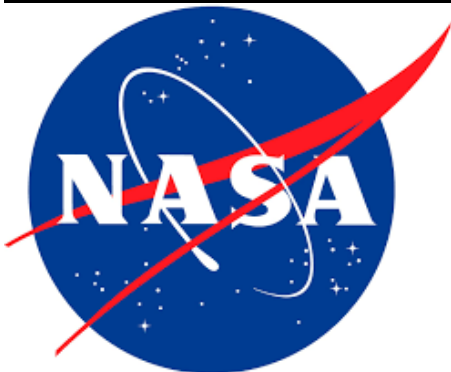


# Coronagraphic Imaging of Exoplanets with NIRCarn

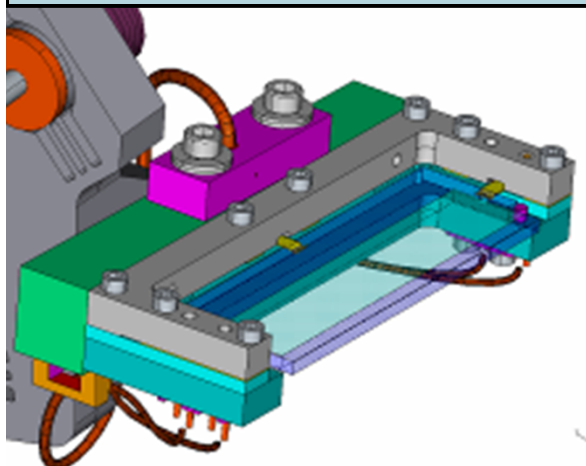
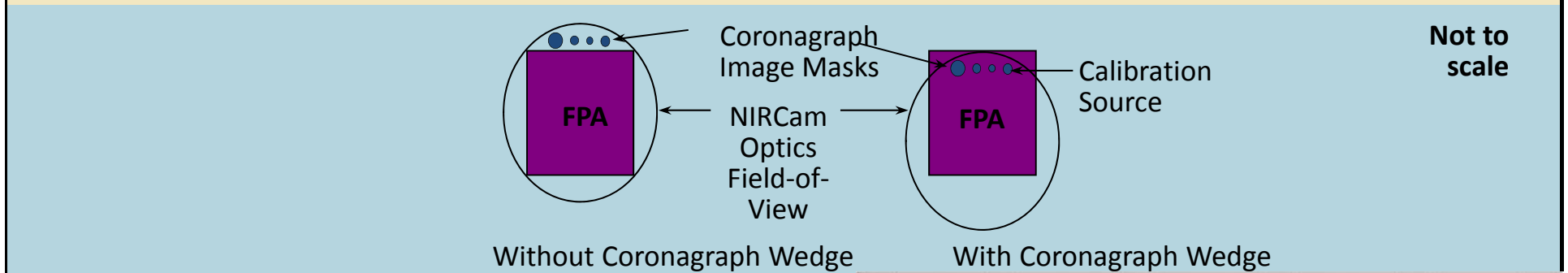
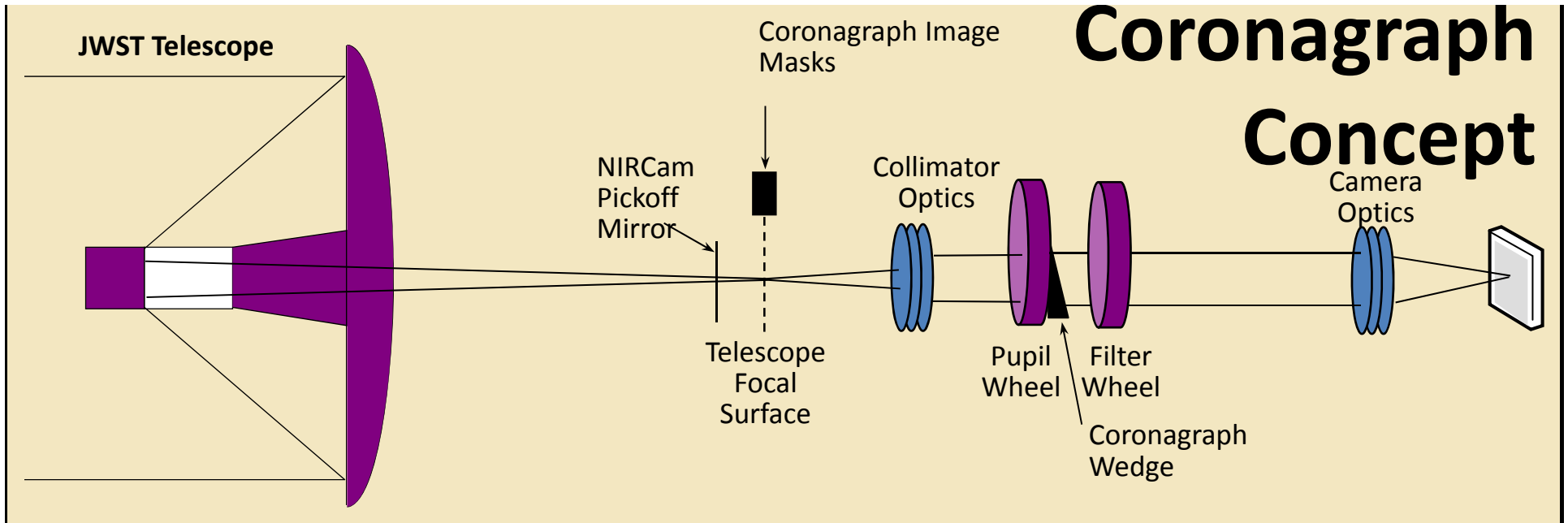
C. Beichman

NASA Exoplanet Science Institute,  
Jet Propulsion Laboratory, California Institute of Technology  
For the NIRCarn Team  
September 27, 2016

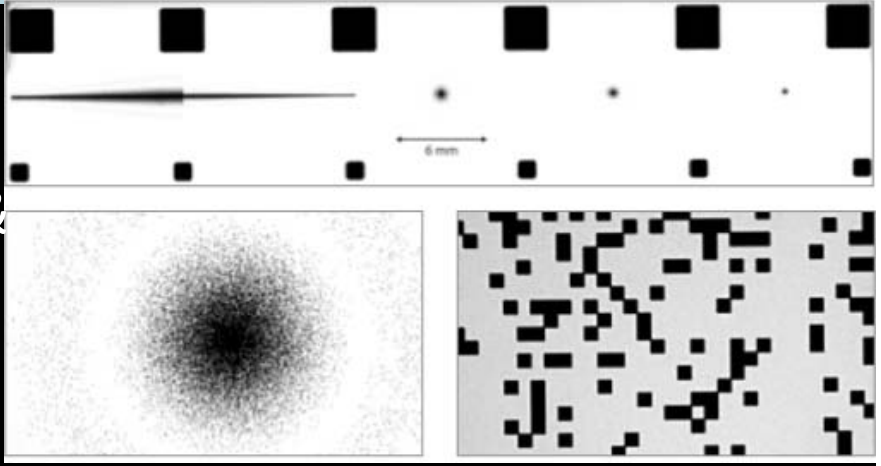


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Government sponsorship acknowledged.

