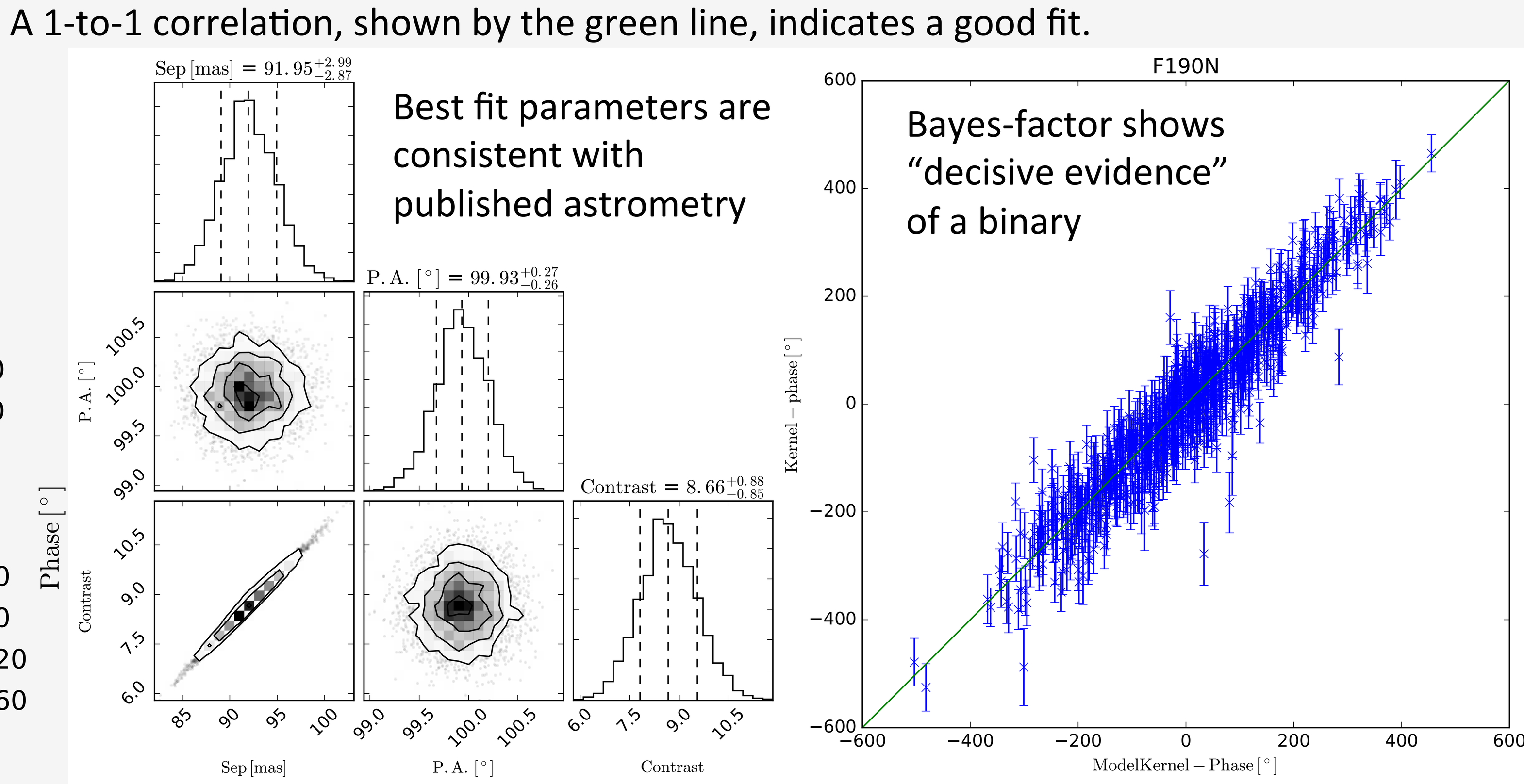


Figure 4: Results of fitting a simple double point source model. *Left*: Corner plot showing the 1- and 2D posteriors of the three parameter fit. *Right*: Kernel-phases generated from the image (using SAO 179809 as a calibrator) plotted against those from the best fit model. A 1-to-1 correlation, shown by the green line, indicates a good fit.



What is a Kernel-Phase?

Non-redundant masking (NRM) interferometry, the most common interferometric analysis technique for single-aperture telescopes, places a mask in the pupil plane, transforming a large single aperture into a sparse interferometer.

