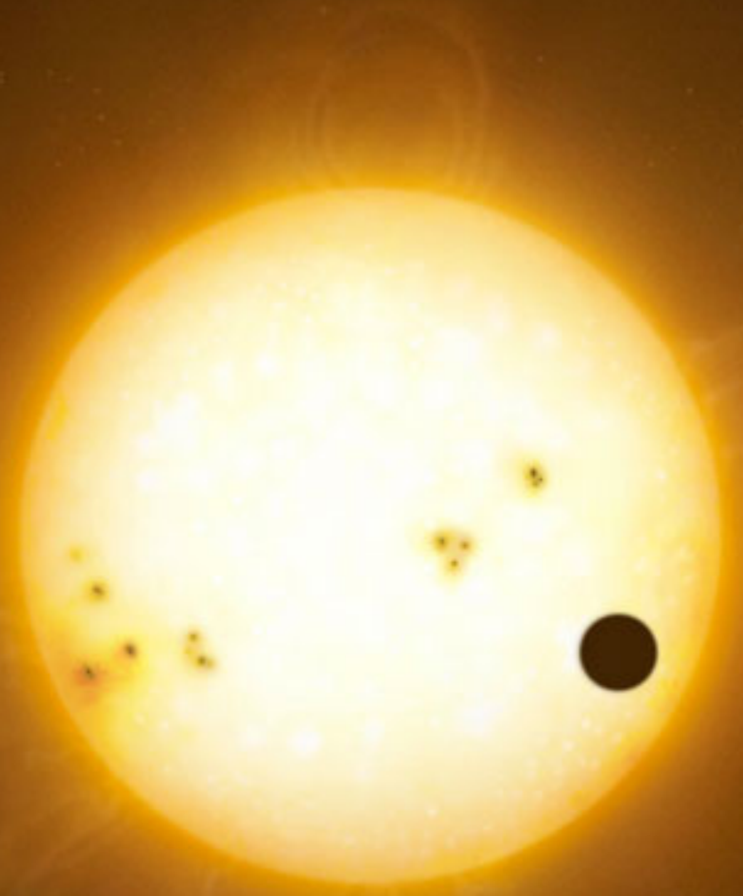
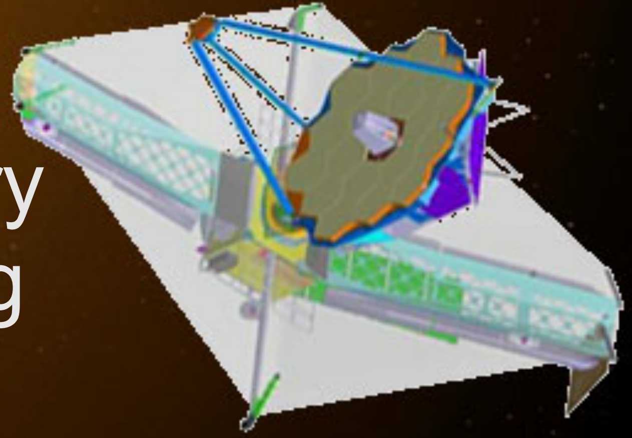
Exoplanet transit, eclipse, and phase curve observations with JWST NIRCam



