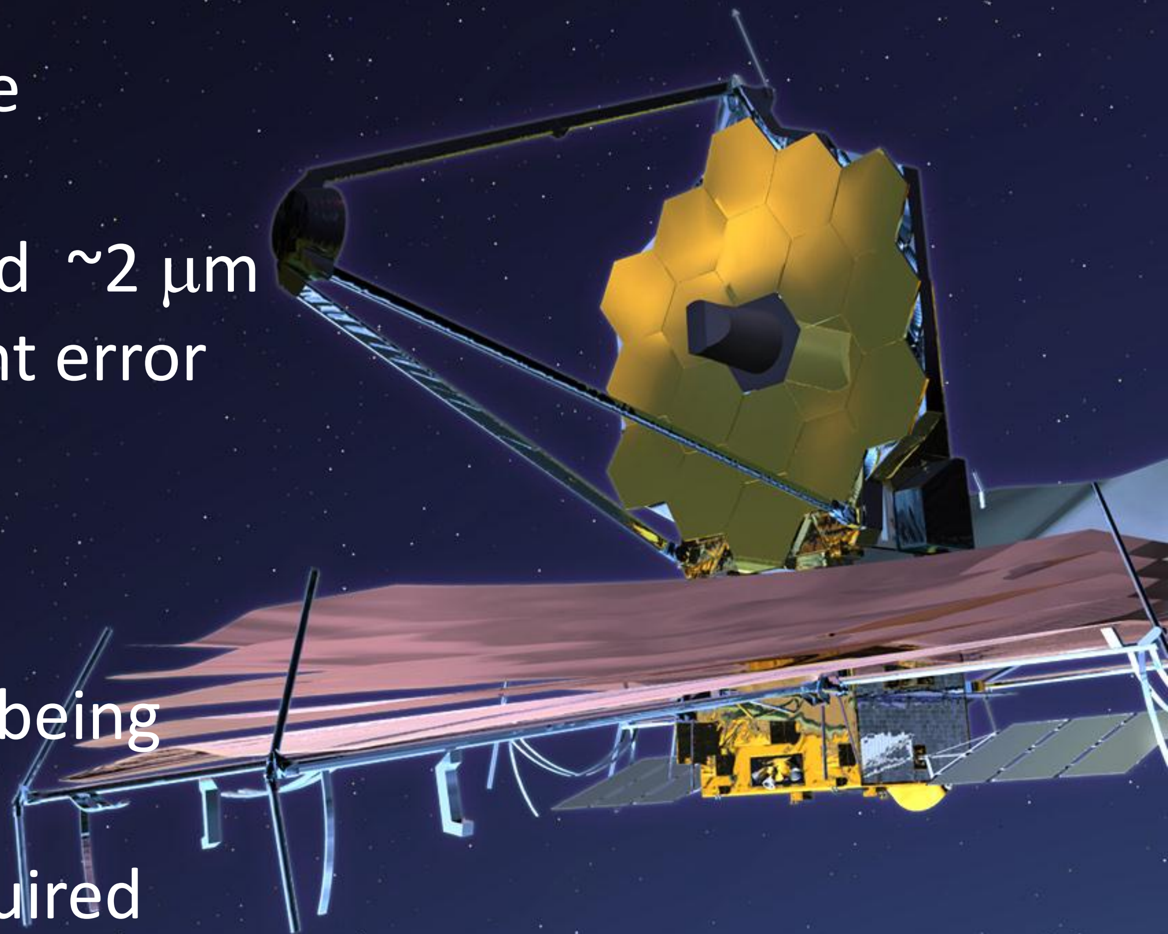
The James Webb Space Telescope: The Next BIG Step in Exoplanets

C. Beichman, John Krist,
Tom Greene, M. Rieke, Rene Doyon, et al.

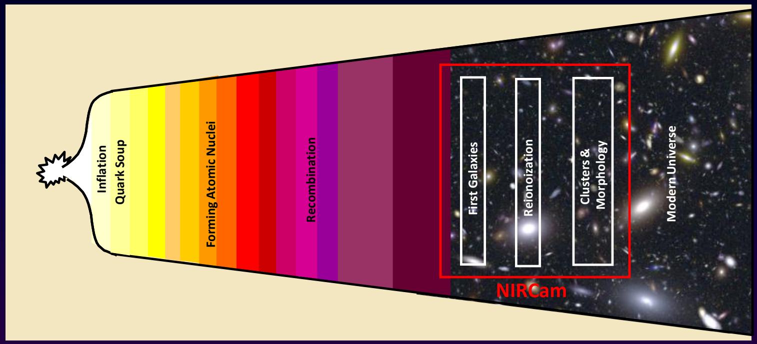
ExoPag Meeting, Reno NV
Oct 14 2012

JWST In a Nutshell

- BIG, COLD Telescope
  - 6.5m and 40K
  - Diffraction limited ~2 μm
  - 131 nm wavefront error
- Big Budget
- 4 Instruments
- Stable L2 orbit
- Major components being delivered
- Some assembly required
- Launch by $2018_{-0}^{+?}$



4 Main Science themes

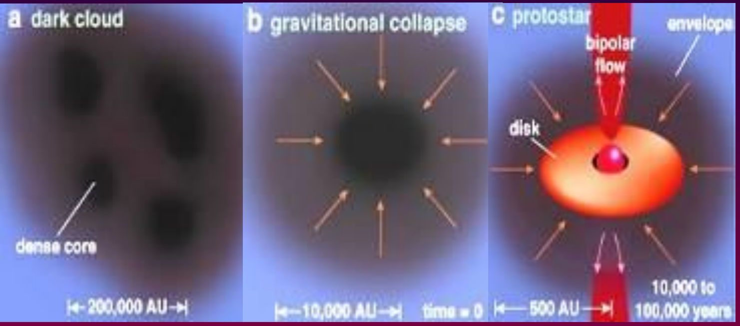


First Light and Reionization:

Conduct deep surveys and follow-up spectroscopy for z~7-15

The Assembly of Galaxies:

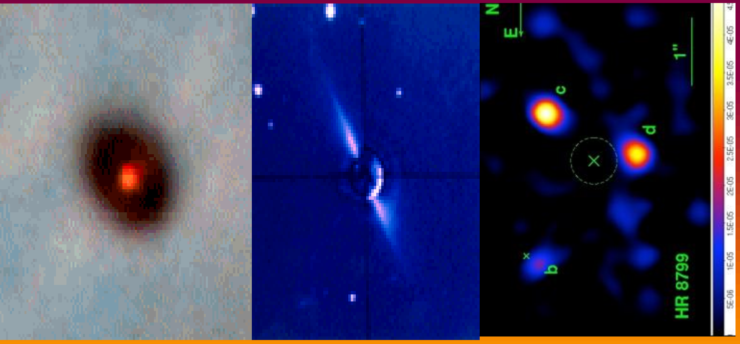
Measure shapes and colors of galaxies, identify young star forming clusters



The Birth of Stars & Planets:

Identify and characterize protostellar objects, probe low and high mass ends of IMF

Follow chemistry through different phases of star formation



Planetary Systems and the Origins of Life:

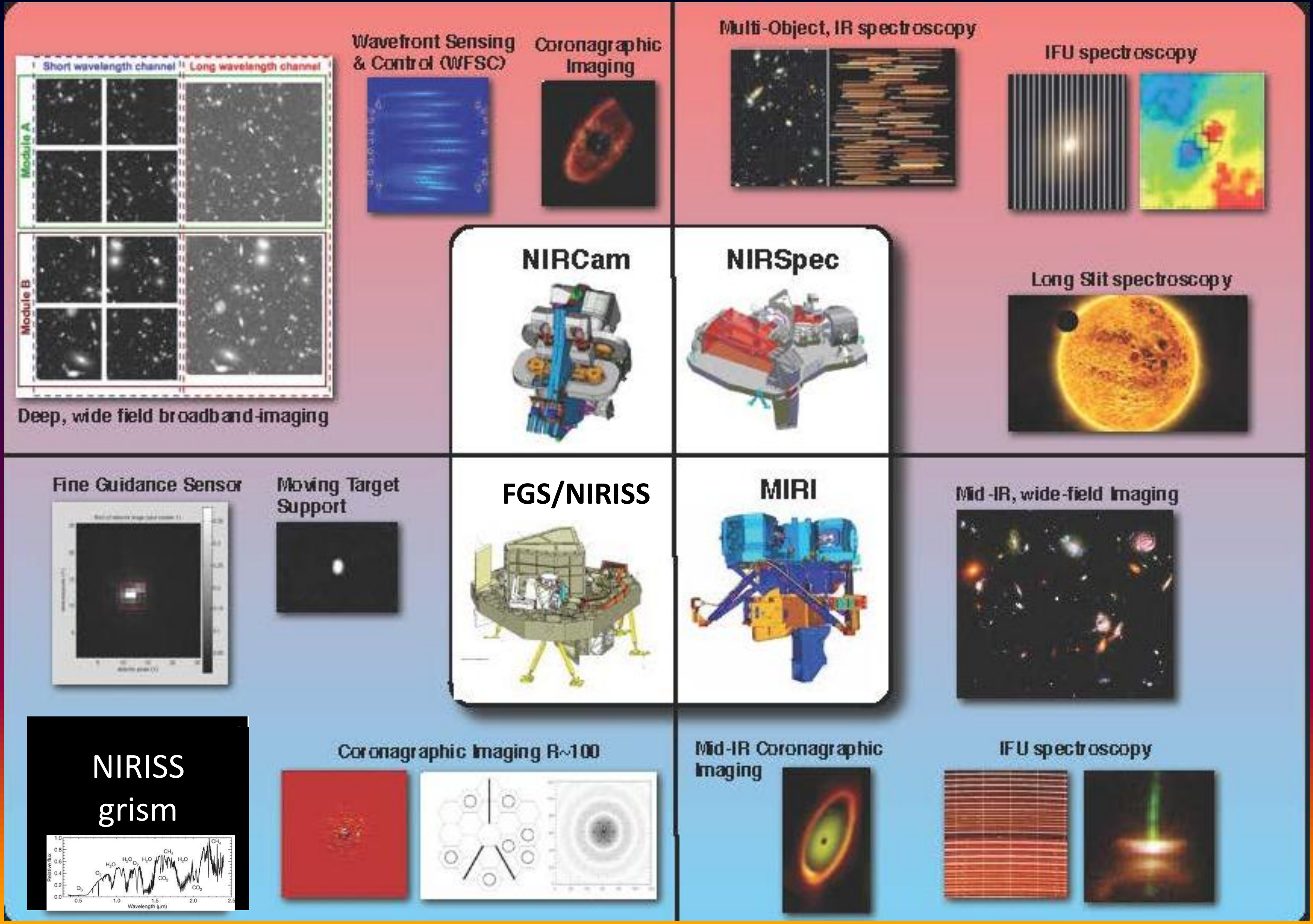
Image and characterize young gas giants

Characterize planetary atmospheres

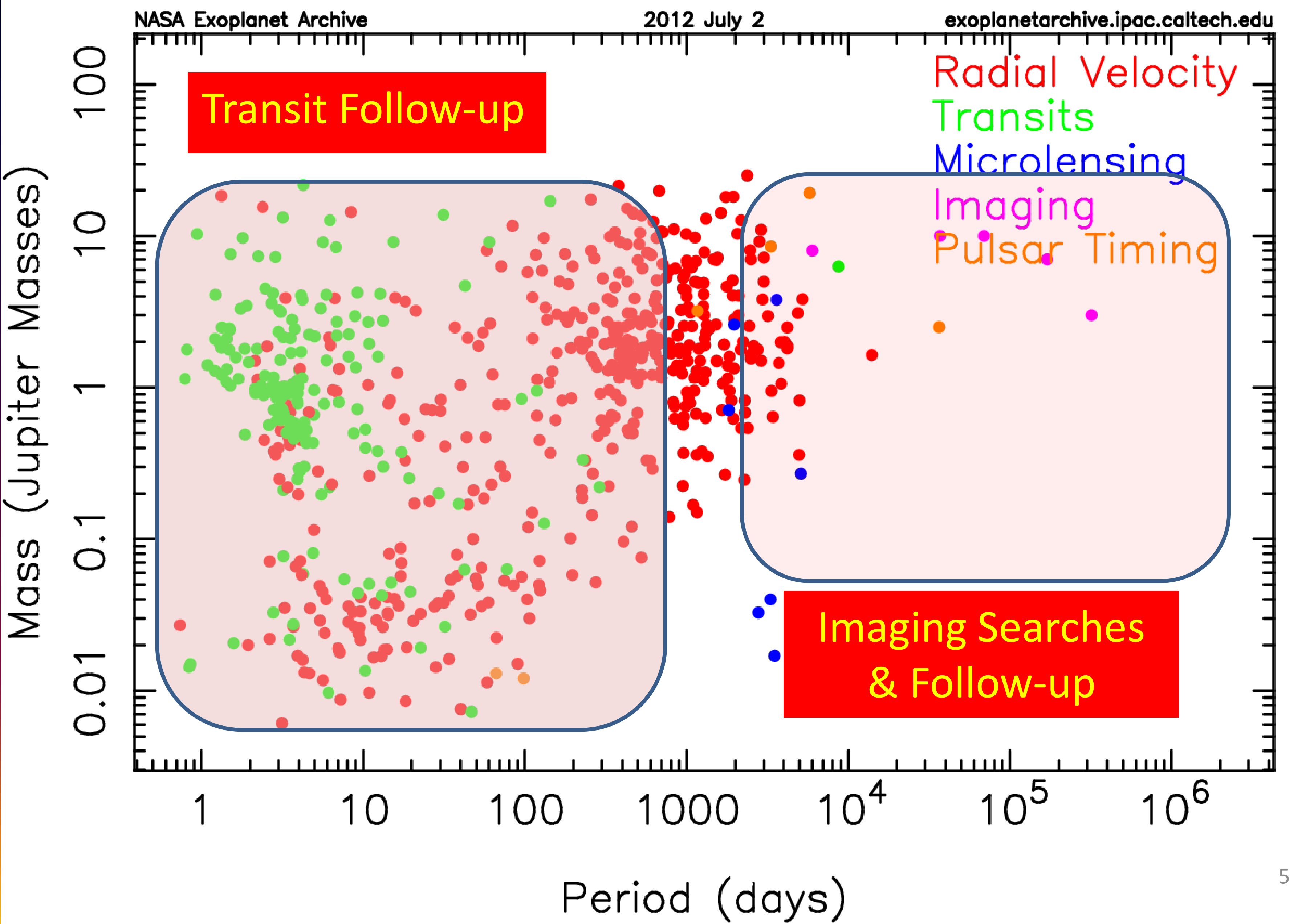
Study planet-debris disks interactions

Study KBOs as debris disk parent bodies

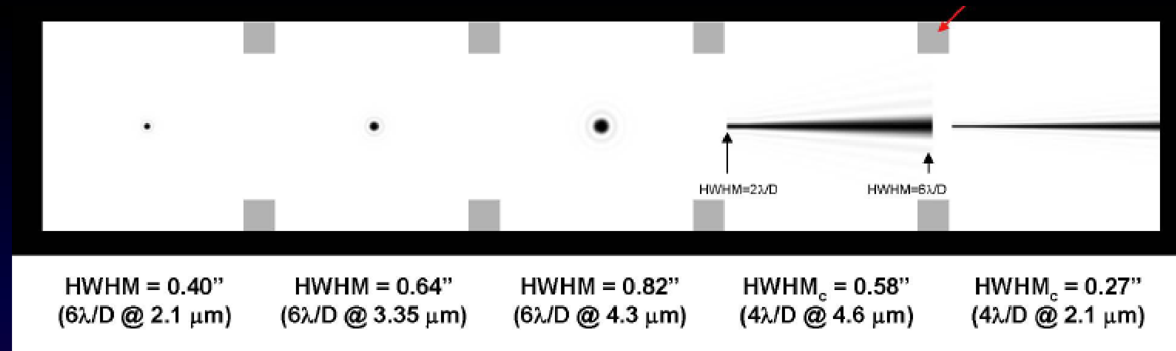
JWST Instruments



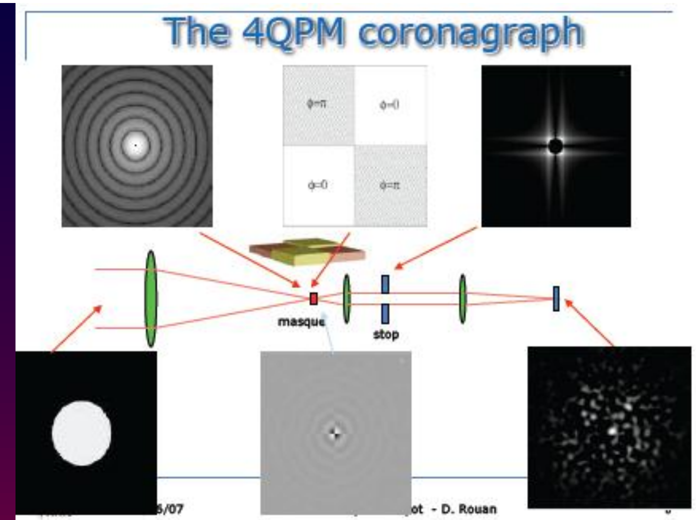
Opportunities for ExoPlanet Science



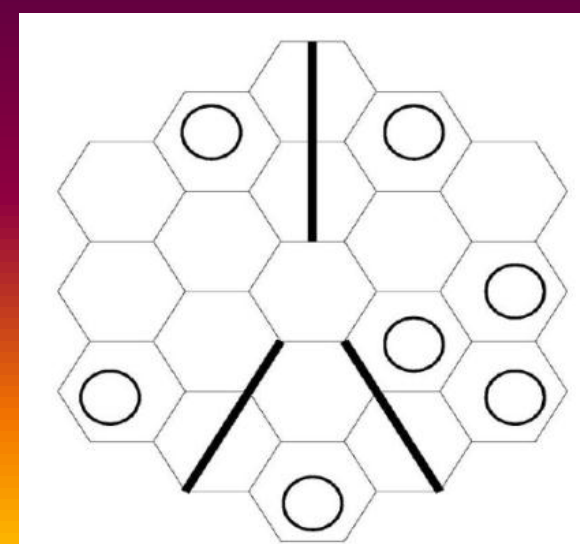
Planet Imaging with JWST



- Coronagraphs in 3 instruments
  - NIRCAM Lyot coronagraph for λ>2 μm with both wedge- and circular occulters.
  - MIRI has 3 λ-specific 4-Quadrant phase masks plus classical Lyot coronagraph
  - NIRISS non-redundant mask (NRM) for high spatial resolution images

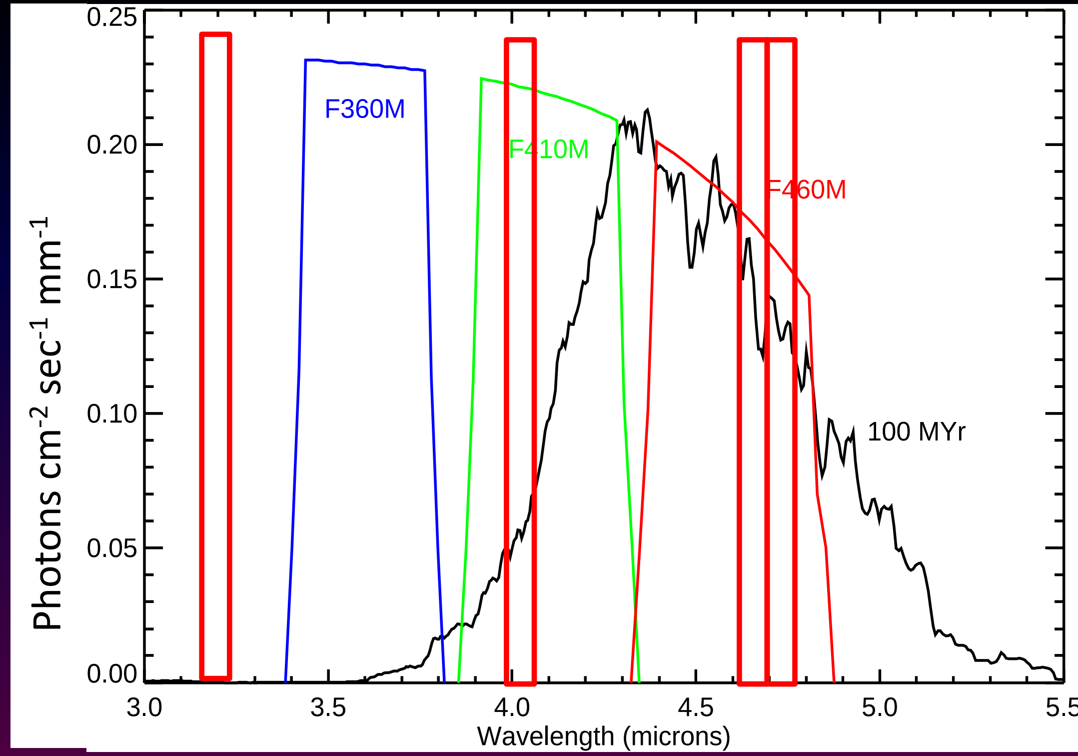


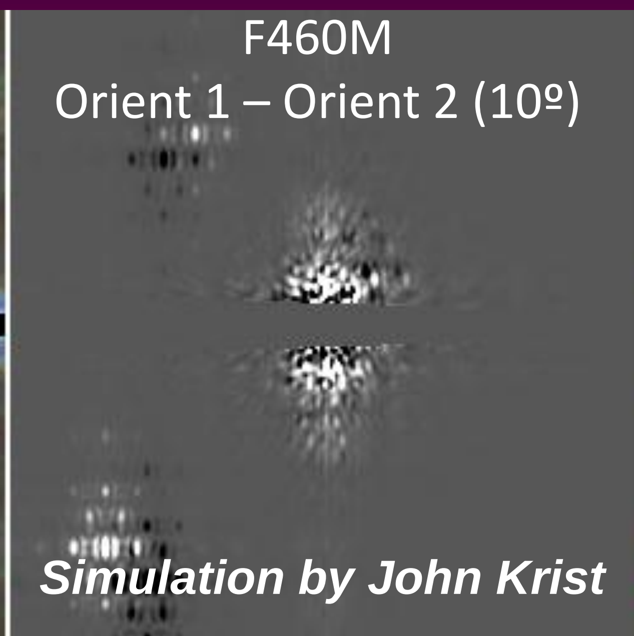
- Ground-space competition
  - 8-10 m ground-based telescopes w ExAO win at λ<2 μm and/or for IWA<500 mas
  - JWST sensitivity advantage at λ>3 μm where space background dominates over diffracted & scattered starlight

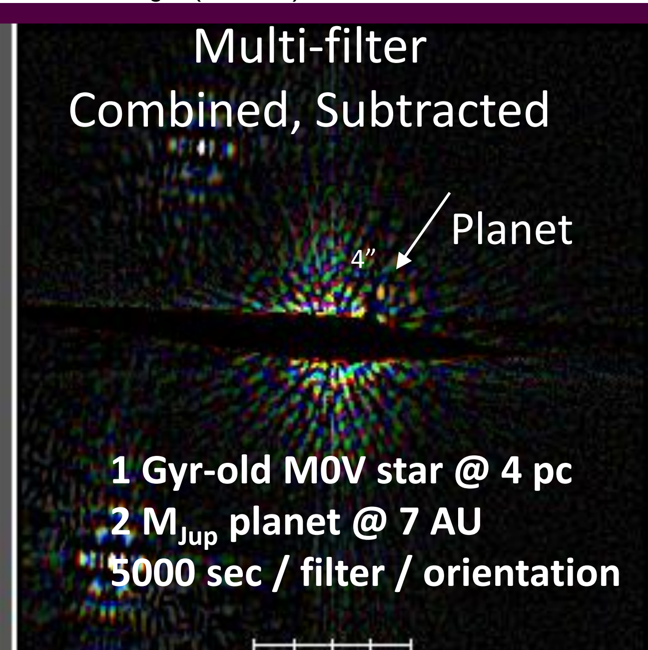


NIRCAM Imaging

- Multiple Lyot coronagraphs tuned for JWST/NIRCAM filters placed to study hot Jupiter atmospheres