- This mask only allows ~5% of the light to reach the detector, imposing a *severe* flux limit. Unmasked apertures would be preferable.
- **Kernel-phase analysis models the *full aperture* as a grid of sub apertures** (shown in Figure 2). This defines which spatial frequencies are sampled.
- Since we are interested in the source geometry, we examine the *phase* of the Fourier transform of the image

Each pair of apertures, or baselines, contributes both the true phase of the source and a phase error from each of the apertures. Combining all the baselines together, we can write a matrix equation for the measured phases:

$$\Phi = \Phi_\circ + \mathbf{A} \cdot \phi \qquad (1)$$

Where Φ is a vector of the measured phases from each baseline, Φ_0 is the true source phase, **A** is a matrix encoding the baselines, and ϕ is a vector of the phase errors from each aperture. Each column of **A** corresponds to an aperture while each row corresponds to a baseline.

To derive an equation which is independent of the phase errors we use singular value decomposition to calculate the kernel (**K**) of **A** such that:

$$\mathbf{K} \cdot \mathbf{A} = 0 \qquad (2)$$

We can then simply multiply both sides of Equation 1 by **K** to get

$$\mathbf{K} \cdot \Phi = \mathbf{K} \cdot \Phi_\circ + \mathbf{K} \cdot \mathbf{A} \cdot \phi$$
$$= \mathbf{K} \cdot \Phi_\circ \qquad (3)$$

This produces observables called kernel-phases which are independent of phase errors, similar to closure-phases used with NRM. **This technique can achieve similar detection limits to NRM in a fraction of the time and can be applied to dimmer sources where NRM is not feasible, as well as archival data sets.** It was first presented by Martinache (2010).

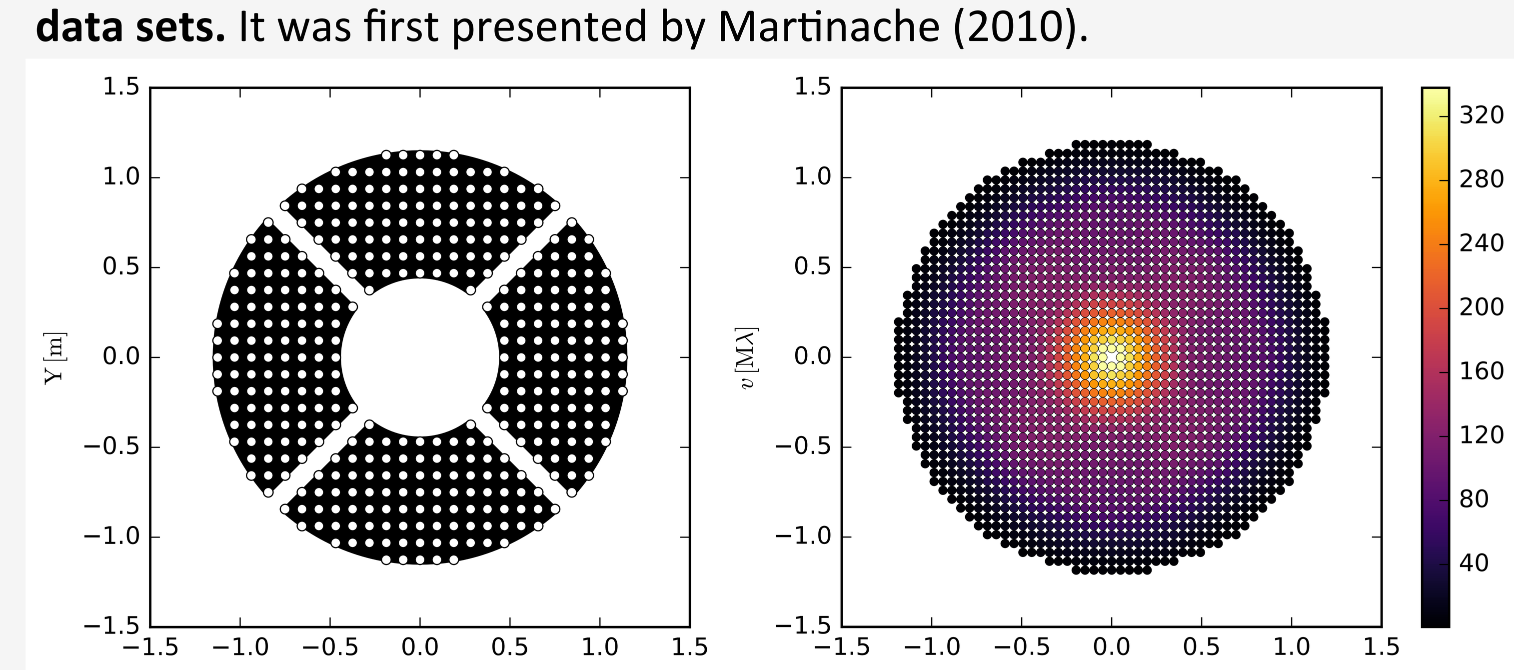


Figure 2: *Left*: Model HST aperture. *Right*: The corresponding baselines (at 1.9 μm), color-coded by the number of distinct pairs of subapertures which contribute to the point. The 392 sub-apertures sample 938 unique baselines and generate 745 kernel-phases.