Imaging Exoplanets with JWST: Capabilities and Comparisons

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Summary

The study of planetary systems beyond our own has grown into one of astronomy's most energetic subfields today, and will unquestionably be a major area of effort for JWST. While spectroscopic studies of planets through transits and secondary eclipses are already routinely achieved with HST & Spitzer, spatially resolved high-contrast imaging of planets is in its relative infancy.

Three of JWST's instruments include coronagraphs, with a variety of different architectures: NIRCam features band-limited image plane occulters, TFI has hard-edged classical Lyot coronagraphs and a non-redundant aperture masking interferometry mode, and MIRI includes three phase masks (optimized for planet detection) and a classical Lyot (optimized for circumstellar dust). These instruments will allow observation and characterization of Jovian exoplanets, preferentially around nearby, young FGKM stars.

Coronagraphic studies are likely to be some of the most technically challenging observations conducted by JWST, with stringent demands for target acquisition accuracy and wavefront stability. While the basic hardware of the coronagraphs are all now defined, there remain significant open questions in operational strategies and optimization. To provide a forum for advancing our understanding of these issues , STScI has recently led in creating a project-wide JWST Coronagraphs Working Group.

We present here

- an overview of the high-contrast imaging modes available on JWST,
- a new set of simulations demonstrating the ability of all three instruments to detect planets around the only currently-imaged multi-planet system HR 8799, and
- descriptions of the key technical challenges needing attention in coming years, specifically development of optimal observing strategies and improved PSF suppression algorithms.

Direct Imaging in the Era of JWST

JWST will operate in an era when direct imaging from the ground will be common for self-luminous young Jovians. By the time JWST launches, hundreds of nearby stars will have been surveyed; many tens of planets will have been found and characterized. From AO observations, we will have good knowledge of the prevalence and distribution functions (with mass, semi-major axis, and stellar properties) of planets more massive than ~1-2 $M_{\rm Jup}$. We will know *a priori* where there exist some planets detectable with JWST, and will have improved insights into where cooler unseen planets may await observation. It is almost certain that JWST's first exoplanetary observations will be follow-up studies of planets found by AO.

JWST's strengths are redward of 3 μm. At wavelengths shorter than 2.5 μm, it is unlikely that JWST will be able to outperform dedicated AO systems for observations of bright (*I* mag < 10) targets, due to terrestrial telescopes having larger diameters and better wavefront quality (for the range of spatial frequencies that are adaptively controlled). But at longer wavelengths, JWST will be vastly more sensitive than warm terrestrial instruments.

It may be that JWST's greatest contributions will be as a planet *characterizer*, rather than discoverer. The expanded wavelength coverage provided by JWST, especially with MIRI, will provide unique constraints on models of atmospheres and planetary interiors that no other observational platform will be able to match. The AO-discovered planet population will provide a very rich dataset, enabling efficient & effective followup studies.

On the other hand, JWST will also have some unique regions of planetary parameter space that only it can probe. Observations at >3 μm will allow detection of cooler planets (hence lower mass or older) than will be observable with AO. And freedom of not needing a bright AO guide star will enable JWST to conduct studies of planets orbiting very close but intrinsically dim M stars. Lastly, observation of nearby star forming regions with TFI's NRM mode will reveal Jovian planets at extremely young ages (<5 Myr), which are too close to their stars for conventional coronagraphic techniques to resolve.