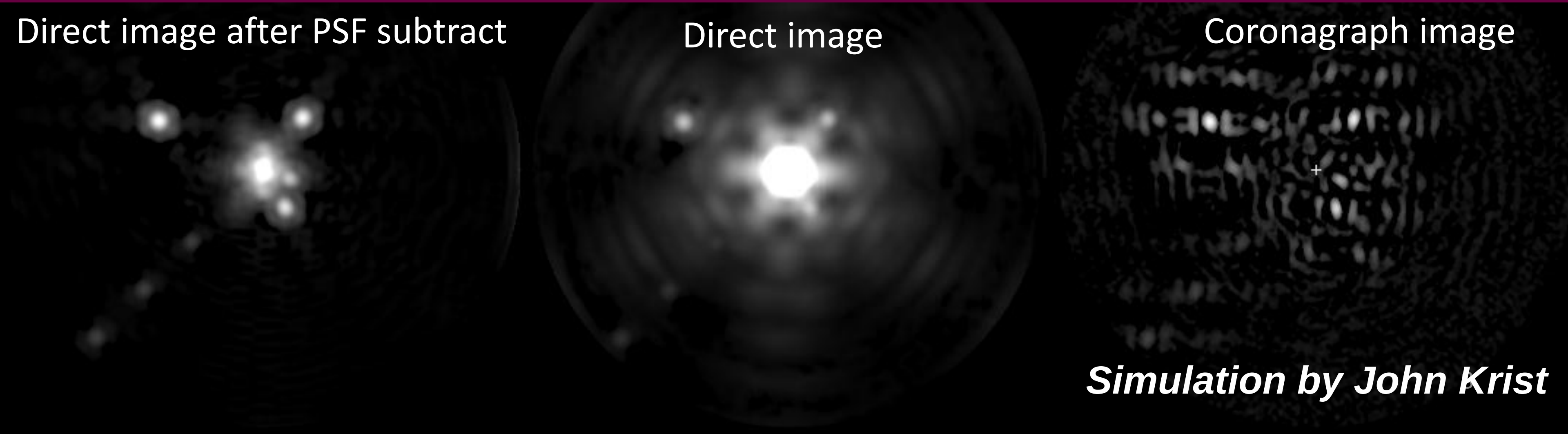






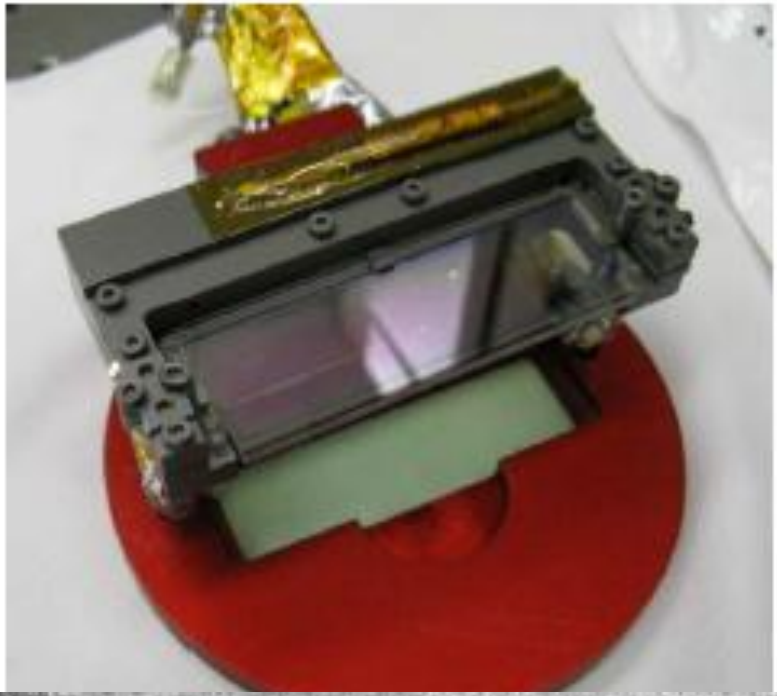
Direct Imaging of HR8799

- Highly stable PSF (few nm drift over few hours) with roll subtraction enables imaging of bright planets w/o coronagraph
  - SNR>50 on (50 Myr, 5 Mjup) at 3-5 μm in 1800 sec
  - SNR>5 on (50 Myr, 0.5 Mjup) at 5 μm
- Better PSF, higher throughput but lower contrast
- Simulation properties in F405N narrow-band filter
  - 1000×0.181 subarray exposures (8.3″ FOV) incl 4 roll angles
  - Known planets b,c,d,e (all 5 Mjup, 50 Myr COND models)
  - Plant 4 more planets at 0.5", 1.5", 2.5", and 3.5“ (0.5 Mjup, 50 Myr)



Coronagraph Status

- Coronagraphic masks fabricated by JPL and installed into NIRCam at LM
- Analysis suggests negligible impact of higher WFE segments when placed under struts hidden by Lyot mask



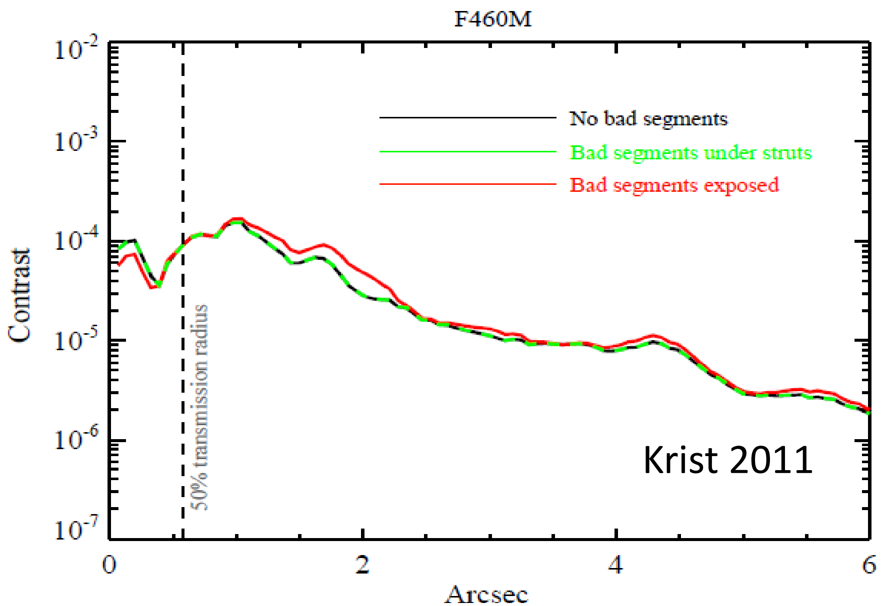
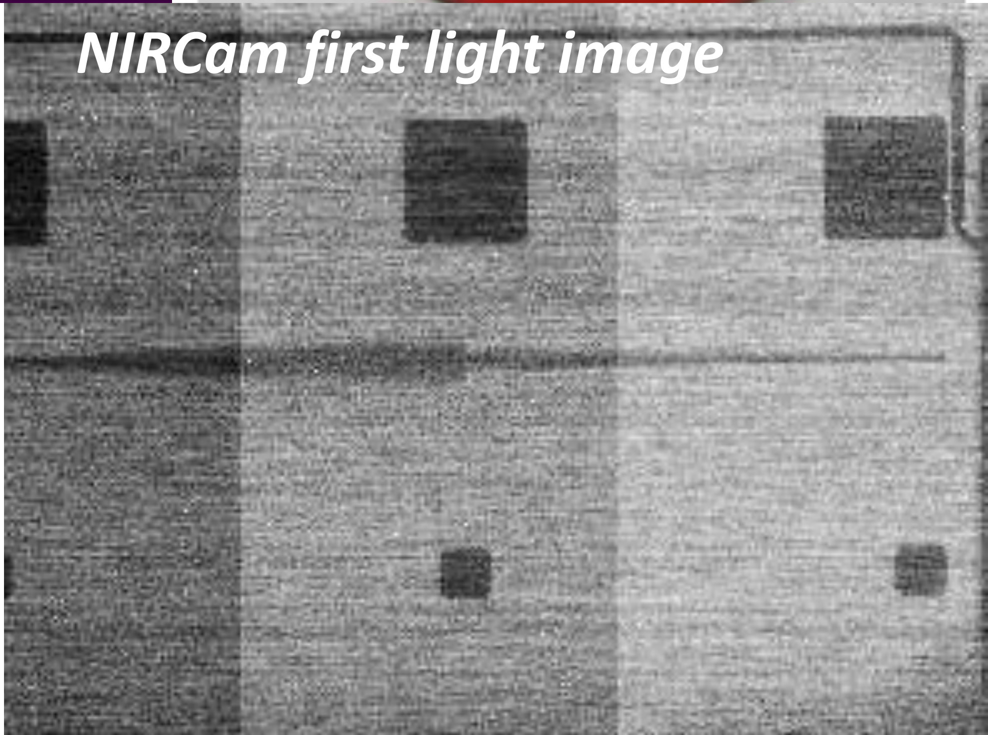
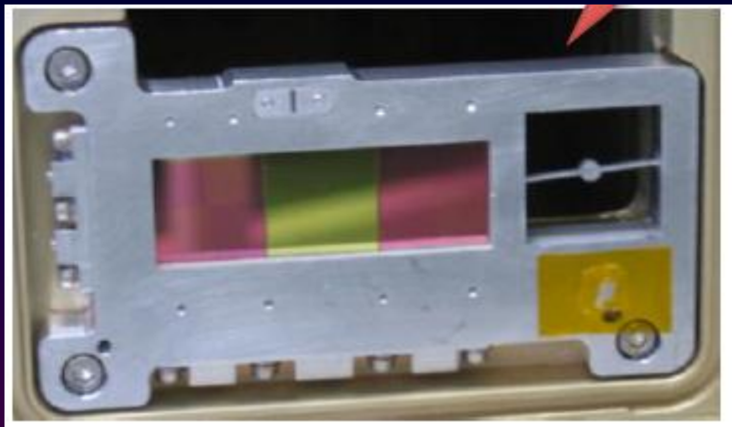
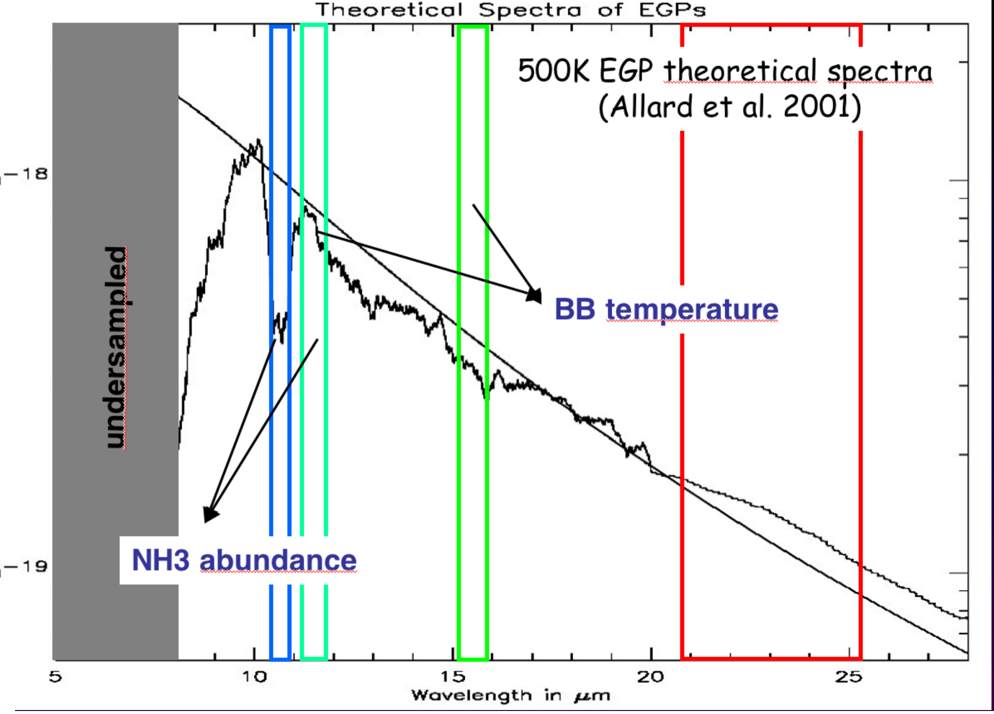


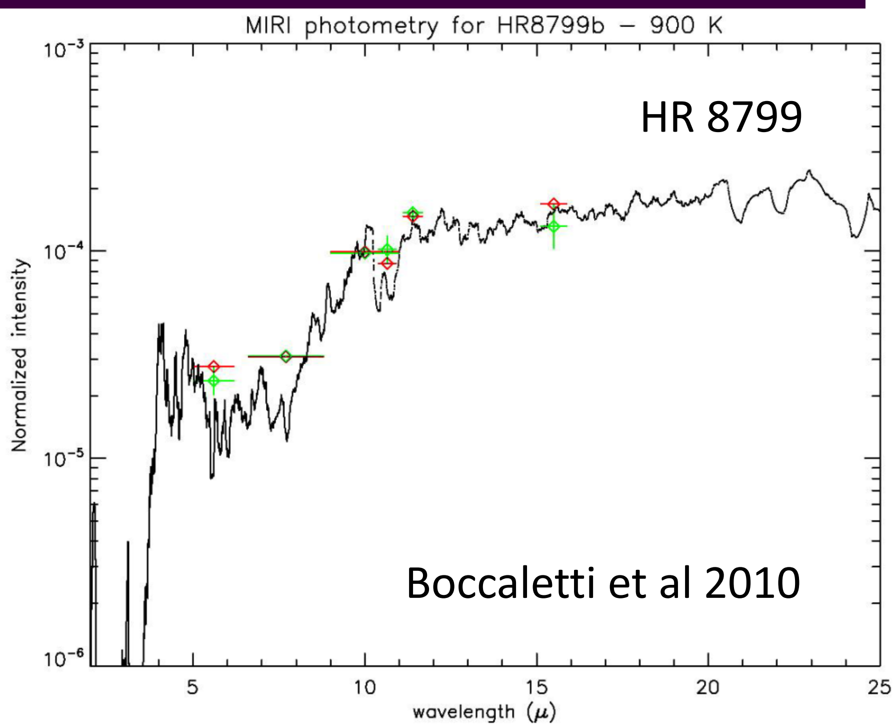
Figure 5. Azimuthal average profiles for F460M (long wavelength wedge) computed within sectors ±30° from the vertical axis.