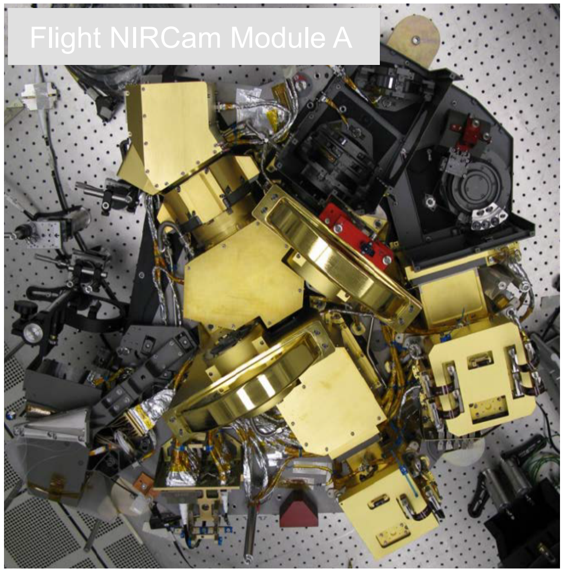


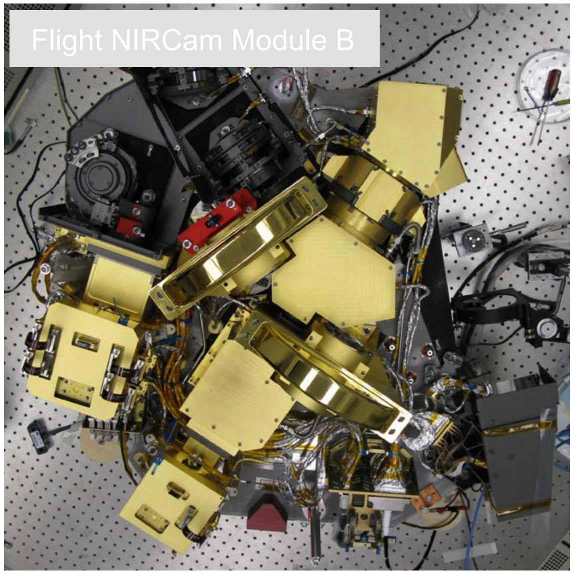
Tom Greene & John Stansberry
JWST NIRCam transit meeting
March 12, 2014

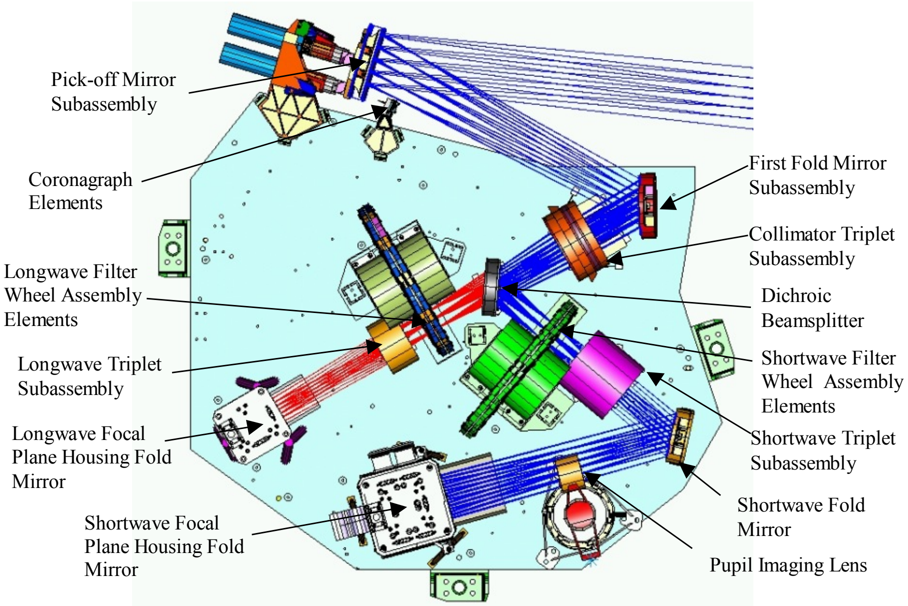
Scope of Talk

- NIRCam overview
- Suggested transit modes
- Bright star limits / subarrays
- Target acquisition & pointing
- Expected performance
- Simulated spectra and potential JWST science
- Operational limitations
- Observing examples