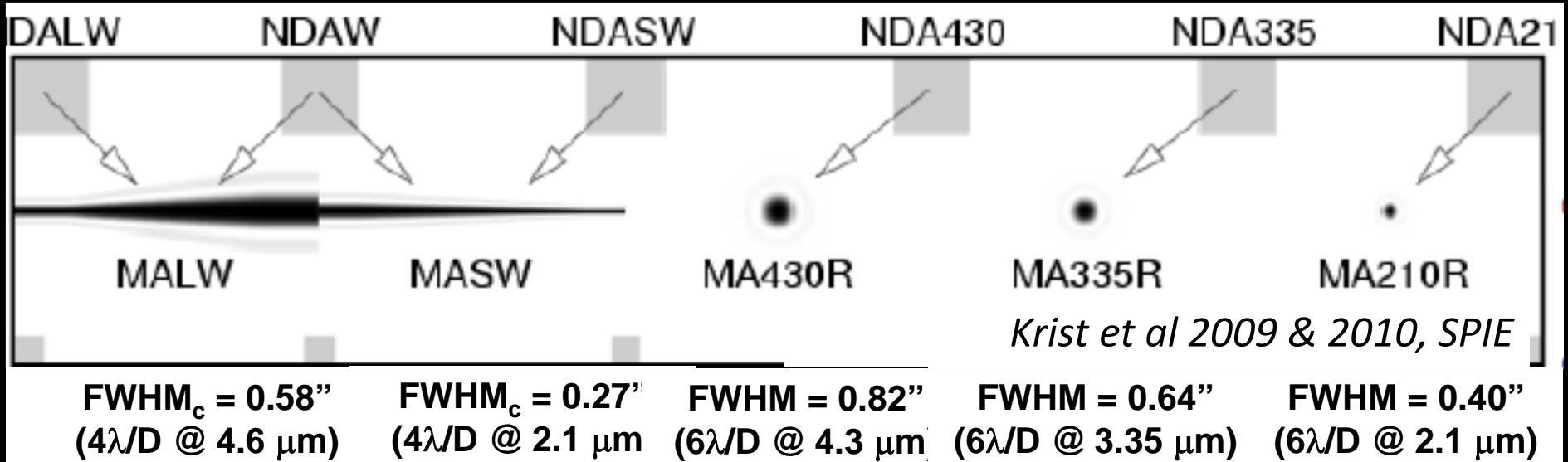
# Coronagraph Concept



*Krist et al 2009 & 2010, SPIE*

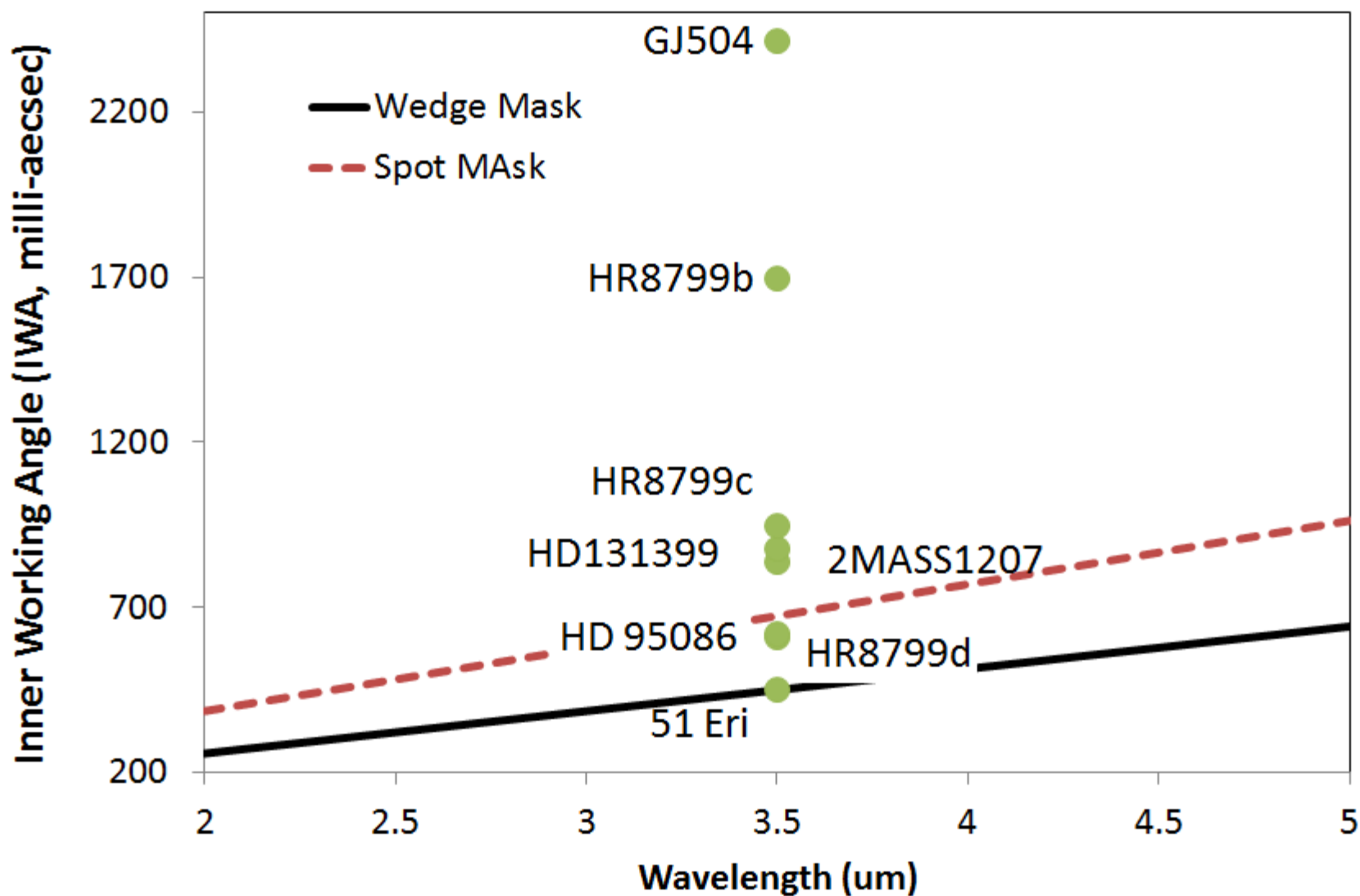


# NIRCam Focal Plane Masks



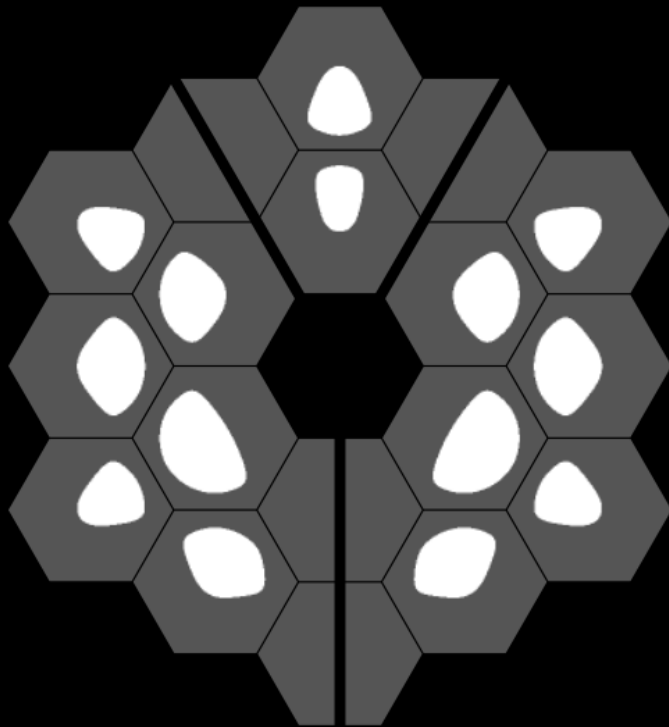
- 2 wedge-shaped masks for known geometries give best inner working angle  $(IWA)=4\lambda/D\sim 0.13\lambda''$
- 3 circular (sombbrero) masks for  $360^\circ$  coverage with larger  $IWA=6\lambda/D\sim 0.19\lambda''$