High-Contrast Capabilities

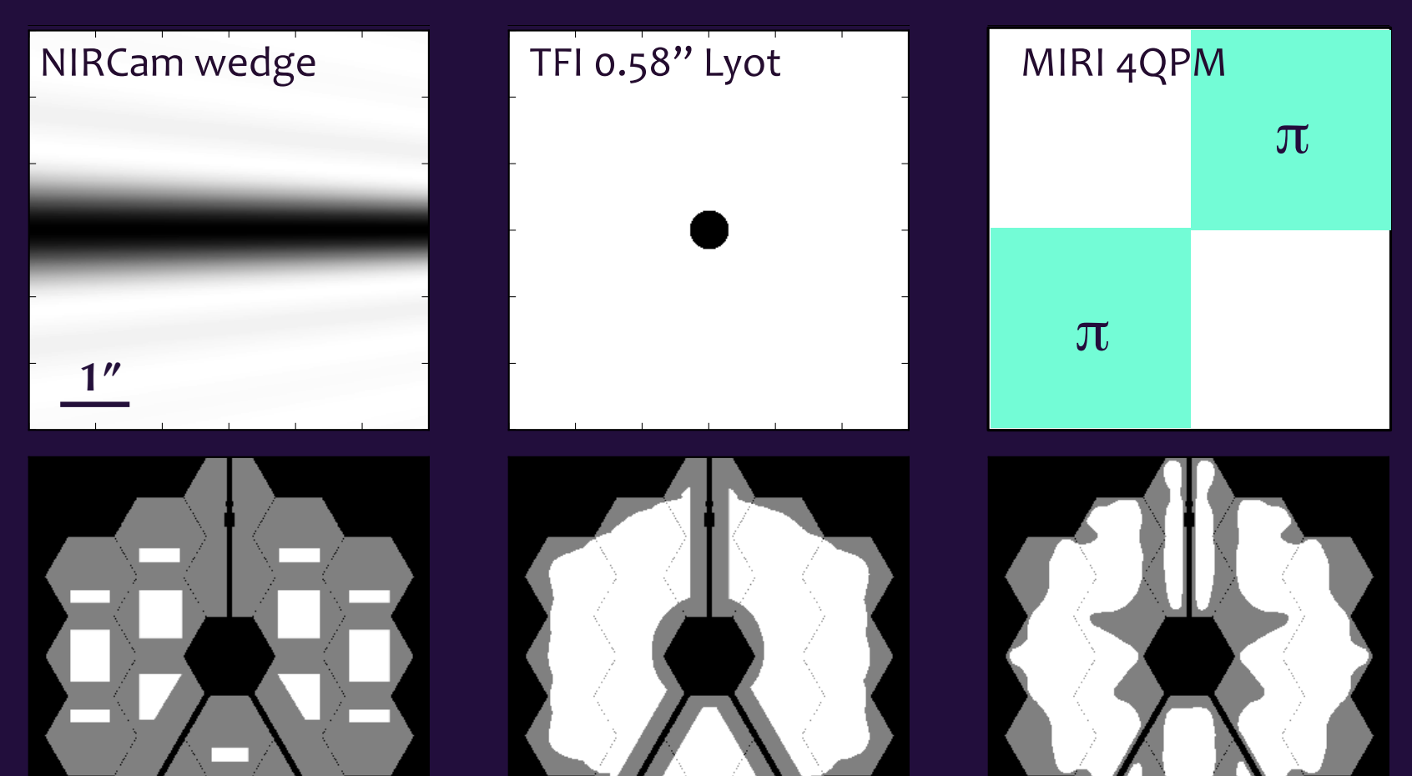
The different coronagraph architectures and instrumental capabilities yield a complex trade space for observation design.

NIRCam's band limited masks and aggressive Lyot stop design provide superior diffraction suppression (Krist et al. 2007, 2010), but at a cost of low throughput and a complex multi-lobed PSF for off-axis sources (i.e. planets). The full filter complement is available, including wide filters for maximum sensitivity (though increased need for color-matched PSF references.

TFI's etalon allows wavelength scanning for improved PSF suppression, and can yield low-res spectra of planets (Doyon et al. 2008, 2010). Its classical Lyot coronagraph design is less sophisticated but more robust to misalignments. The Non-Redundant Aperture Masking mode will provide moderately high contrast at extremely small separations < λ/D. (Sivaramakrishnan et al. 2010)

MIRI's QPMs are needed for good inner working angle at these long wavelengths, but are extremely sensitive to target alignment. Its classical Lyot is much more robust but has a very large inner working angle. Because the pupil masks are co-mounted with filters, coronagraphy is limited to only four possible filters.