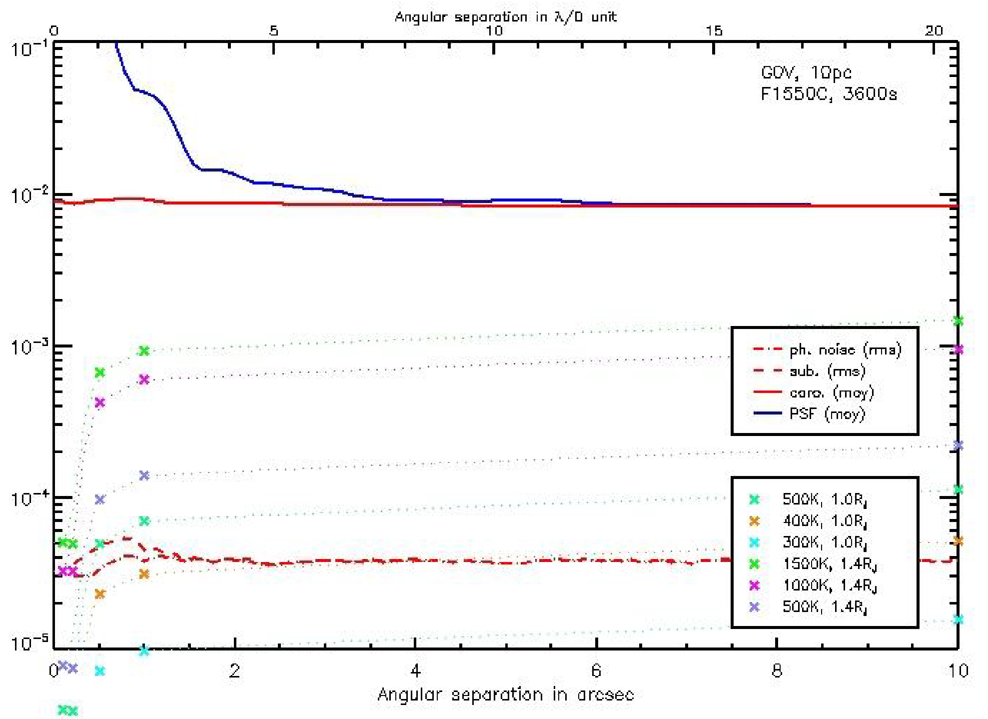


MIRI 4-Qudrant Phase Masks



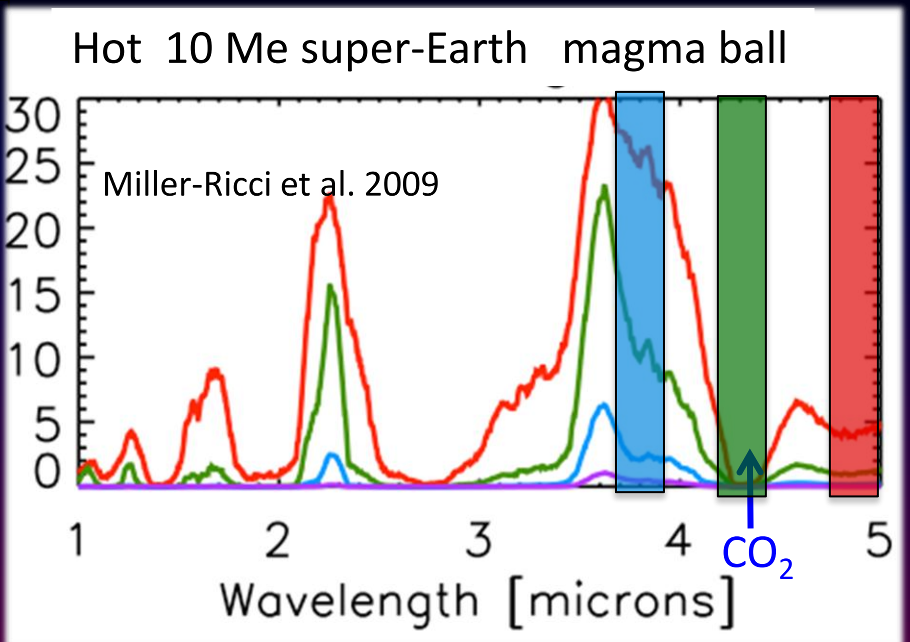




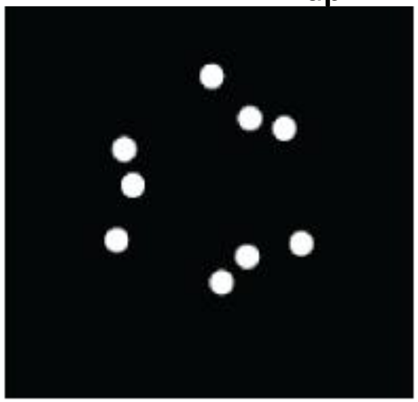


NIRISS: Aperture Interferometric Imaging (AMI)

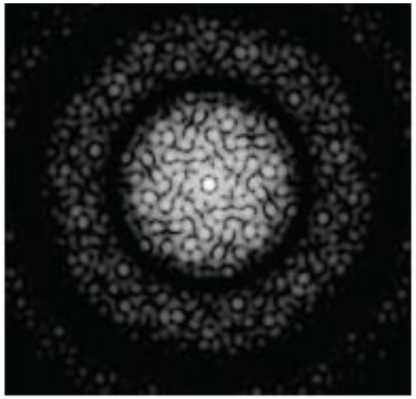
- Non redundant mask providedes very high resolution (0.5 λ/D) at moderate contrast (10^{-4}) and limited outer working angle.
- Medium-band filter set optimized for exoplanet SED; good diagnostic of Teff and Log g.
- Complements NIRCam & MIRI.



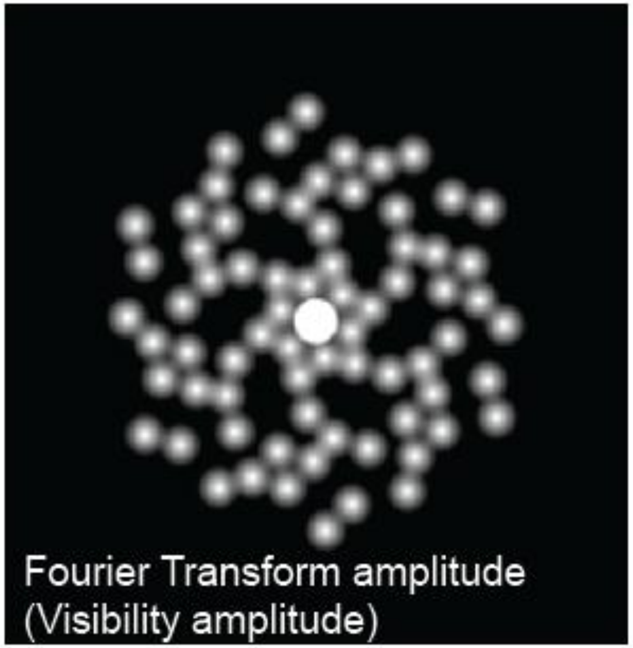
Non Redundant Mask
Resln~0.5 λ/D_{base} (70 mas) out to OWA~λ/D_{ap} (400 mas) at 4.6 μm



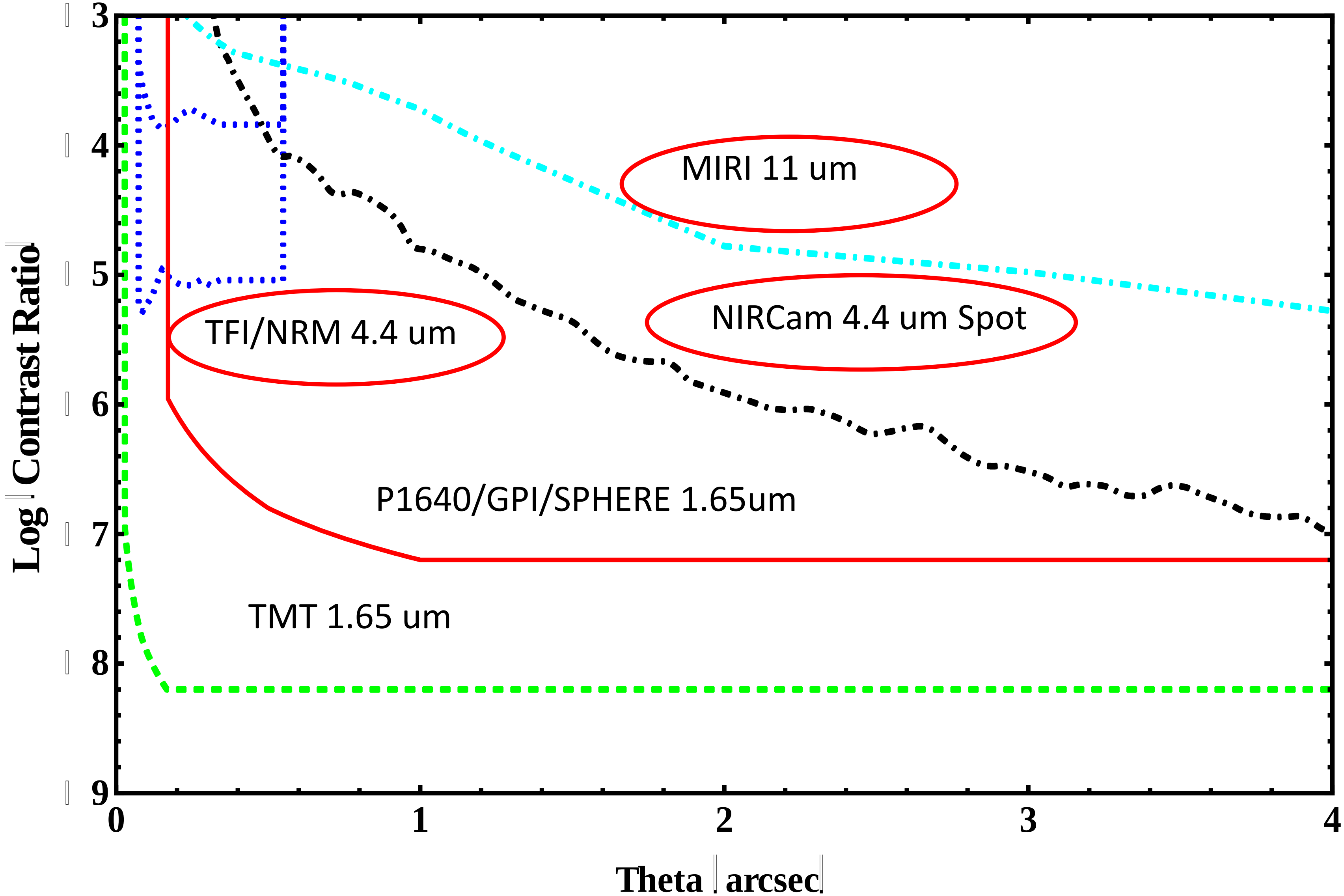
Pupil mask



Interferogram



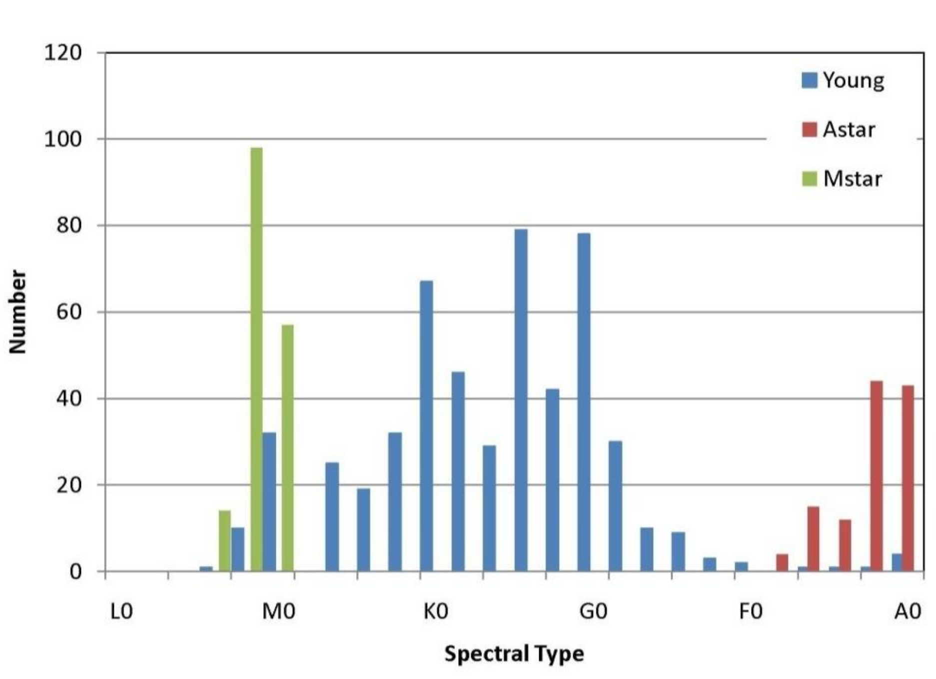
Comparison of Coronagraphic Capabilities: Ground and Space