## NIRCam Coronagraph Inner Working Angle

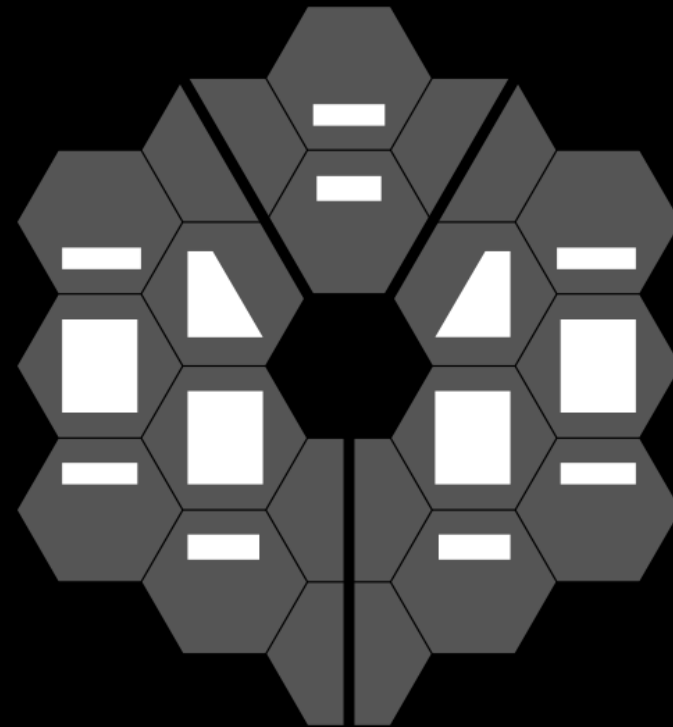


# NIRCam Coronagraph Lyot Stops

Clear regions superposed on JWST pupil  
Throughput  $\sim 19\%$ .



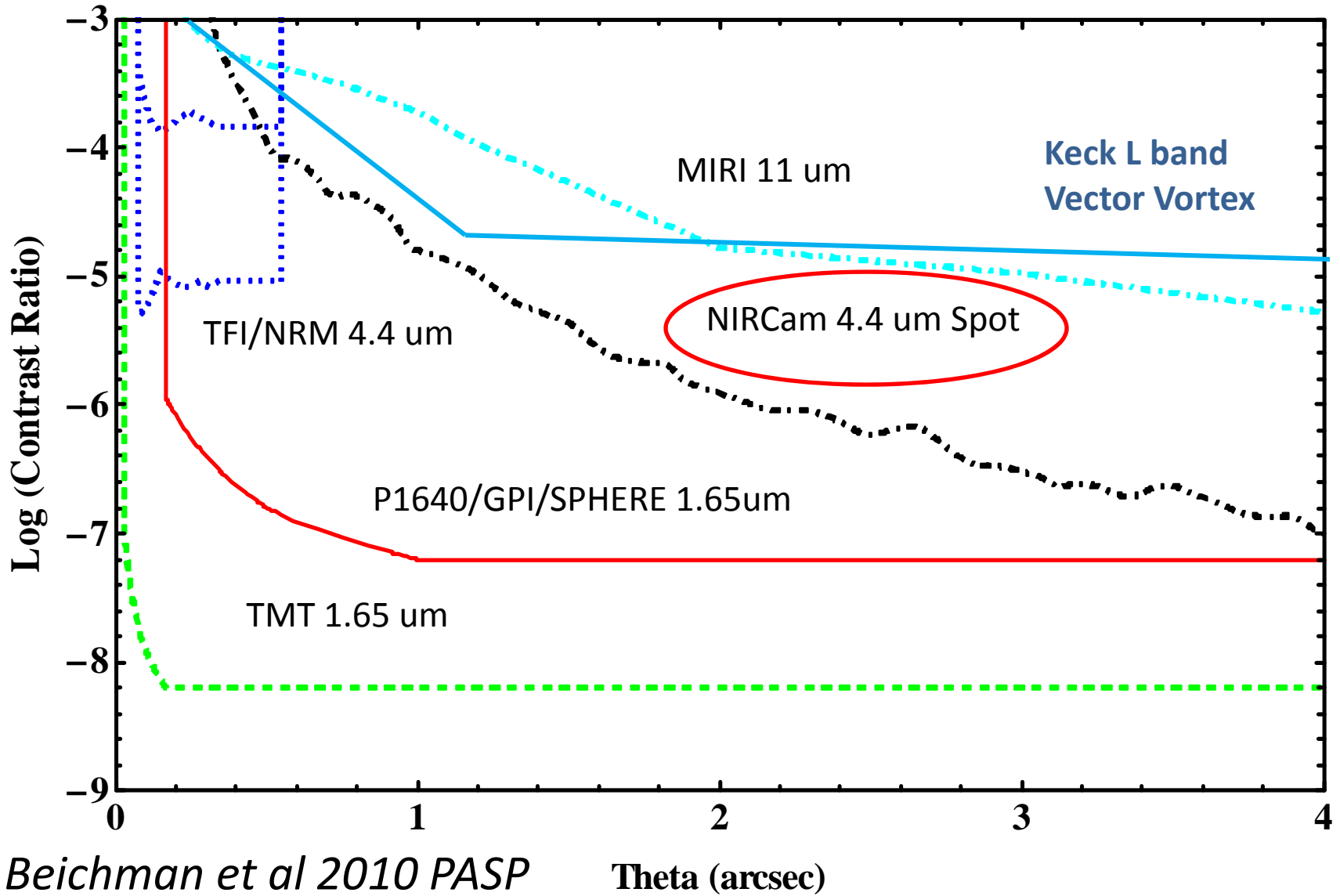
Lyot stop for  
 $6\lambda/D$  spot occulters