	Wavelengths [μm]	Inner Working Angle [arcsec]	Contrast at 1 arcsecond
NIRCAM sombrero BLC s	0.6 - 5	0.4, 0.64, 0.8	~ 12 mag.
NIRCam wedge BLCs	0.6 - 5	0.14 - 0.41, 0.29 - 0.87	~ 12 mag.
TFI Lyot coronagraphs	1.5 - 2.5, 3.2 - 5	0.29, 0.38, 0.75, 1.0	~ 10 mag.
TFI Non-redundant mask	3.8 - 5	0.06 - 0.08	10 - 12 mag at 50 - 400 mas
MIRI 4 Quad Phase Masks	10.6, 11.4, 15.5	0.35, 0.38, 0.5	~ 10 mag.
MIRI Lyot Coronagraph	23	2.1	~ 10 mag.



Right: Occulting masks (top) and Lyot stops (white regions in lower plots) for the three modes used in the HR 8799 simulations. Note the complex shapes of the Lyot masks for NIRCam and MIRI.

Observing HR 8799 with JWST

To illustrate the types of coronagraphic data that JWST will produce, we present here simulations using three different instrument modes and three different PSF subtraction techniques. We choose as our subject the HR 8799 system (Marois et al. 2008, 2010) with 4 planets located from 0.36 - 1.7 arcsec. Planet fluxes are extrapolated from 1-3 μm photometry using spectral models fit by Currie et al. 2010.

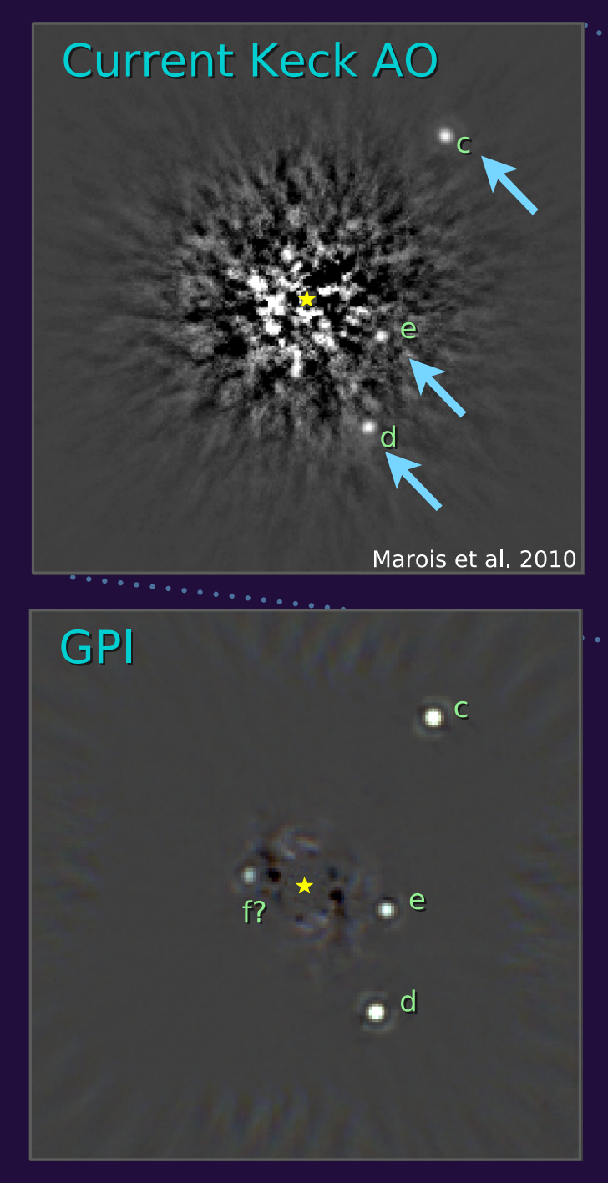
We model these observations using WebbPSF, the first simulation package that models all of JWST's coronagraphs with one code. WebbPSF has been validated against existing simulation codes by the various SI teams and produces consistent results. We emphasize these are preliminary results (simulated just last week!) and uncertainties are significant.