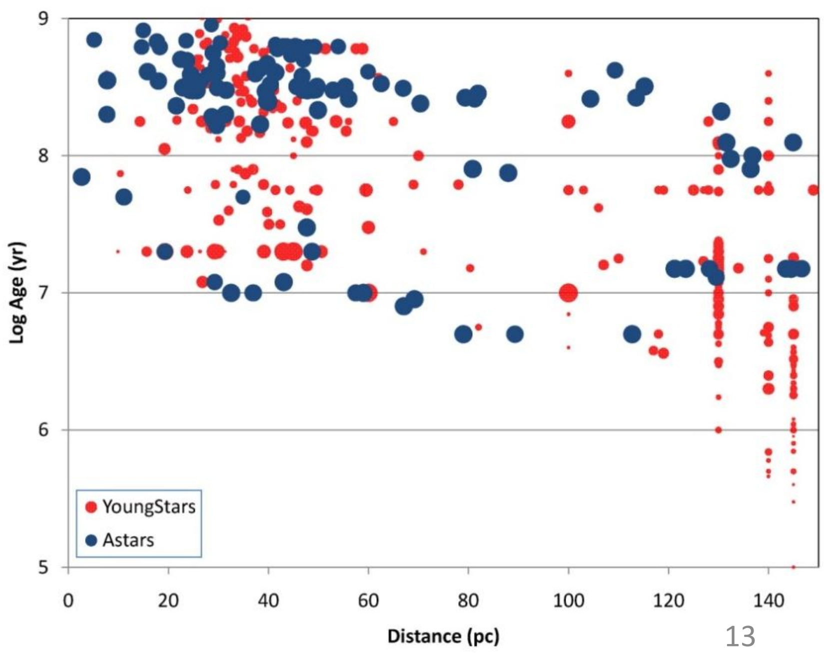


Sample of Nearby Young Stars

SIM Young Star Project	217
Spitzer FEPS Project	306
Spitzer plus nearby A stars	188
Nearby M stars (< 15 pc)	196

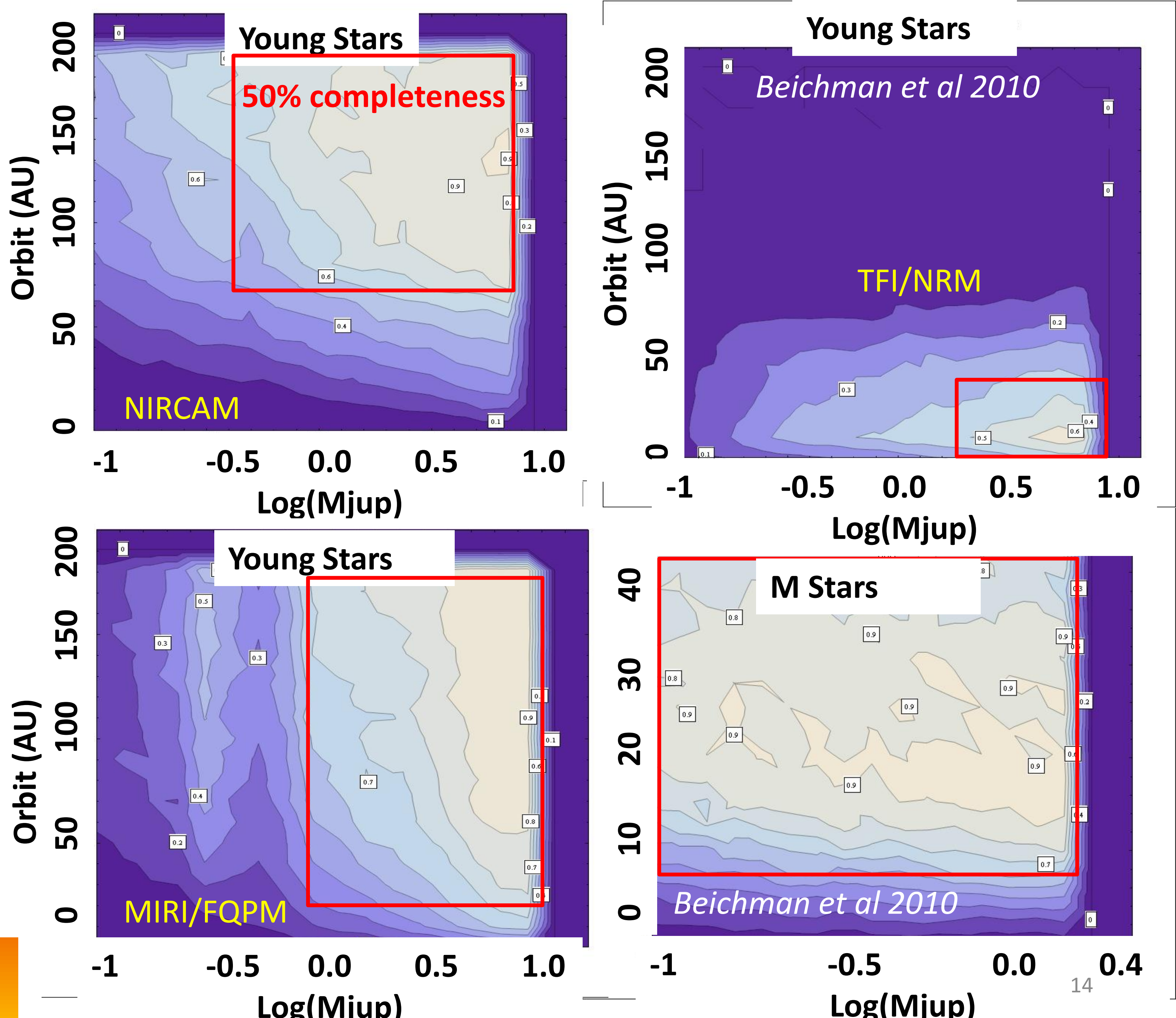
Cluster	Age (Myr)	Distance (pc)	Cluster	Age (Myr)	Distance (pc)
β Pic	20	10-50	Pleiades	125	130
Tucanae	20	45	Chamaeleon	1-10	140
Horlogium	30	60	Taurus-Aurigae	1-10	140
TW Hya	10	60	Upper Sco	1-10	145
ScoCen	5-20	130	IC2391	50	155





Direct Imaging Survey

Nearby Young Stars finds Jupiters to Saturns



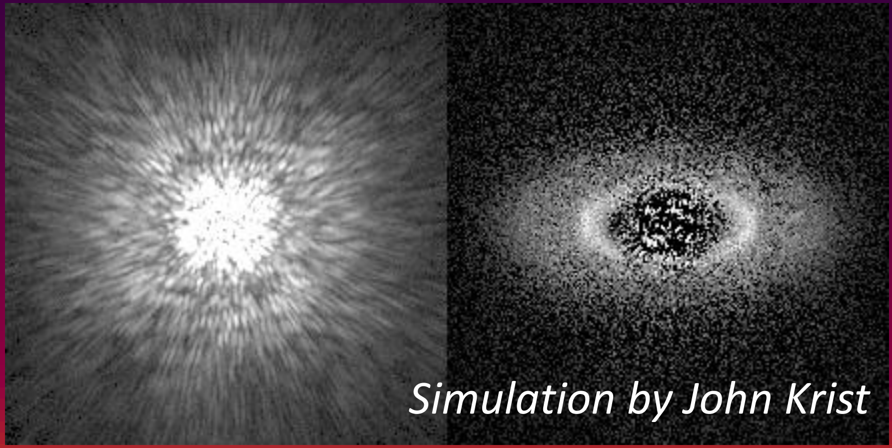
Imaging Score Card

- NIRCAM/MIRI: highest sensitivity/contrast over large field.
- TFI/NRM: Youngest, closest-in planets
- Ground-based: Higher mass planets, closest-in (TMT)
- **Unique JWST science for nearby M stars too faint for Extreme AO**

Instrument	Avg Mass M_{Jup}	Avg. Age (Myr)	Avg SMA (AU)
NIRCam F440W	1.2	90	105
NIRCAM F356W	1.8	62	110
TFI/NRM (~F440N)[1]	2	16	35
TFI/NRM (~F440N)[2]	4	10	45
MIRI/FPQM	2.6	21	53
P1640	5.0	14	85
TMT	3.8	20	70

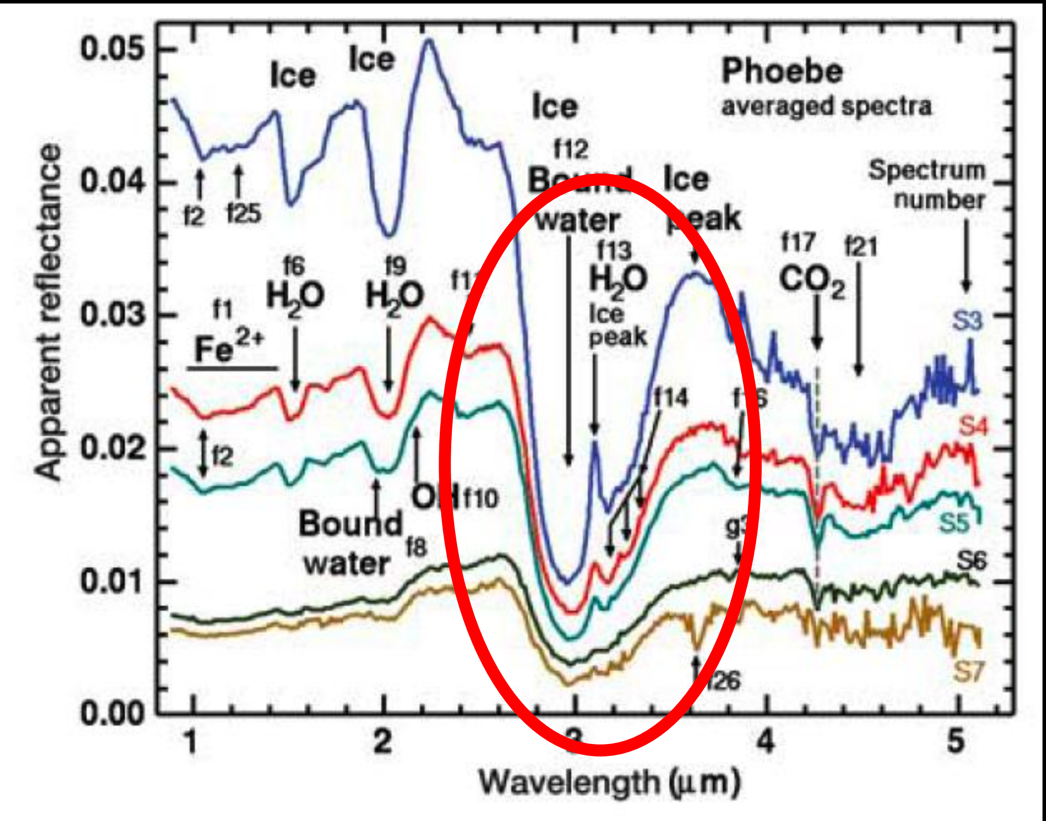
JWST Extends Spitzer/Herschel/HST Results on Circumstellar Disks

- Probe debris disks to complete picture of disk evolution
- Resolve disks & structures looking for rings, gaps, etc. Planets?
- Maps of scattered light and thermal emission to trace dust populations, composition (*3 μm ice feature*), planet interactions
- Combined NIRCAM & MIRI observations for scattered and thermal emission