Lyot stop for  
 $4\lambda/D$  wedge occulters

*Krist et al 2009 & 2010, SPIE*

# Coronagraphic Capabilities: Ground and Space



**$10^{-5}$  contrast sources,  $10^\circ$  roll, iterative roll subtraction**

*RMS wavefront change between rolls indicated*

0.25 nm

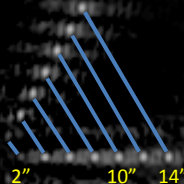
1 nm

5 nm

15 nm

F430M spot

F210M spot



$10^{-6}$  contrast sources,  $10^\circ$  roll, iterative roll subtraction

*RMS wavefront change between rolls indicated*

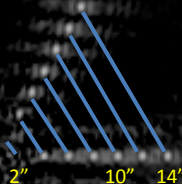
0.25 nm

1 nm

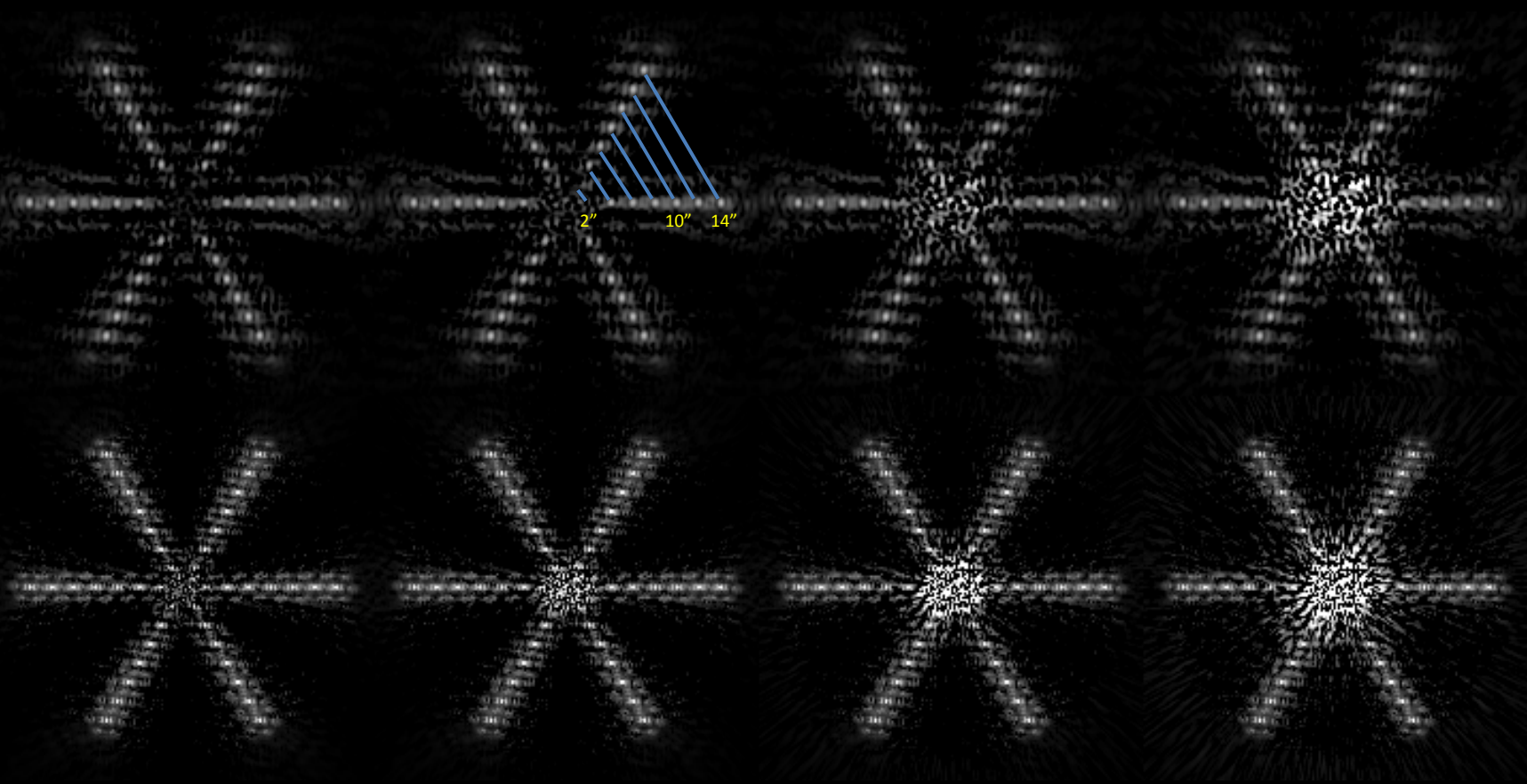
5 nm

15 nm

F430M spot



F210M spot





$10^{-7}$  contrast sources,  $10^\circ$  roll, iterative roll subtraction

*RMS wavefront change between rolls indicated*

0.25 nm

1 nm

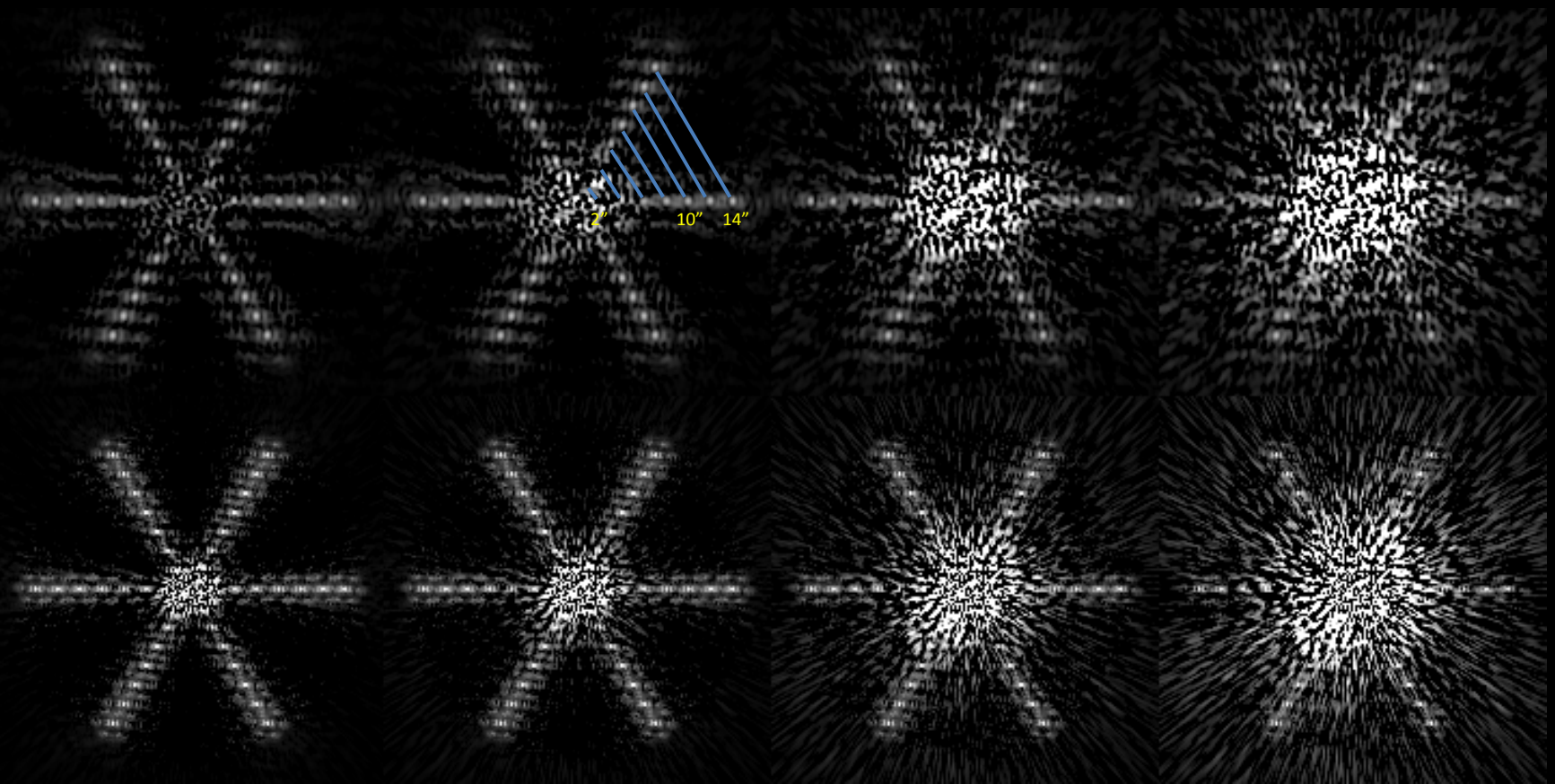
5 nm

15 nm

F430M spot

7" 10" 14"