NIRCam: 0.7-5 μm imaging + 3-5 μm spectroscopy





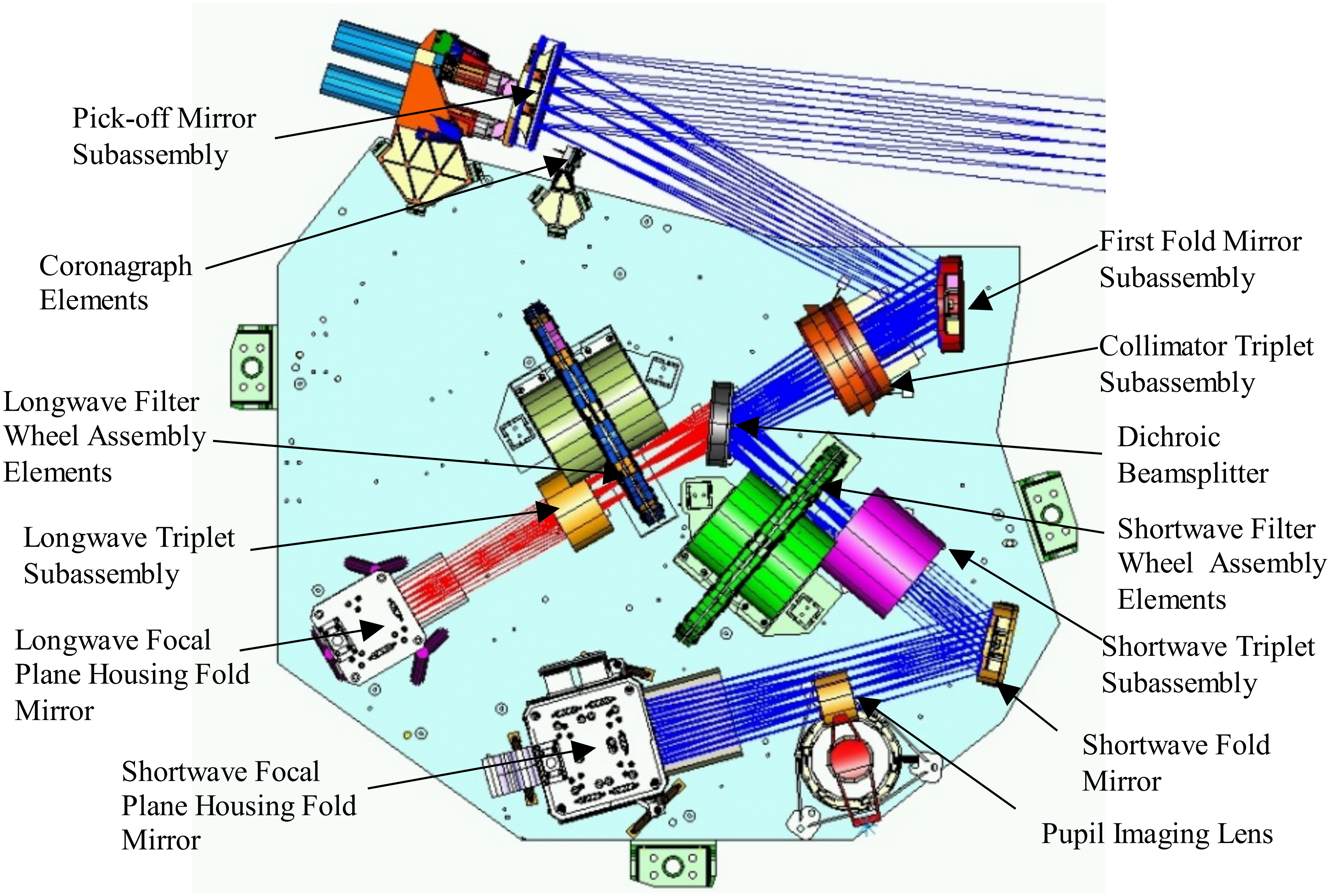


Developed by the University of Arizona with Lockheed Martin ATC

- Operating wavelength: 0.6 – 5.0 microns
- Spectral resolution: 4, 10, 100 filters; R ~ 1700 slitless grisms; coronagraphic imaging
- Field of view: 2.2 x 4.4 arc minutes
- Angular resolution (1 pixel): 32 mas < 2.3 microns, 65 mas > 2.4 microns
- Detector type: HgCdTe, 2048 x 2048 pixel format, 10 detectors, 40 K passive cooling
- Refractive optics, Beryllium structure