Following Beichman et al. 2010, we adopt a 10 nm RMS change in WFE between observations. We optimistically assume target acquisition at the observatory pointing limit, ~ 7 mas RMS. We add photon and read noise for 0.5 hr exposures, but these are negligible compared to PSF subtraction residuals.

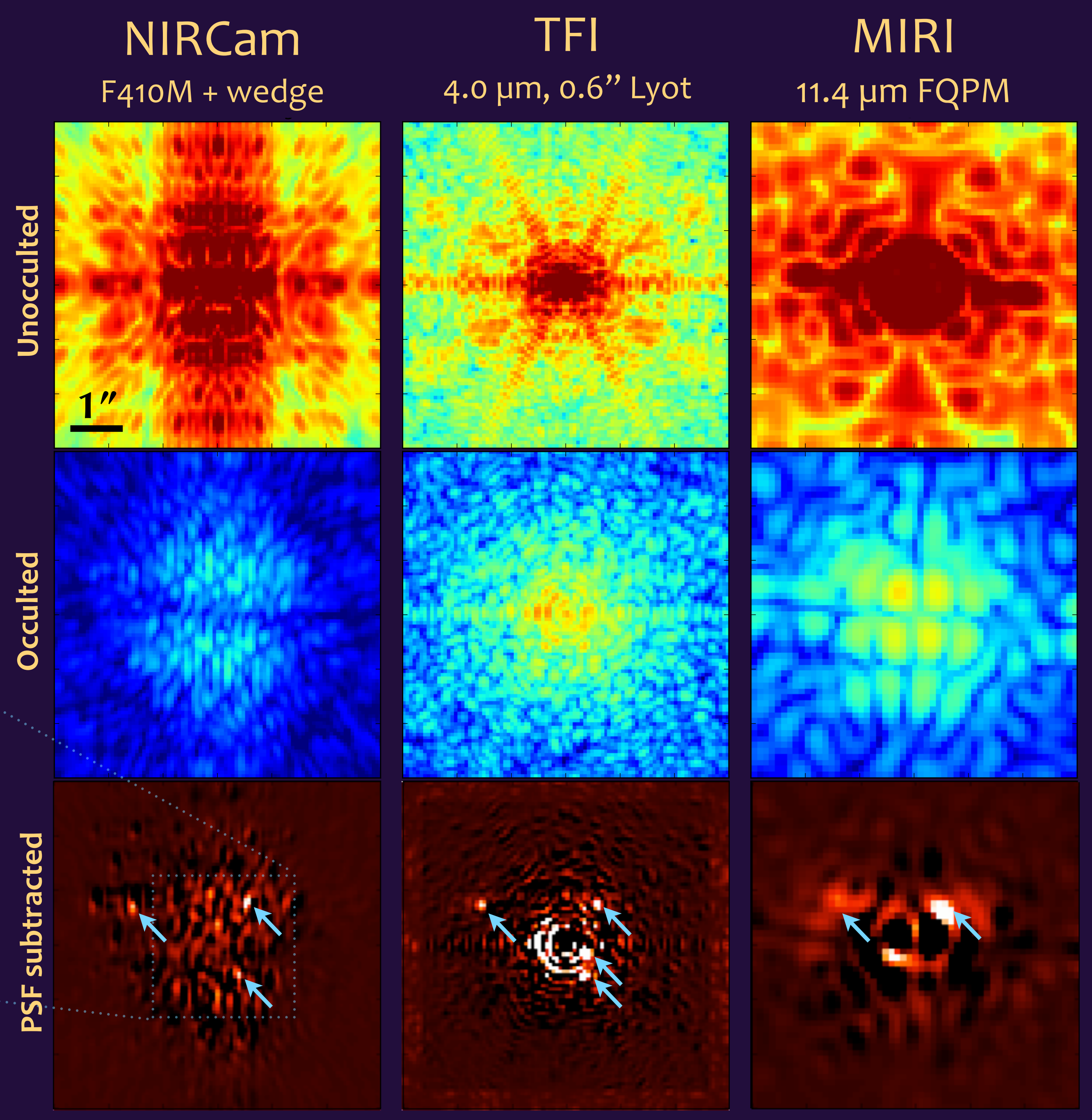
The outer two planets are detected in all three cases. Planet d is not seen in the MIRI image. Impressively, the TFI simulation shows the inner fourth planet; this is not seen in the NIRCam data because it self-subtracts given only 10° roll difference.