F210M spot



$10^{-8}$  contrast sources,  $10^\circ$  roll, iterative roll subtraction

*RMS wavefront change between rolls indicated*

0.25 nm

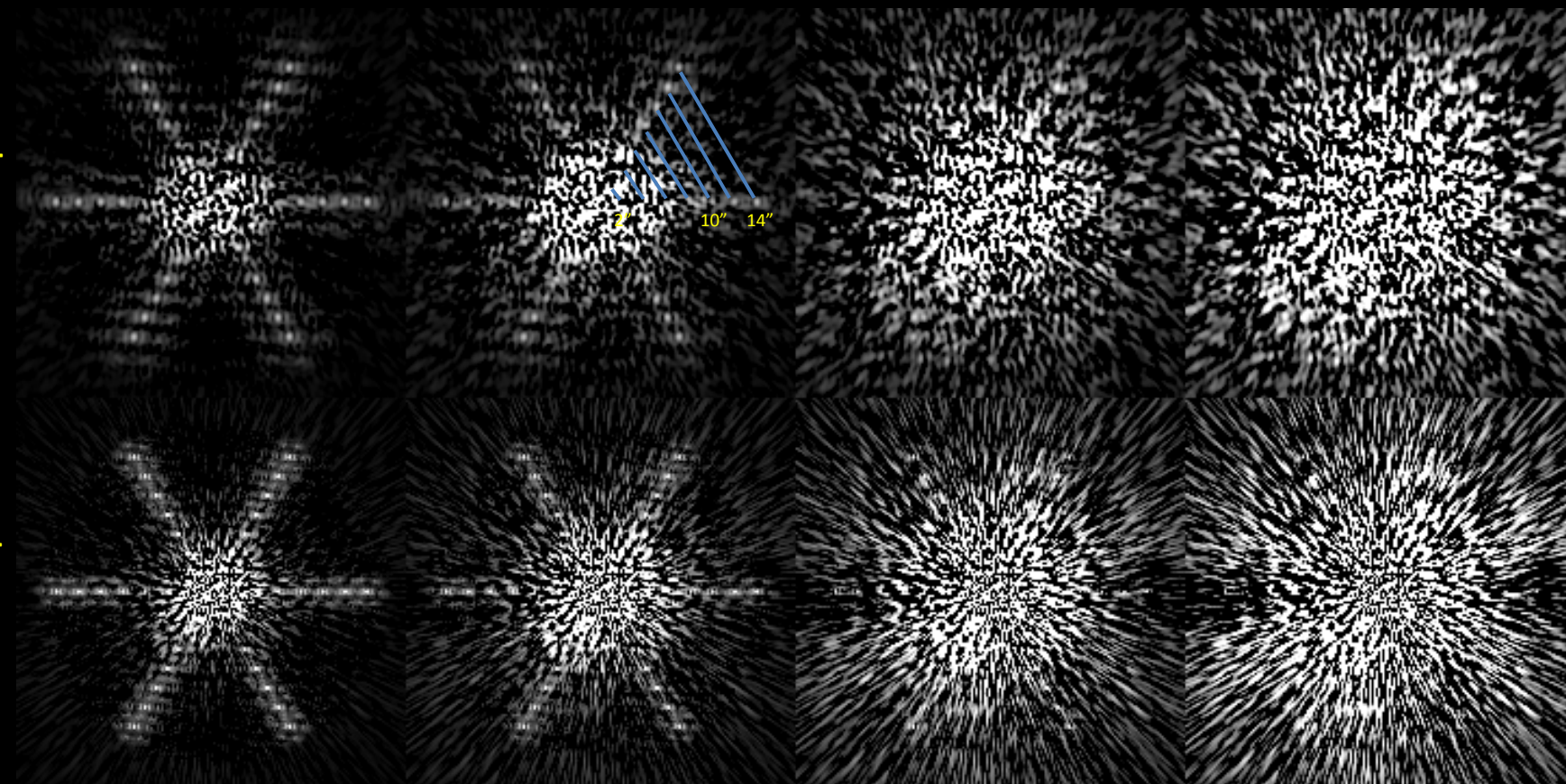
1 nm

5 nm

15 nm

F430M spot

F210M spot



# PSF Simulation Tools

The image displays the 'Webb PSF GUI' software interface, titled 'James Webb PSF Calculator'. The interface is divided into several sections:

- Source Properties:** Includes 'Spectral Type' (set to G0V), 'Source Position' (RA=0.0, PA=0), and a 'Plot spectrum' button.
- Instrument Config:** Features tabs for 'NIRC2', 'NIRSpec', 'MIRI', 'TFI', and 'FGS'. The 'NIRC2' tab is active, showing 'Configuration Options for NIRC2' (Filter: F200W, Consec, Pupil) and 'Configuration Options for the OTE' (ORD File: ORD\_RevV\_nircam\_155.fm, # 1, 155 nm RMS for OTE+ISIM + NIRC2).
- Calculation Options:** Includes 'Field of View' (5 arcsec/side), 'Output Oversampling' (2x finer than instrument pixels), 'Coronagraph Oversampling' (2x finer than Nyquist), '# of wavelengths' (Leave blank for autoselect), and 'Jitter model' (Just use OPDs).

At the bottom, there are buttons for 'Compute PSF', 'Display PSF', 'Display profiles', 'Save PSF As...', 'More options...', and 'Quit'. A note states 'All PSFs shown on log stretch.'