Supports telescope wavefront sensing

NIRCam Optomechanics



Pick-off Mirror Subassembly

Coronagraph Elements

Longwave Filter Wheel Assembly Elements

Longwave Triplet Subassembly

Longwave Focal Plane Housing Fold Mirror

Shortwave Focal Plane Housing Fold Mirror

First Fold Mirror Subassembly

Collimator Triplet Subassembly

Dichroic Beamsplitter

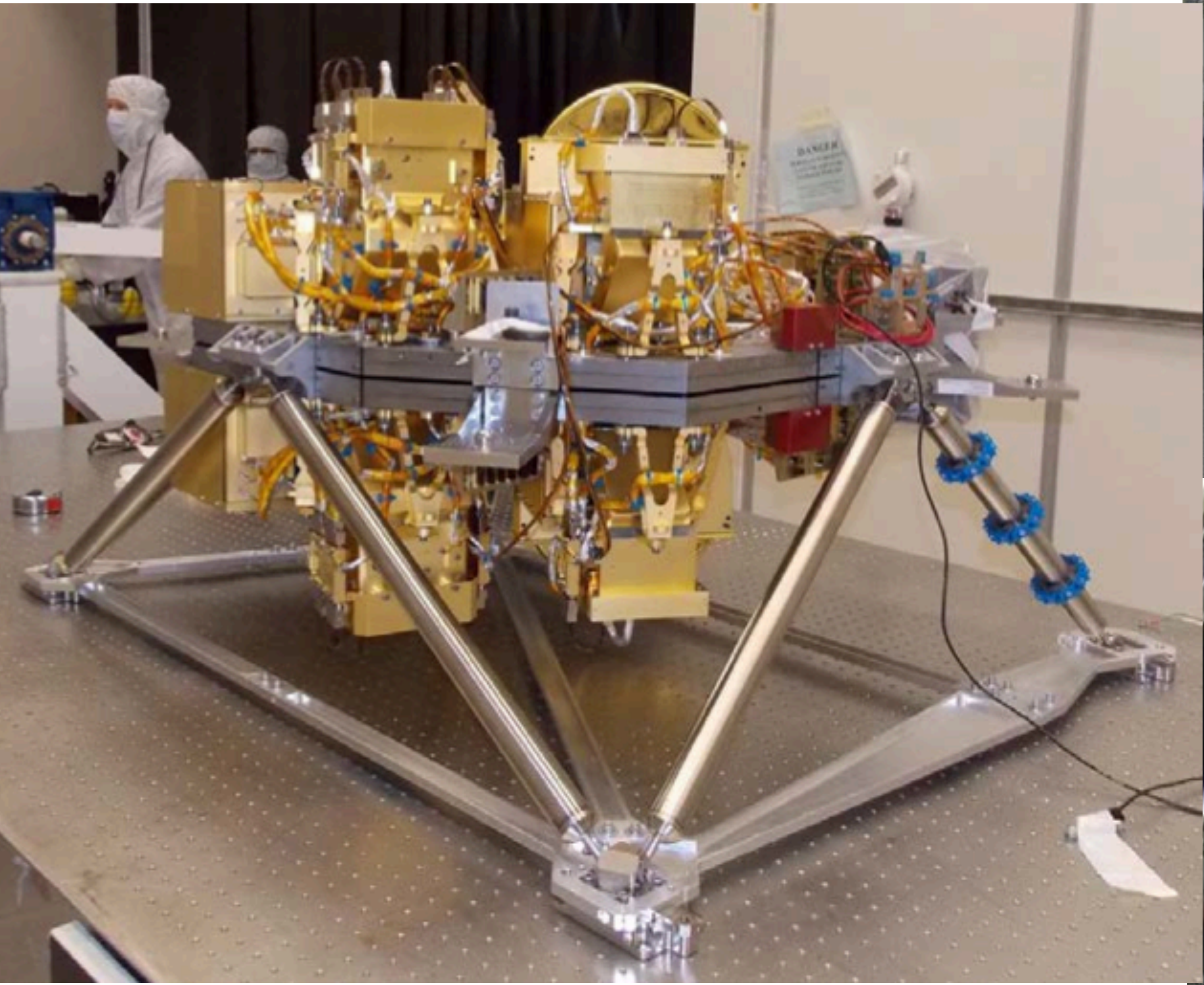
Shortwave Filter Wheel Assembly Elements