The significant speckle residuals present in all these images show the need for improved PSF subtraction over the very basic approaches used here.

AO:



GPI sim by Perrin, Marois, Poyneer



PSF subtraction of another image rolled by 10°.

PSF subtraction of rescaled 3.5 & 4.0 μm observations

PSF subtraction of a reference PSF star

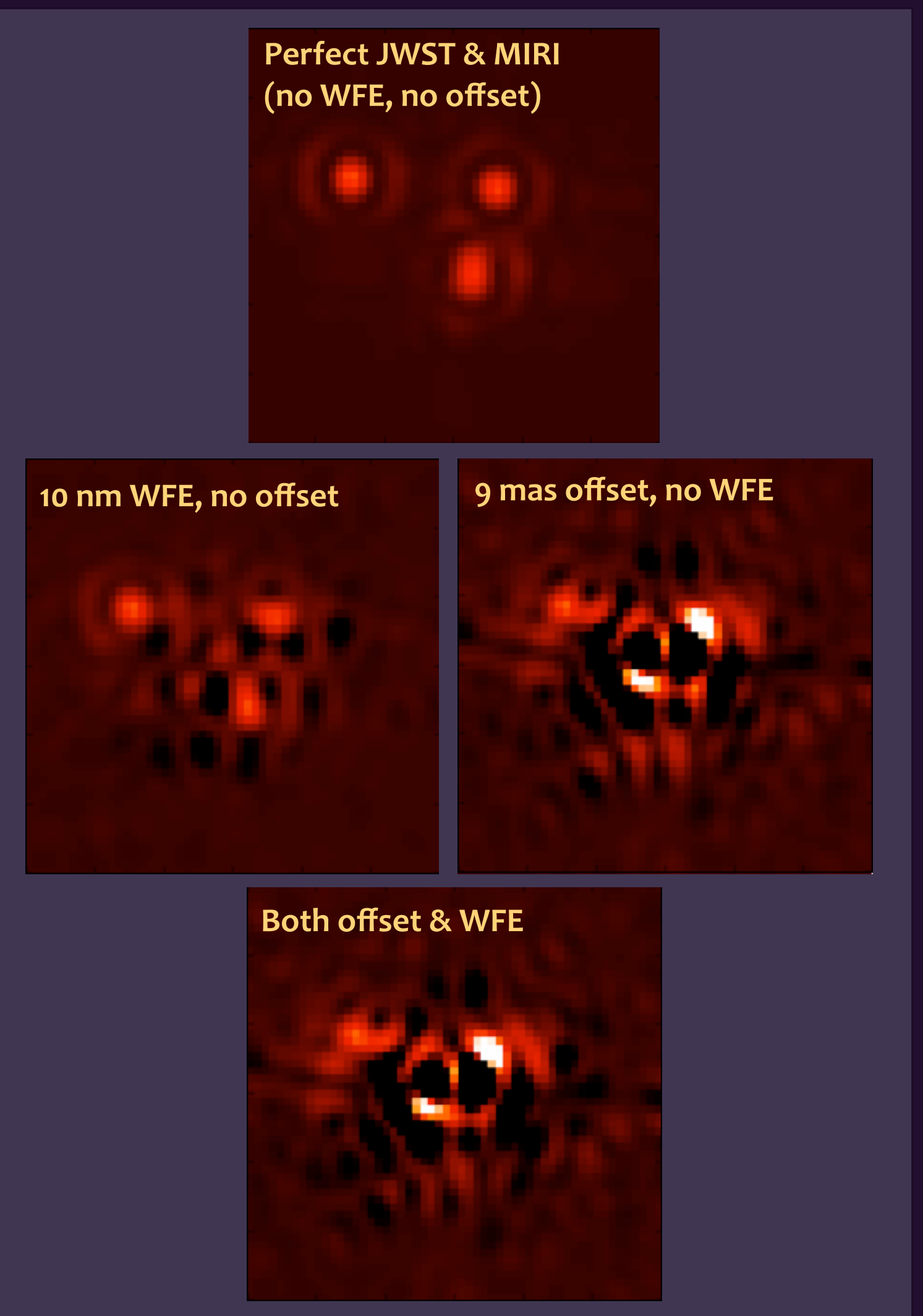
Top two rows: log stretch from 1e-8 - 1e-2 of the unocculted image's peak pixel. Bottom row: linear stretch, varying min/maxes.