Surrounding the central window are several example PSF plots:

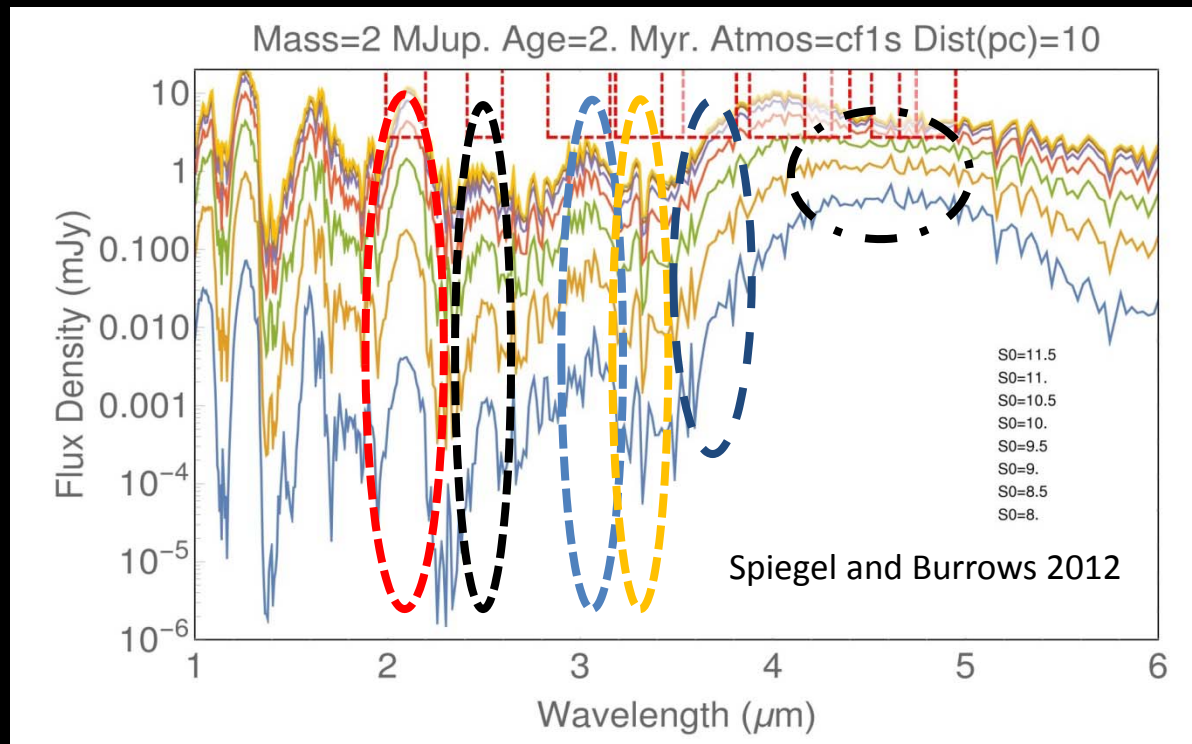
- NIRC2 F200W:** A blue, star-like PSF with a central bright spot and surrounding diffraction spikes.
- NIRSpec F140X acq:** A dark, star-like PSF with a central bright spot and surrounding diffraction spikes.
- TFI 4.0  $\mu\text{m}$ :** A red, star-like PSF with a central bright spot and surrounding diffraction spikes.
- FGS:** A dark, star-like PSF with a central bright spot and surrounding diffraction spikes.
- MIRI F1165C + FQPM coron:** A blue, star-like PSF with a central bright spot and surrounding diffraction spikes.

Two plots on the right side show 'Scale Profile' and 'Radial Profile' graphs, plotting intensity against radius in arcseconds.

<http://www.stsci.edu/~mperrin/software/webbpsf.html>

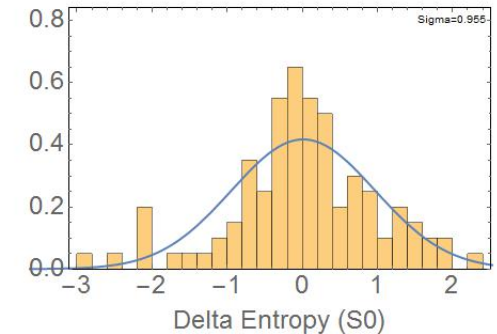
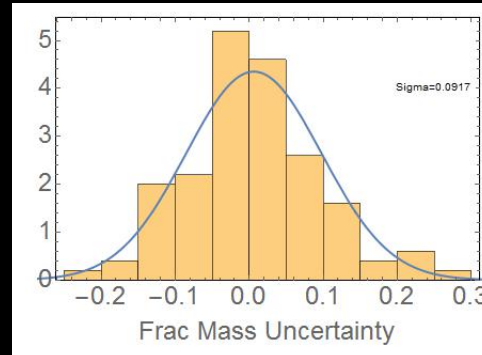
# Illustrative Coronagraphic Observations

- Observe  $\sim 5$  known planetary systems with the NIRCam and MIRI coronagraphs to recover physical and atmospheric properties
  - Mass, Radius,  $T_{\text{eff}}$ , Luminosity, Clouds, Composition Initial Entropy
- Search for lower mass planets down to  $\sim 0.1\text{-}0.3 M_{\text{Jup}}$
- Select targets in angular separation range  $0.4''\text{-}3''$ , masses  $< 13 M_{\text{Jup}}$

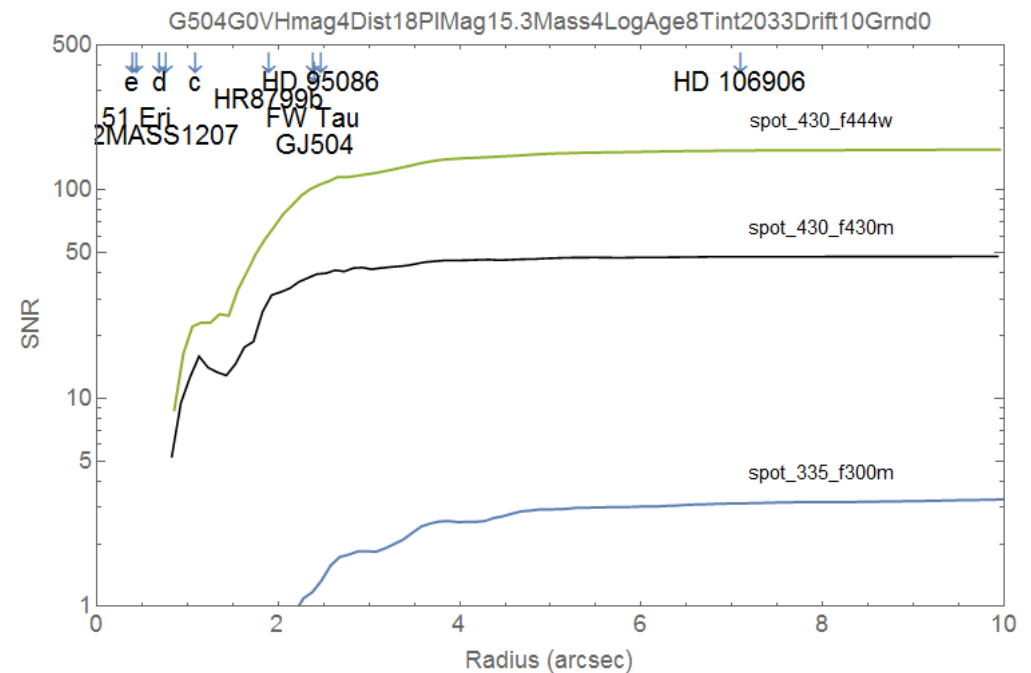


# Coronagraphic Observations -2

- Monte Carlo analysis over broad range of masses, ages, shows NIRCcam (F210M, F250M, F300M, F335M, F430M) + MIRI (F1065C, F1140C, F1550C) yields masses, radii, entropy, etc to 10% for known planets.