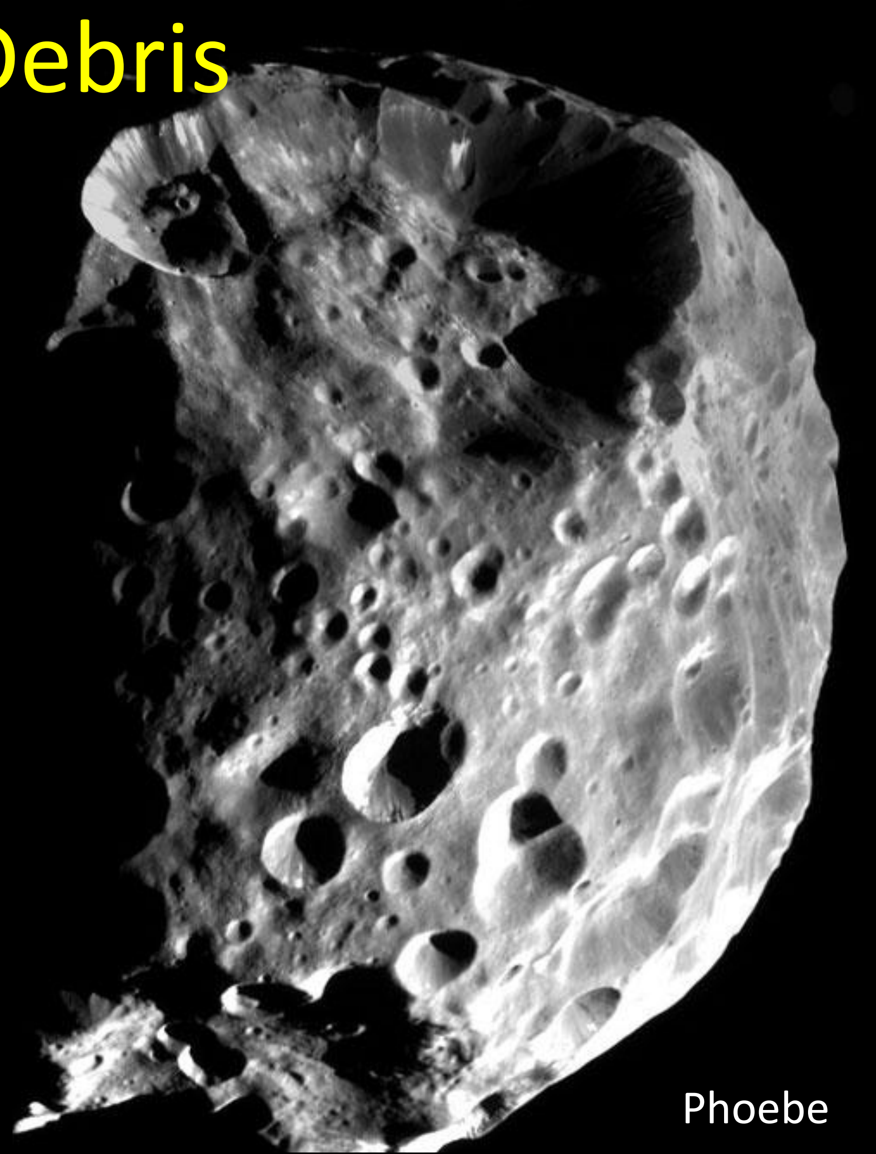


F360M coronagraph simulation of the HD 92945 debris disk. Disk is ~1/20th of β Pic disk, $6x10^{-4}$.
Two 1000 sec exposures with 10 degree rotation, 2nm RMS change and 15 mas position shift
Reference PSF with a 5 nm change an another 15 mas offset
The PSF was subtracted from each and then the two registered in orientation and added.

Kuiper Belt Objects As Debris Disk Parent Bodies



Spectra from D = 220 km "KBO", Clark et a 2005

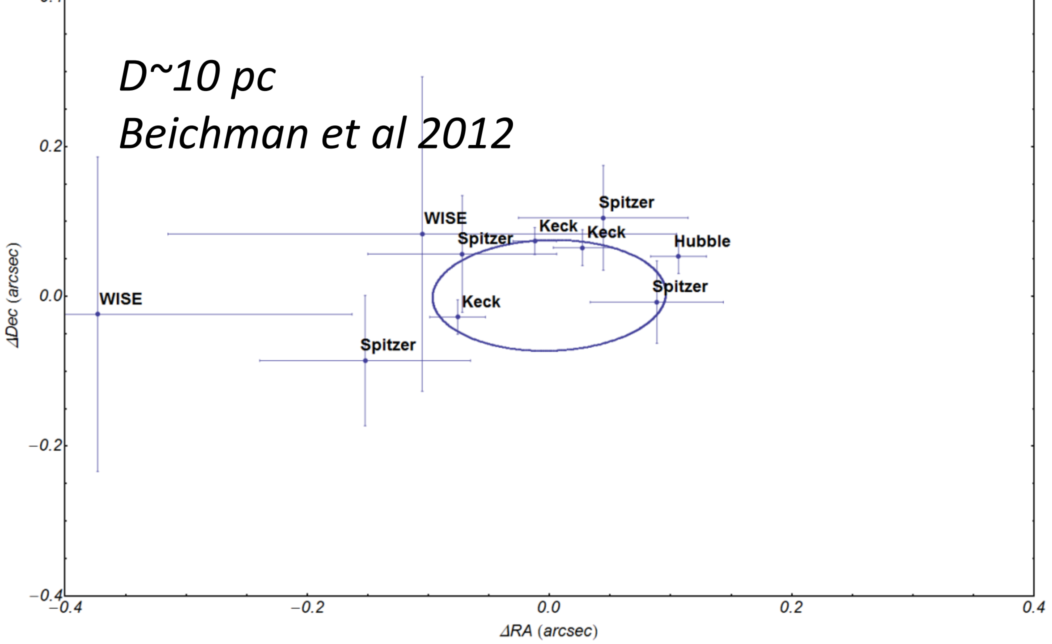


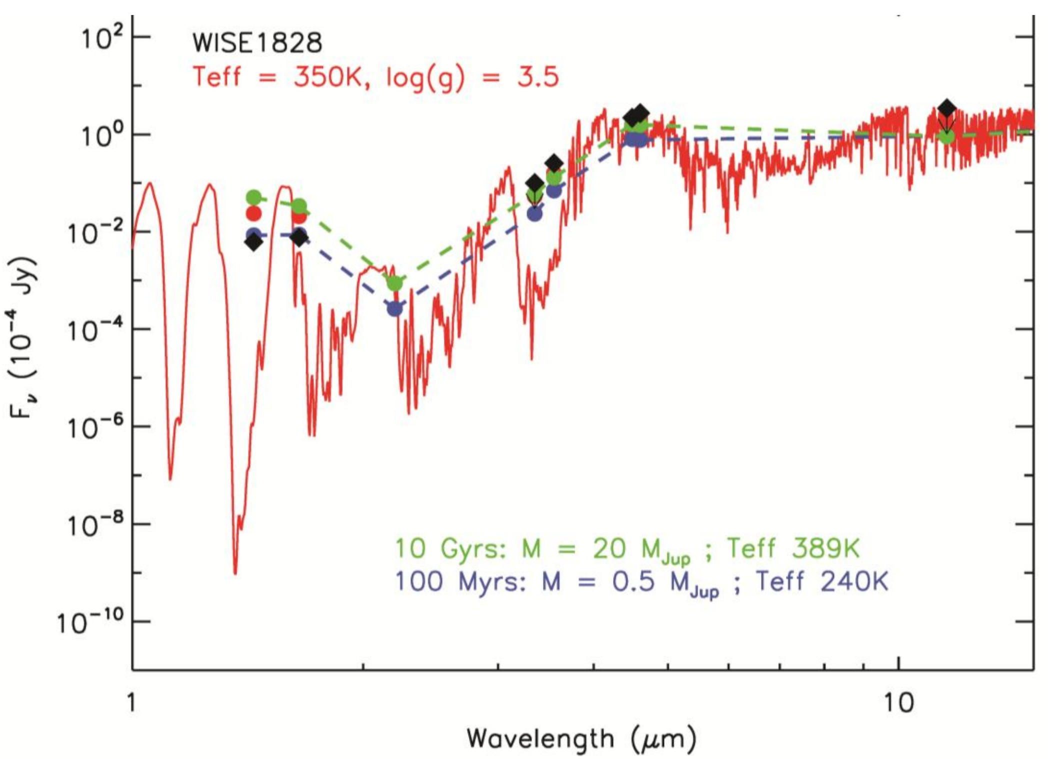
Phoebe

- Filter photometry of dozens of KBOs with d>100 km at R~100 to investigate surface properties
- Astrometry for binaries ➔ mass & density

Nearby Y Dwarfs: The Closest Planets?

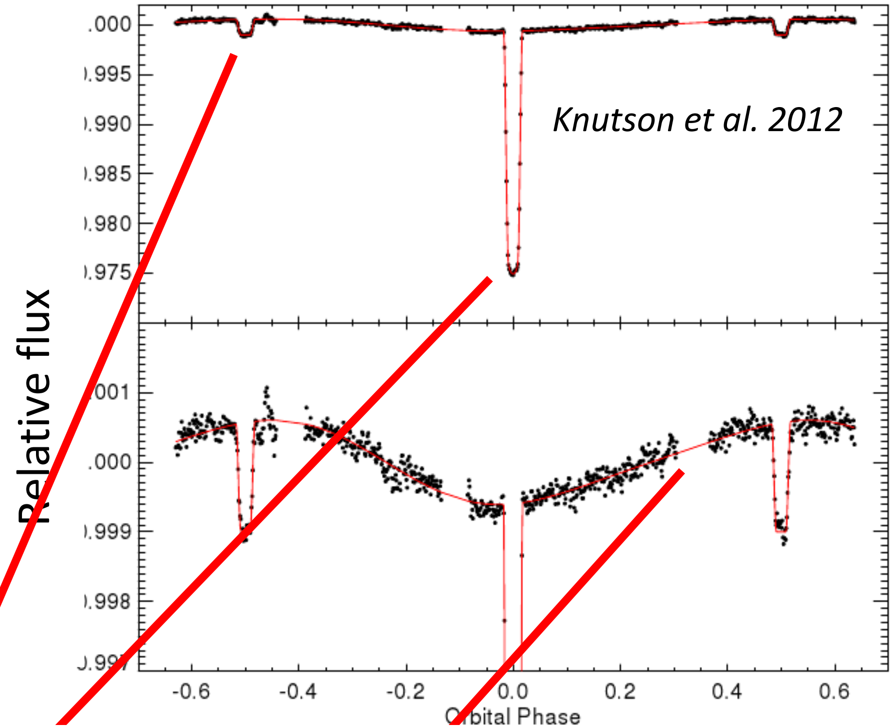
- WISE & Spitzer objects
  - T ~ 300 K
  - Mass ~1-20 M_{Jup}
  - Ages ~0.1-5 Gyr
  - Distances < 20 pc
- Astrometry and binarity
  - 100-200 mas parallax and 10s mas orbital motions detectable w. ref stars
- Bright sources (≥100 μJy)
  - Grism and NIRSpec spectra
  - Compare with spectra of bound planets formed via disk fragmentation