Challenges: Modeling Wavefront Evolution and Acquisition

Our ability to model coronagraphy with JWST is currently limited by our imperfect understanding of its wavefront stability. Thermal and optical modeling efforts at Goddard and Northrup Grumman have thus far concentrated on the 'worst-case' hot-to-cold slew defined in mission requirements, a case we will try to avoid in practice. Modeling of more typical thermal conditions is lacking. Improved models should become available over the next 1-2 years, but it is likely that there will still be significant uncertainties until empirical assessment of performance on orbit. Depending on stability levels, it may be possible to use wavefront knowledge from WFS&C measurements to aid in refining PSFs for subtraction.

Operationally, the most significant challenge appears to be target acquisition - the process of accurately placing the target centered behind the coronagraph occulter. This task is complicated by the need to centroid on extremely bright sources compounded by slew uncertainties and pointing jitter. The MIRI quadrant phase masks are the architechture most sensitive to, and dependent upon, very accurate (≤20 mas) acquisitions -- but it is also the most difficult to acquire, given the complicated behavior of even off-axis PSFs in the vicinity of the phase mask center. See at right how even just 9 mas offset causes worse subtraction residuals than 10 nm WFE.

Understanding both of these issues better will be major areas of effort for the JWST Coronagraphs Working Group organized by Soummer & Hines.