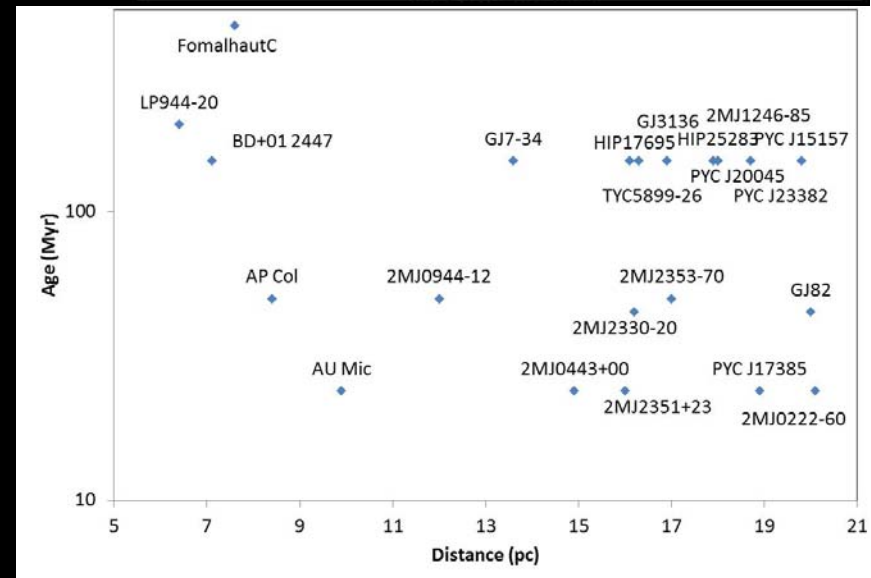
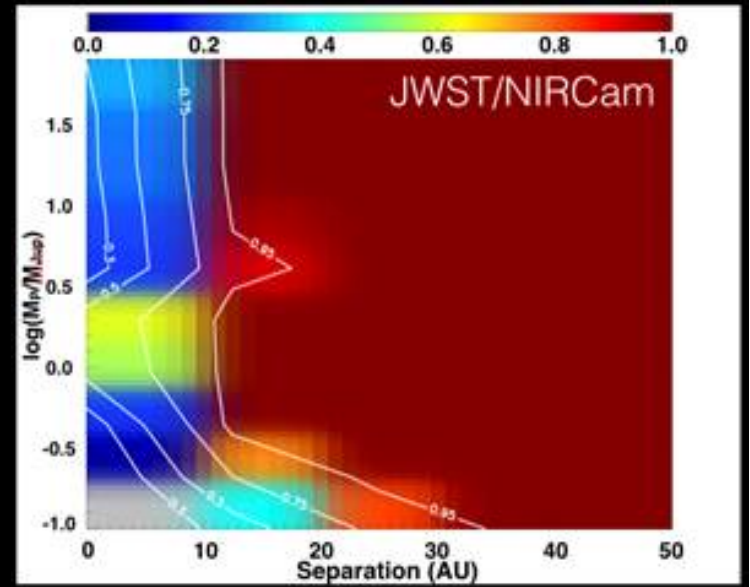


- Are systems like HR8799 the exception or rule?
- Use JWST's sensitivity to probe to lower masses outside of ~1-2" in F444W where planets brightest and F322W2 to reject stars & galaxies



# M Star Survey

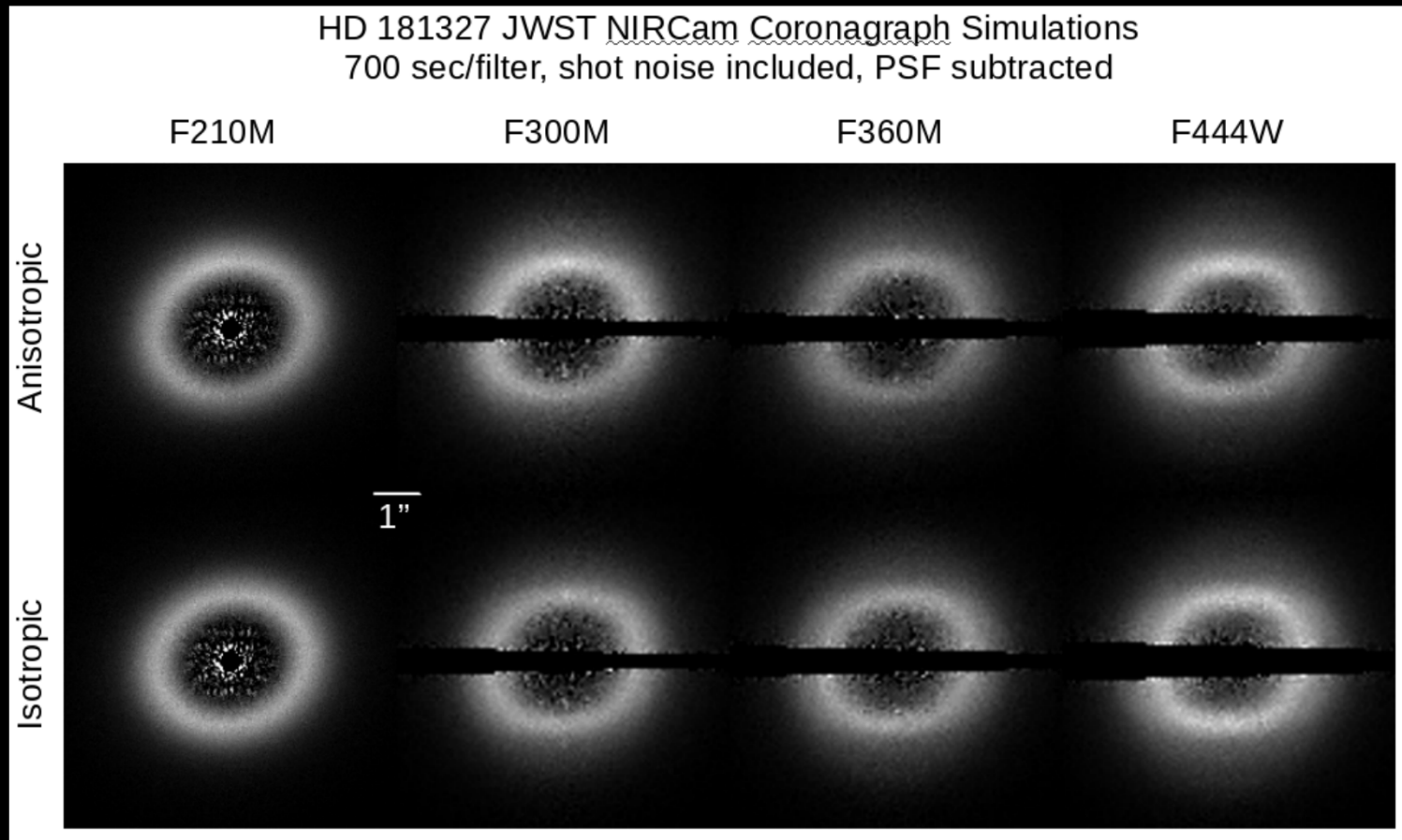
- Kepler and microlensing suggest many small planets orbiting M stars
- NIRCcam coronagraphy can reach Saturn - Uranus masses for <150 Myr planets within 15 pc.
- Probe 10-15 AU: CO snow line favored for ice giant formation
- Survey ~15 objects at F322W2 and F444W at 3.5 hr/obj
- Use entire sample to create reference star library



Dist (pc)	Med Spec Type	Min Age (Myr)	Med Age (Myr)	MaxAge (Myr)	WISE W2 (Mag)
16.25	M4	24	150	440	7.26

# Disk Imaging

- JWST wavefront error (132 nm) precludes more sensitive searches for debris disks compared with HST
- Ultimate performance depends on stability between target and reference stars (5-10 nm?)