Shortwave Triplet Subassembly

Shortwave Fold Mirror

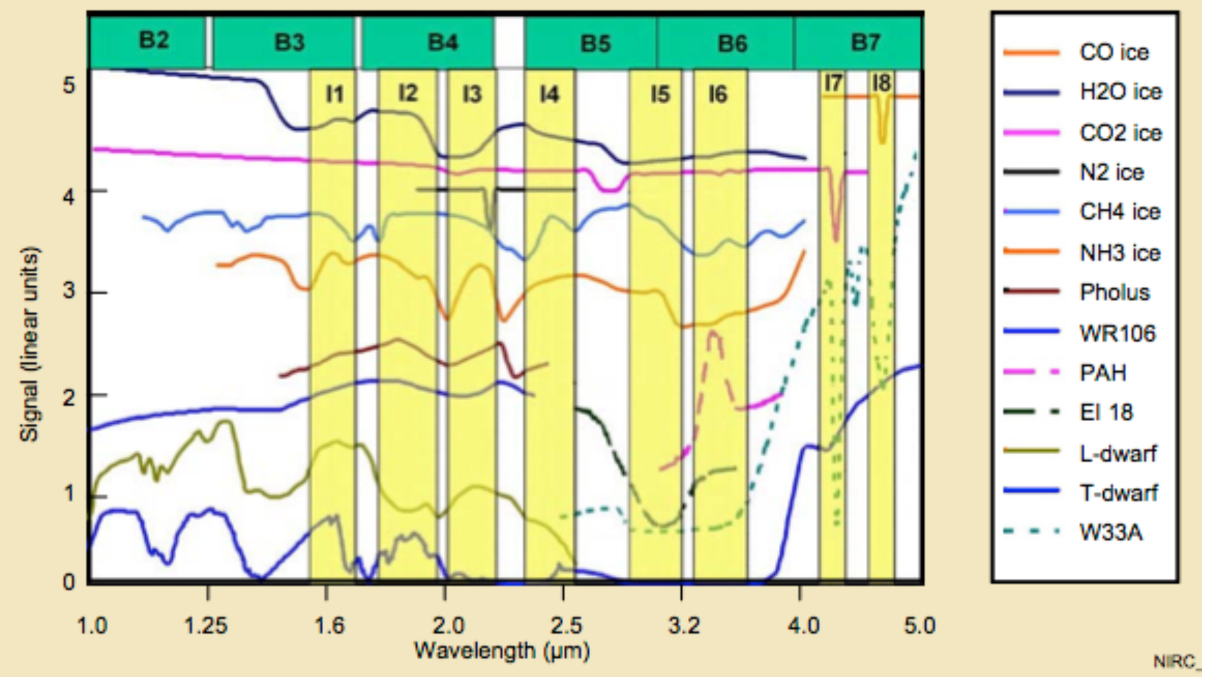
Pupil Imaging Lens

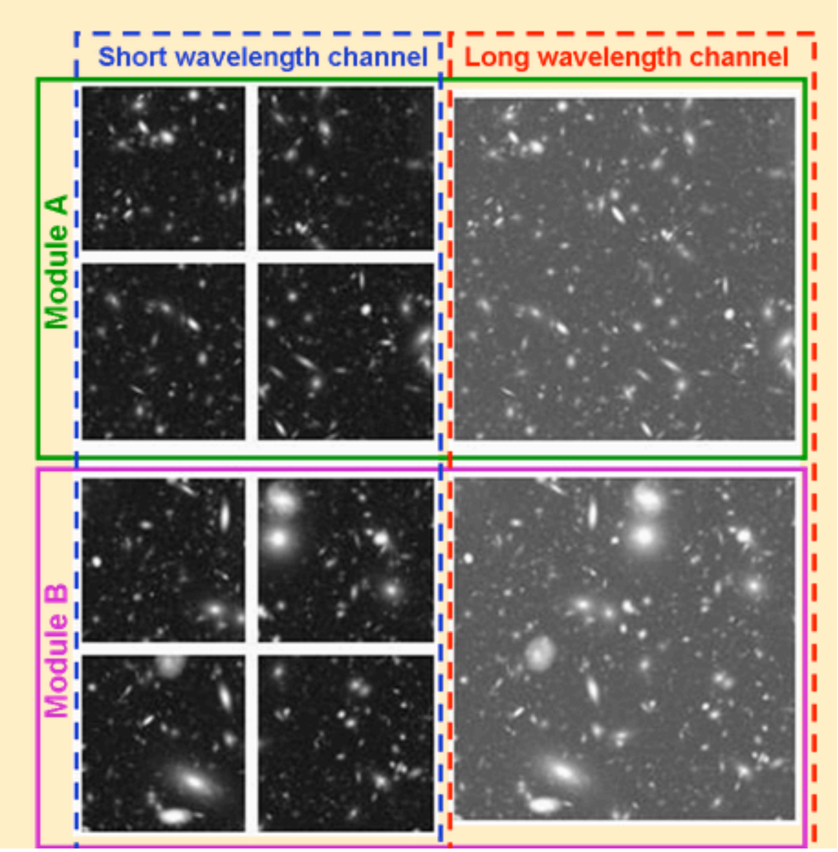
NIRCam consists of 2 identical modules with adjacent FOVs