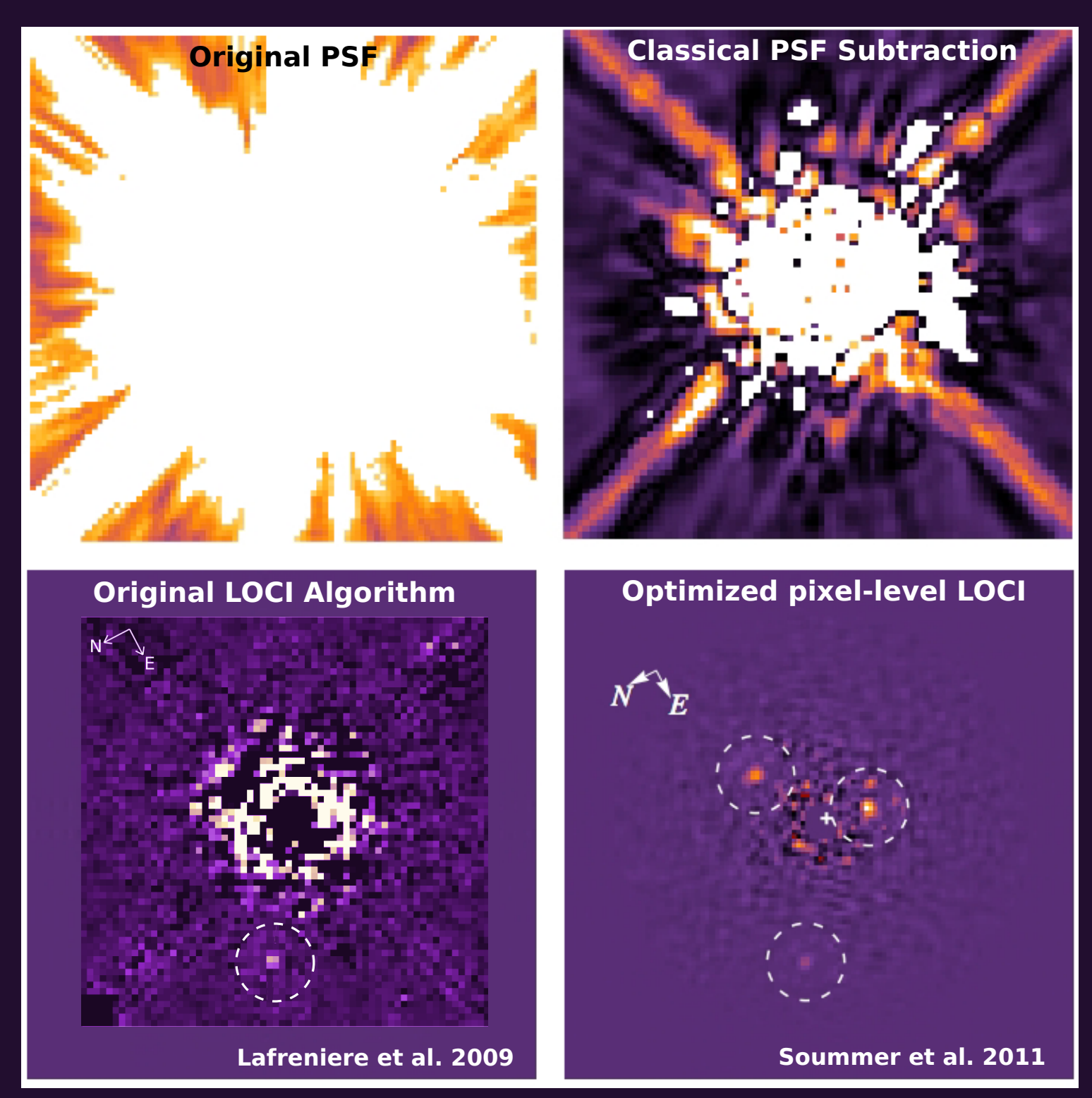
Improvements in PSF Subtraction Algorithms

Classical PSF subtraction is obsolete. Dramatic improvements in algorithmic image processing to remove PSFs have been central to the successes of AO direct imaging in recent years. The principle technique is the LOCI algorithm (Lafreniere et al. 2007).

The fundamental insight is that a large library of reference PSFs can provide diversity spanning the multidimensional parameter space of PSF variation, and suitable combination of library entries can provide a synthetic PSF that is optimally matched to the science data. This is a generic truth that applies for any available diversity source, applicable equally to the use of PSF reference stars, multi-wavelength observations, or multiple roll angles.

More sophisticated variants of LOCI are now available that yield unbiased spectrophotometry and 10-mas accurate astrometry for AO observations. Application to HST data has recently recovered the outer 3 planets of HR 8799 in decade-old data; see at right. Such optimized subtraction algorithms must be part of JWST coronagraphic practices from day one.

In fact, as with HST, coronagraph optics are not required for high contrast. Good subtraction may in some cases enable detection of faint companions or disks in direct imaging, which is particularly exciting for high contrast with the IFUs.



Top left: NICMOS coronagraphy of HR 8799 from 1998. Top right: "Classical PSF Subtraction" without the LOCI algorithm. No planets are visible. Bottom: results using the LOCI algorithm reveal the outer planet clearly (left), while a further optimization (right) shows all three planets b, c, & d. Application of similar techniqes to JWST would benefit greatly from a policy of making all PSF calibration data have no proprietary period, to enable population of a global PSF library.

WebbPSF software:

The PSF simulations presented here were created using WebbPSF, a new program for producing simulated PSFs for any of JWST's instruments and modes. This package is now available from http://www.stsci.edu/software/webbpsf or http://www.stsci.edu/~mperrin/software/webbpsf.html As our understanding of JWST on-orbit performance grows, WebbPSF will likewise improve toward a high fidelity PSF simulation system comparable to the role that TinyTIM has played for HST.

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