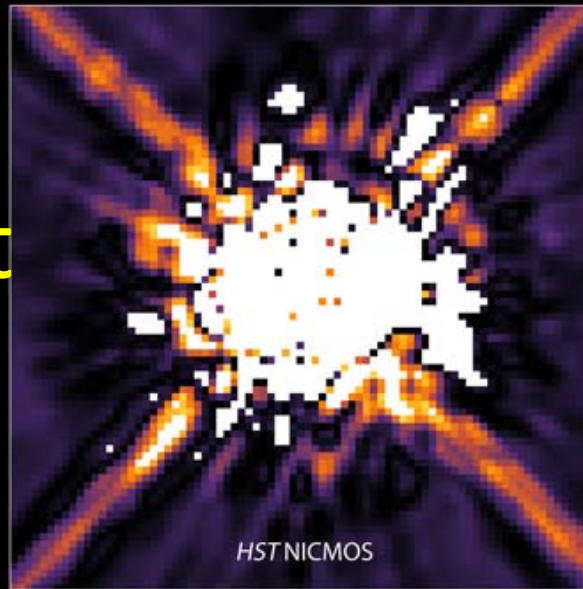
# Use APT 24.3 to Define Program & Estimate Overheads (!)

- NIRCam: 5 medium + 2 wide filters, 2 rolls, one ref star
- MIRI: 3 4QPM filters, One ref. star

Instrument	Star	Observation	Filters	Time to complete Observing Sequence (minutes)				Total	Effic
				Science	Instr OH	Slew	Obs OH		
NIRCam	Reference	LongBar	5	33	18	15	11	77	43%
NIRCam	Reference	Short Bar	1	33	18	3	9	62	52%
NIRCam	Reference	Long Spot	2	26	18	2	7	53	49%
MIRI	Reference	F1550C-Ref	1	29	18	4	8	60	49%
MIRI	Reference	F1140C-Ref	1	29	18	2	8	57	51%
MIRI	Reference	F1065C-Ref	1	29	18	2	8	57	51%
MIRI	Target	F1065C	1	29	18	15	10	72	40%
MIRI	Target	F1550C	1	29	18	2	8	57	51%
MIRI	Target	F1140C	1	29	18	2	8	57	51%
NIRCam	Target+5deg	+5 Deep Search	2	33	18	3	9	63	52%
NIRCam	Target+5deg	+5 Long Bar	5	33	19	2	9	62	53%
NIRCam	Target+5deg	+5 Short Bar	1	26	18	0	7	51	51%
NIRCam	Target-5deg	-5 Short Bar	1	26	18	4	8	56	46%
NIRCam	Target-5deg	-5 Deep Search	2	33	18	0	8	59	55%
NIRCam	Target-5deg	-5 Long Bar	5	33	19	0	8	60	55%
<b>Total (hours)</b>				<b>7.5</b>	<b>4.6</b>	<b>0.9</b>	<b>2.1</b>	<b>15.0</b>	<b>50%</b>

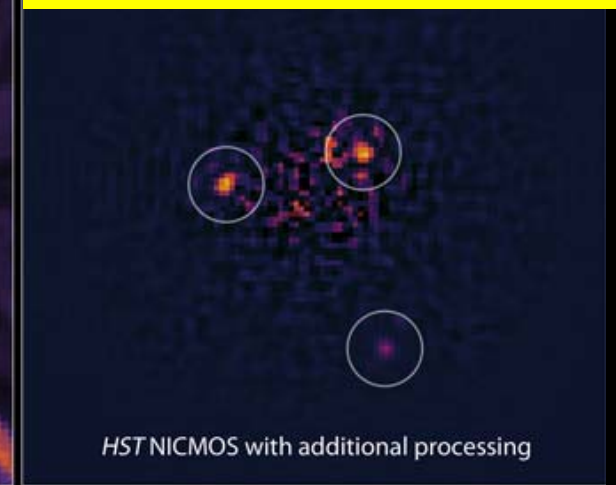


# Pipeline Image Processing Built on HST Experience



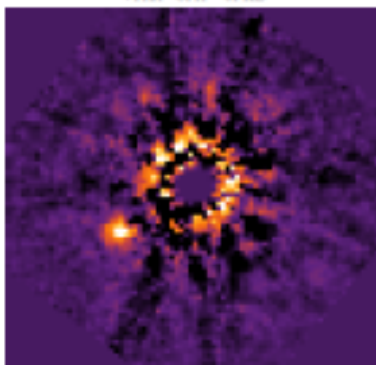
NASA, ESA, and R. Soumerai (STScI)

Chart from Remi Soumerai

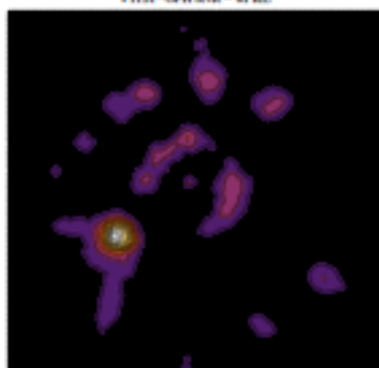


- JWST will accumulate PSF references for LOCI, KLIP, PCA, etc. Individual ref stars may be non-proprietary
- Generate pipeline subtracted images as high level product

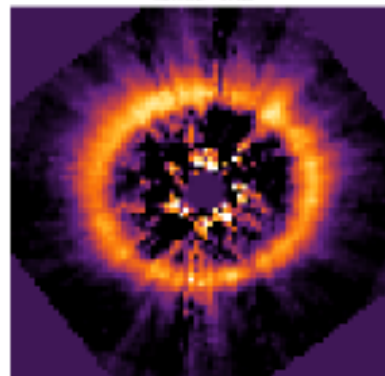
Subtracted product  
V1121-OPH - 61 KL



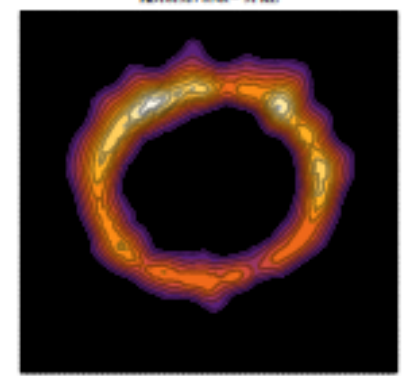
SNR map  
V1121-OPH - 61 KL



Subtracted product  
HD 1507 - 51 KL



SNR map  
HD 1507 - 51 KL



# Conclusions

- NIRCcam coronagraphic capabilities are limited by telescope wavefront error --- large by standards of Extreme AO or future observatories
- NIRCcam's coronagraphic power comes from JWST's WF stability (10 nm?) and low background at  $\lambda > 2.4 \mu\text{m}$  and  $\theta > 1''$
- Acquisition overheads are significant but APT and ETC tools will help with observation planning
- STScI will provide PSF library and advanced data processing