Integrated NIRCam Flight Model


NIRCam Modules A & B In Test Chamber

NIRCam filters and modes

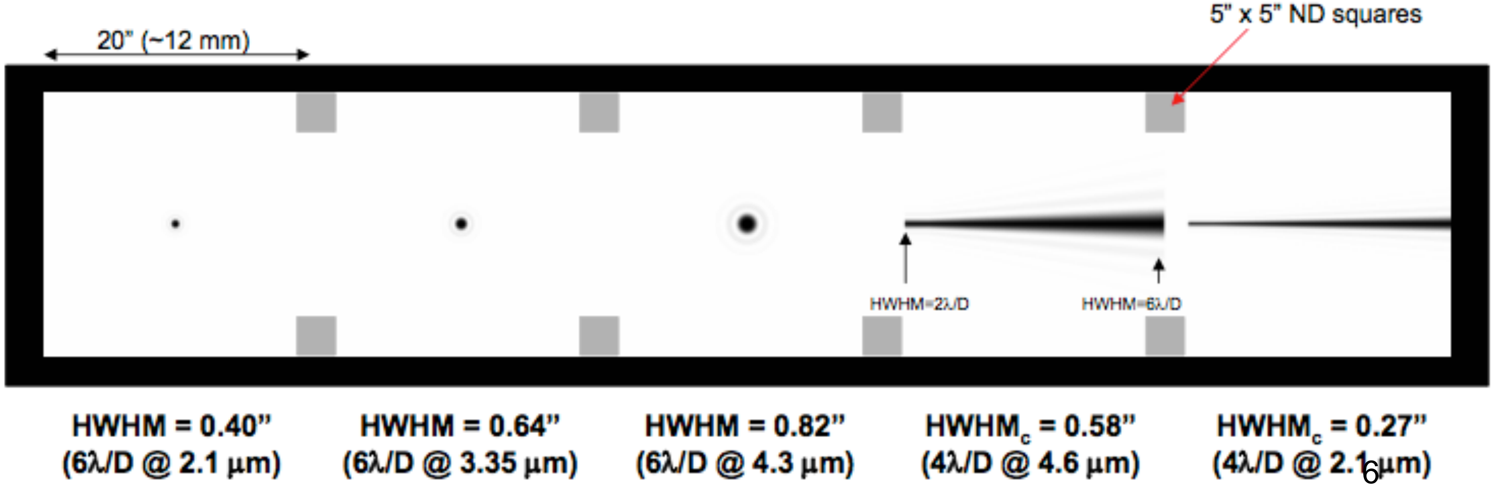