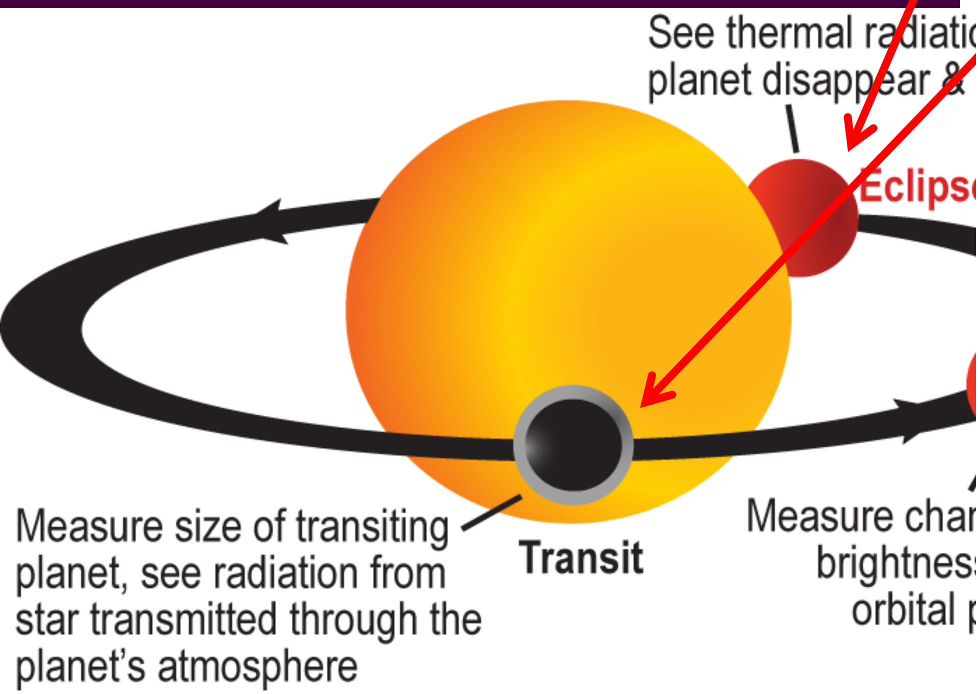


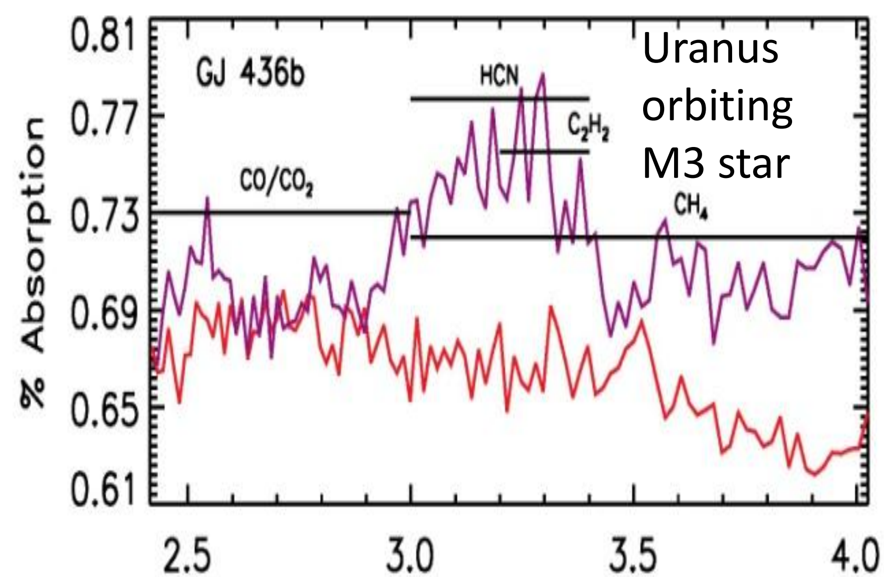


JWST Transit Science

- High SNR/precision photometry & spectra from *stable* L2 orbit will revolutionize transit observations: 7.6xSNR(Spitzer), 2.7xSNR(HST)
- Wide spectral coverage (0.5-20 μm) and resolution (R~5-2,000)

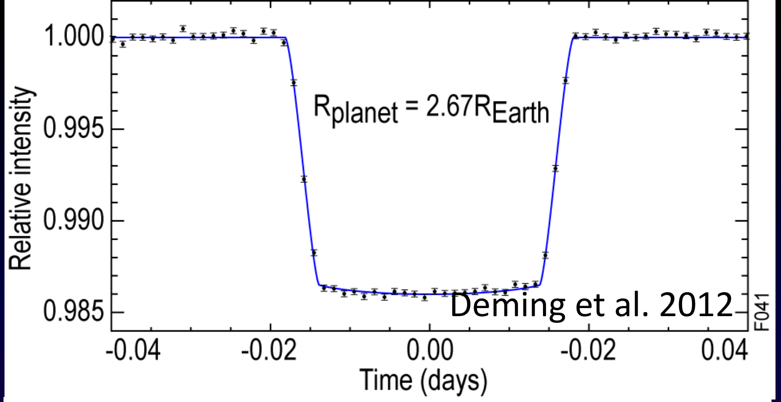


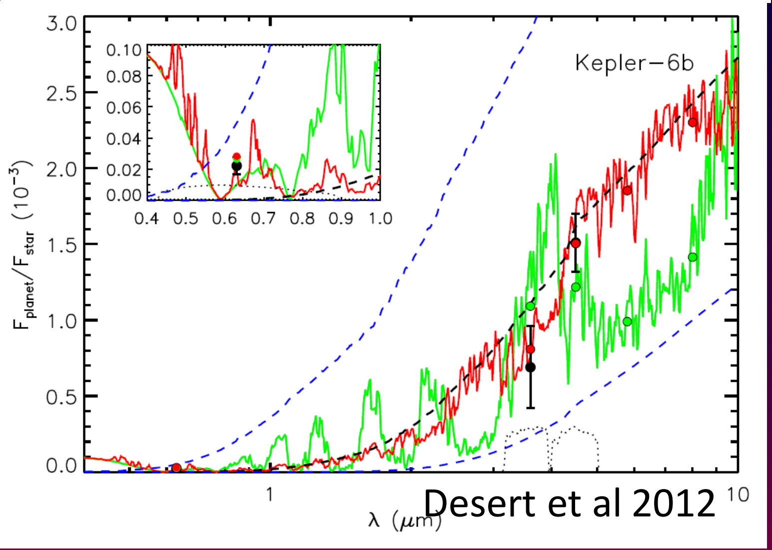


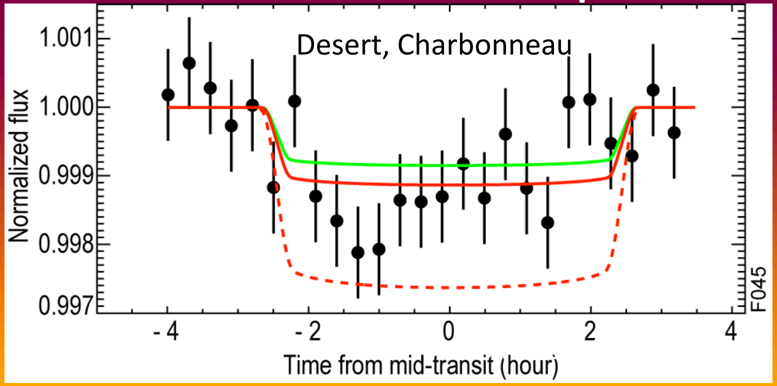


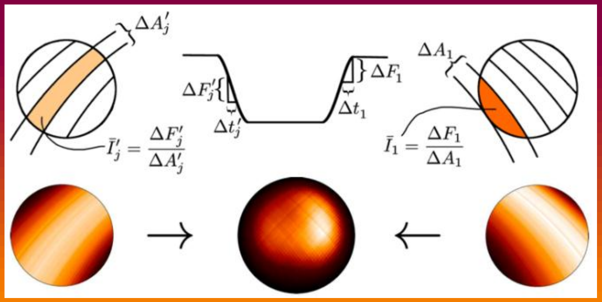
Transit Science Opportunities

- Characterize Earths/Super Earths transiting M dwarfs
- Dayside temperature from secondary eclipse depths
- Composition (K, Na, CO_2,CH_4,H_2O), atmospheric structure from multi-band secondary eclipses
- Global atmospheric circulation from full-phase light curves
- Validate & characterize smallest Kepler candidates orbiting brightest stars









Majeau, Agol & Cowan 2012

All JWST Instruments Will Be Used For Transits

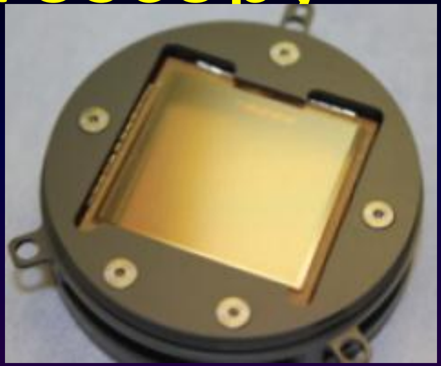
Instrument Mode	λ (μm)	R (λ/δλ)	FOV	Application
NIRCam Imaging	0.6 - 2.3 2.4 - 5.0	4, 10, 100 4, 10, 100	2 x (2.2' x 2.2') 2 x (2.2' x 2.2')	High precision light curves of primary and secondary eclipses.
NIRCam Phase Diversity Imaging	0.6 – 2.3	4, 10, 100	Image diam. - 57 pixels - 114 pixels	High precision light curves of transits for bright targets that need to be defocused to avoid saturation within the minimum t_{int}
MIRI Imaging	5 – 29	4-6	1.9' x 1.4'	High precision light curves of secondary eclipses.
NIRISS grism	0.7-2.5	2000	slitless	High resolution spectra
NIRCam Spectroscopy	2.4 – 5.0	1700	2 x (2.2' x 2.2')	High precision transmission and emission spectroscopy
NIRSpec Spectroscopy	1.0 – 5.0	100, 1000, 2700	1.6" x 1.6" slit	Transmission and emission spectroscopy of transiting planets.
MIRI Spectroscopy	5 - 11	100	Slitless	High precision emission spectroscopy
MIRI Spectroscopy	5.9 – 7.7 7.4 – 11.8 11.4 – 18.2 17.5 – 28.8	3000 3000 3000 3000	3.7" x 3.7" 4.7" x 4.5" 6.2" x 6.1" 7.1" x 7.7"	High precision emission spectroscopy

NIRCam Can Study Bright Stellar Transits

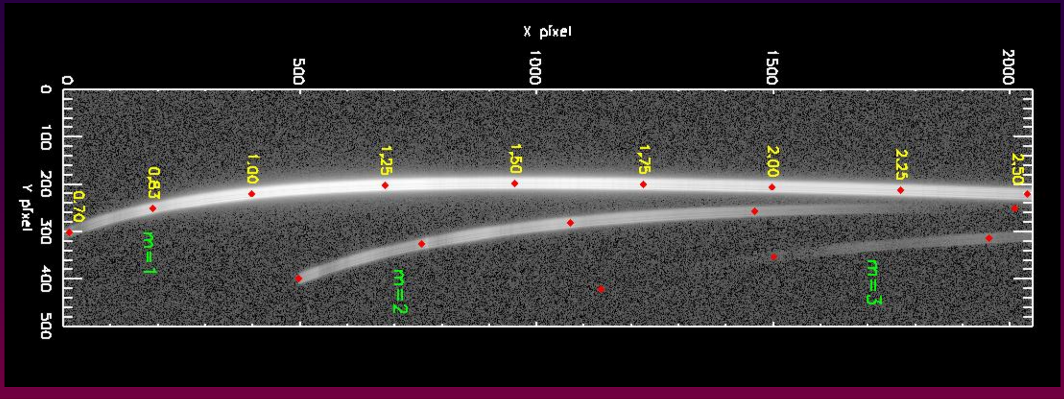
Subarray Size (Pixels)	Exposure Time(sec)	Rate (sec)	Brightest in focus Source (K mag)	Brightest defocused Source (K mag)	Size Short-λ (arc sec)	Size Long-λ (arc sec)
16x16	.00256	.00768	5.3	N/A	0.5	1.0
48x48	.023	.069	7.6	N/A	1.5	3.1
96x96	.092	.28	9.2	3.8	3.0	6.2
160x160	.256	.77	10.3	3.4	5.1	10.4
320x320	1.02	3.1	11.8	N/A	10.1	20.8
640x640	4.1	12.2	13.3	N/A	20.3	41.6
1024x16	0.16	0.48	3.3	N/A	N/A	Grism spec.
Full Frame*	10.6	31.8	14.3	N/A	135*	135

- Subarrays to observe bright stars with grism
- NIRCam weak lenses to defocus stars at short lams for better sampling and less saturation on bright stars (2" - 4" diameter)

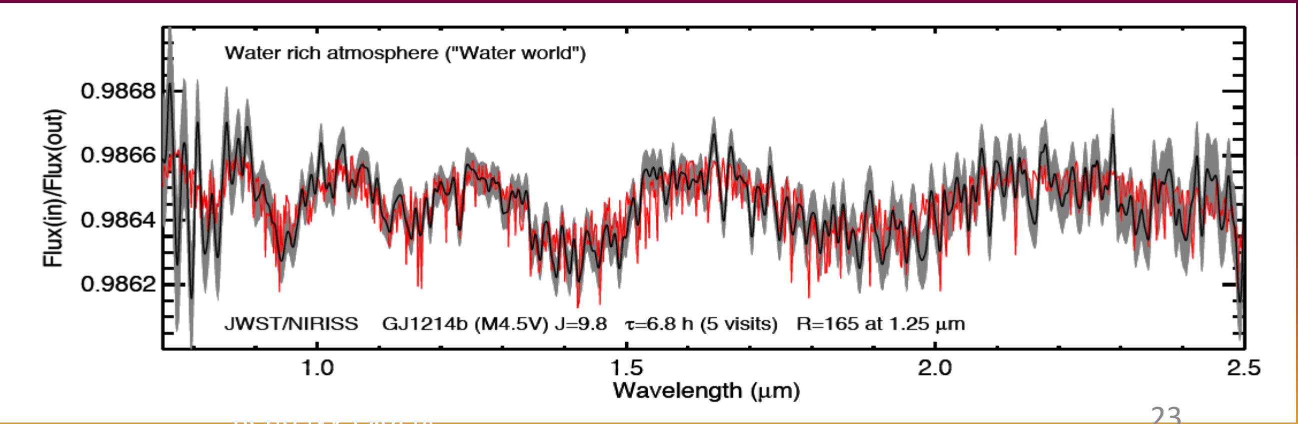
NIRISS: Near-IR Transit Spectroscopy



- Spectral resolution: 700, slitless, cross-dispersed
- Simultaneous wavelength range: 0.7-2.5 µm
  - Includes key atmospheric features of H_2O, CO_2 and CH_4
- Optimized for bright targets: J>5 mag
  - Spectrum is defocussed along spatial direction for high dynamic range operation and to minimize systematic errors due to flatfield (intra-pixel response) and jitter.