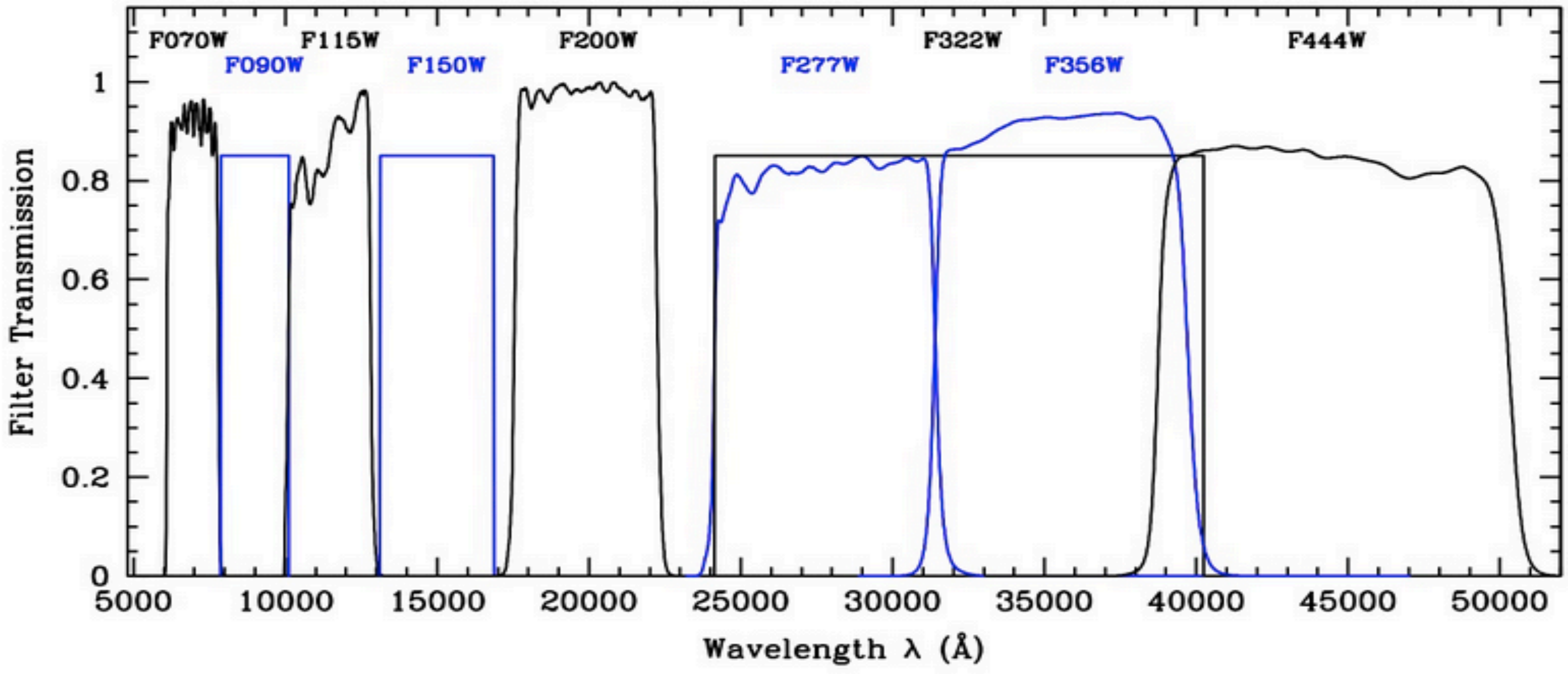
NIRCam Wide, Medium and some Narrow filters (top).
NIRCam also has SW weak lenses to spread out light;