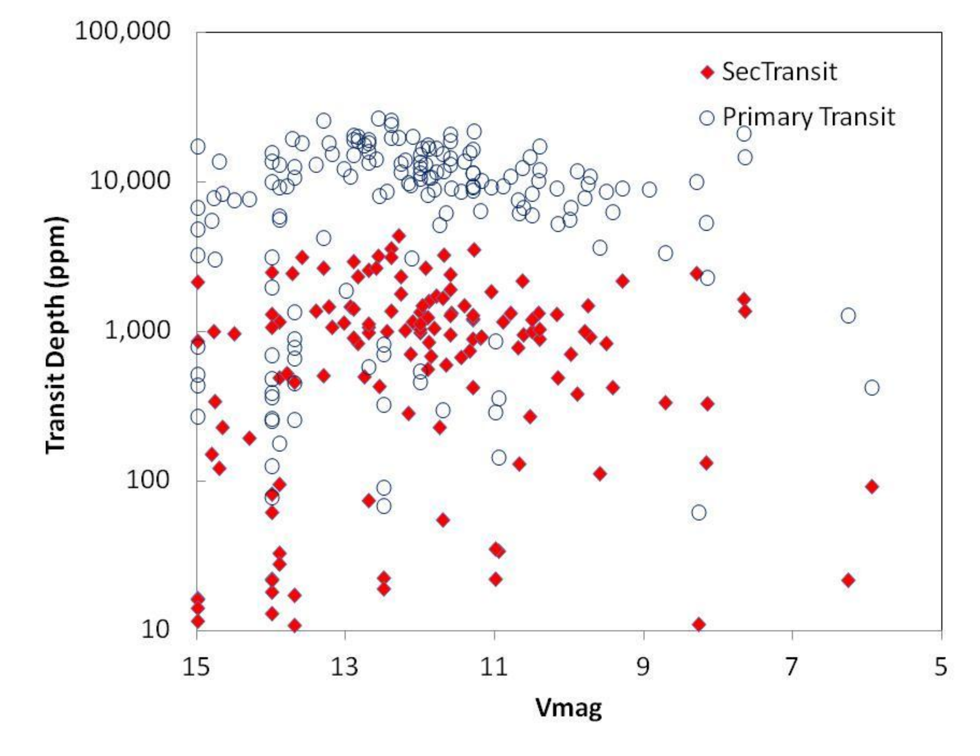


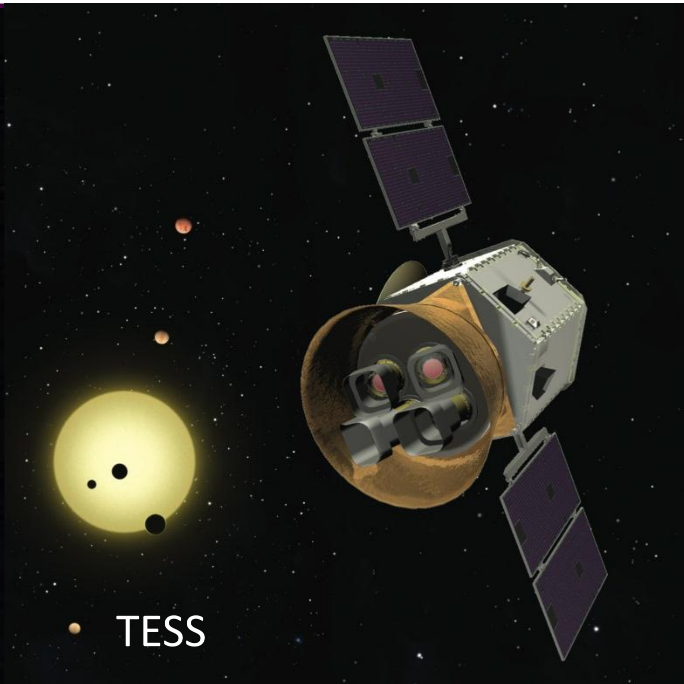
GJ1614b with NIRISS (~7 hrs, 5 visits)



Spectra Need Bright Transit Targets

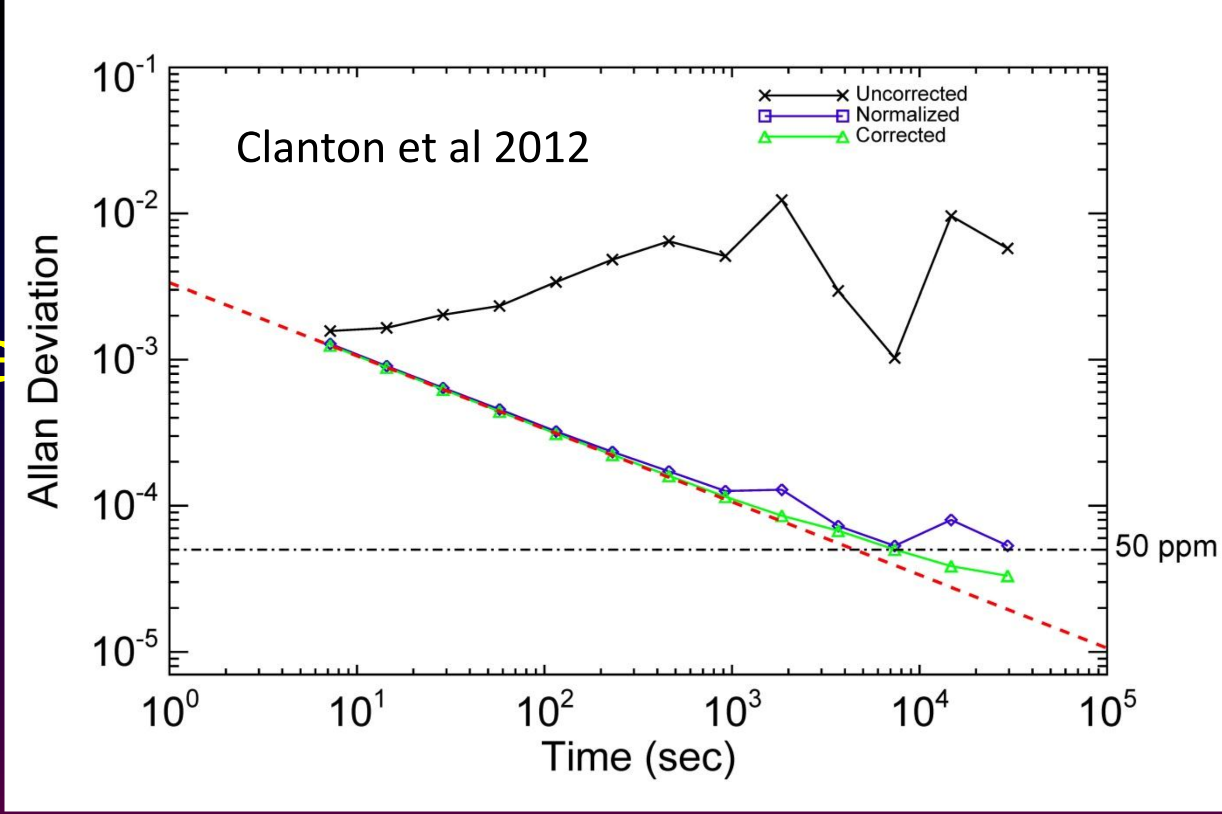
- Ground-based surveys have identified planets transiting bright stars (117 objects w K<11 mag) with many more to come
- **TESS** would find tens of super Earths orbiting bright stars…
- …but **FINESSE** team has identified >100 objects suitable for detailed spectra NOW
- Stay tuned for downselect in March!



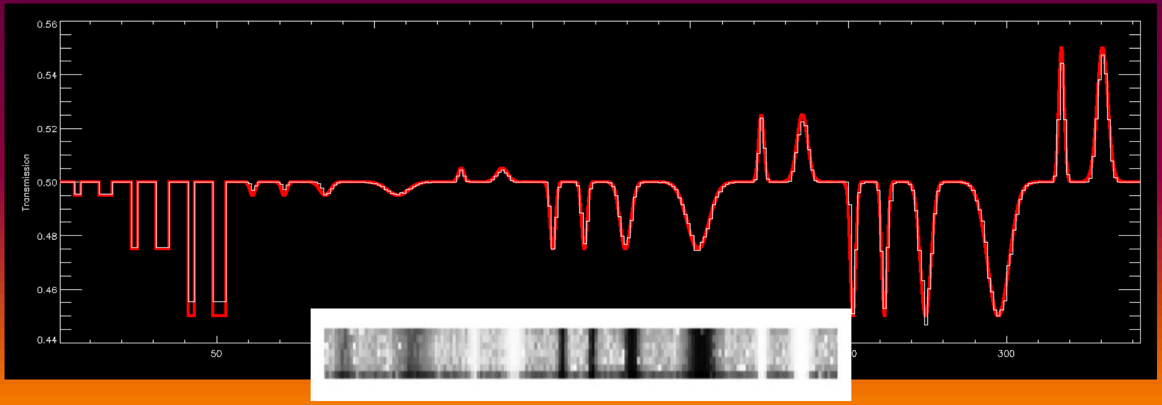


JWST Detectors Capable of High Precision Transit Performance

- H2RG device similar to JWST detectors show noise performance <50 ppm and potentially as good as <20 ppm

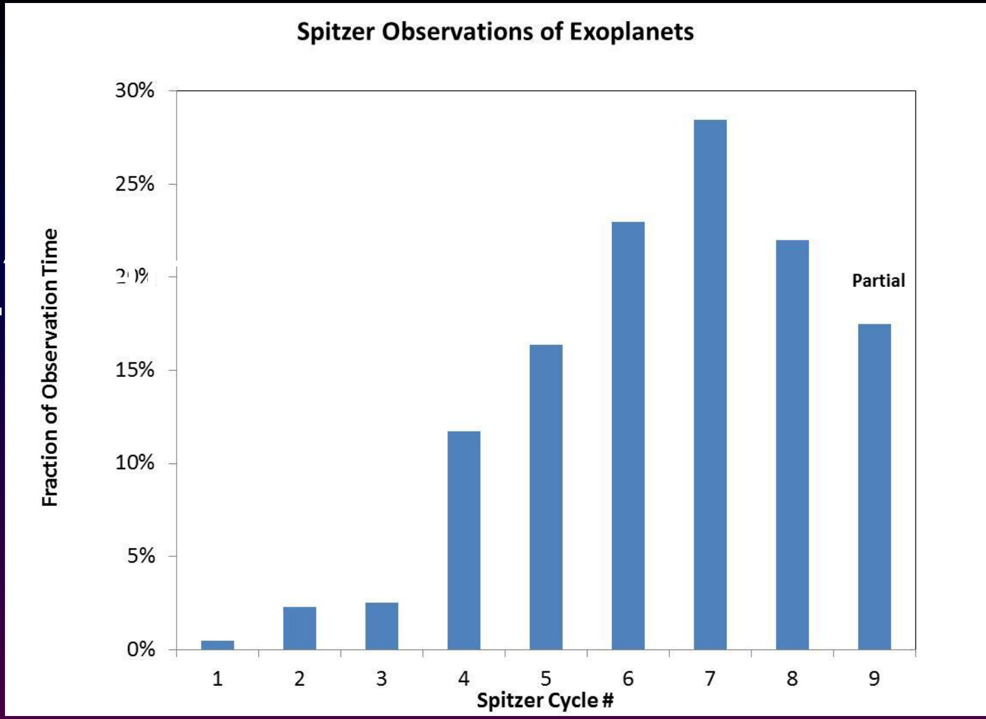


- Decorrelation removes disturbances due to pointing motion, temperature drifts, etc
  - Testbed investigating spectroscopic performance. Initial results <50 ppm for simulated spectra



Goals for Exoplanet Community

- Make the “**New Worlds**” of “New Worlds, New Horizons” a reality
- Reclaim JWST from cosmologists
  - Win more than our fair share with a goal of capturing 25% of mission time
  - Plan comprehensive science programs
- Start preparing now to make sure JWST will do all that it is capable of providing for exoplanets



Optimize JWST For Exoplanet Observations

- Careful pupil alignment and optimized wavefront for coronagraph campaigns
- Multi NIRCam readouts
  - Fast subarray readout for transit target in grism module
  - Slower, full array for pointing references in other module
- Long duration, highly stable uninterrupted data acqn periods essential*__. JWST limit of 9,000 sec problem if not mitigated__*
- High cadence data storage for light curves (10-30 sec)