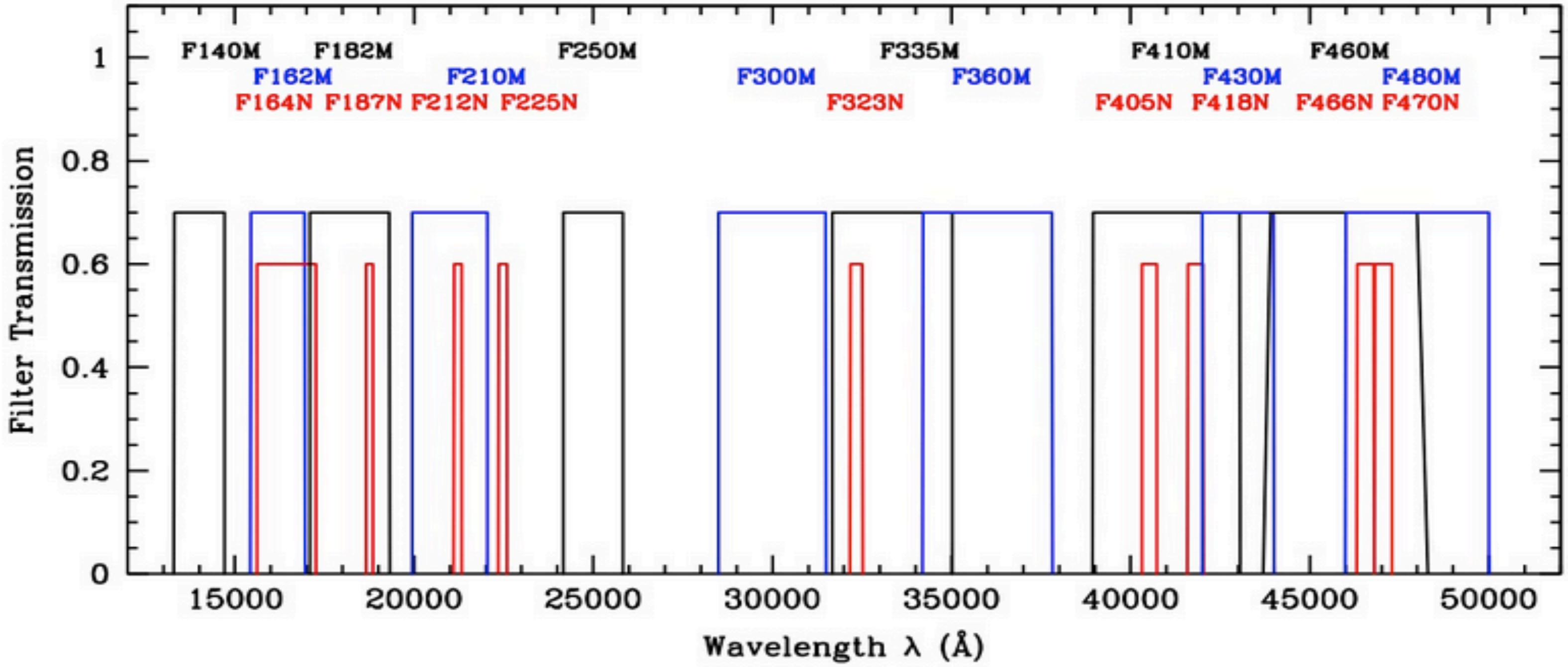
On-sky layout (right);

Coronagraphic masks (right)

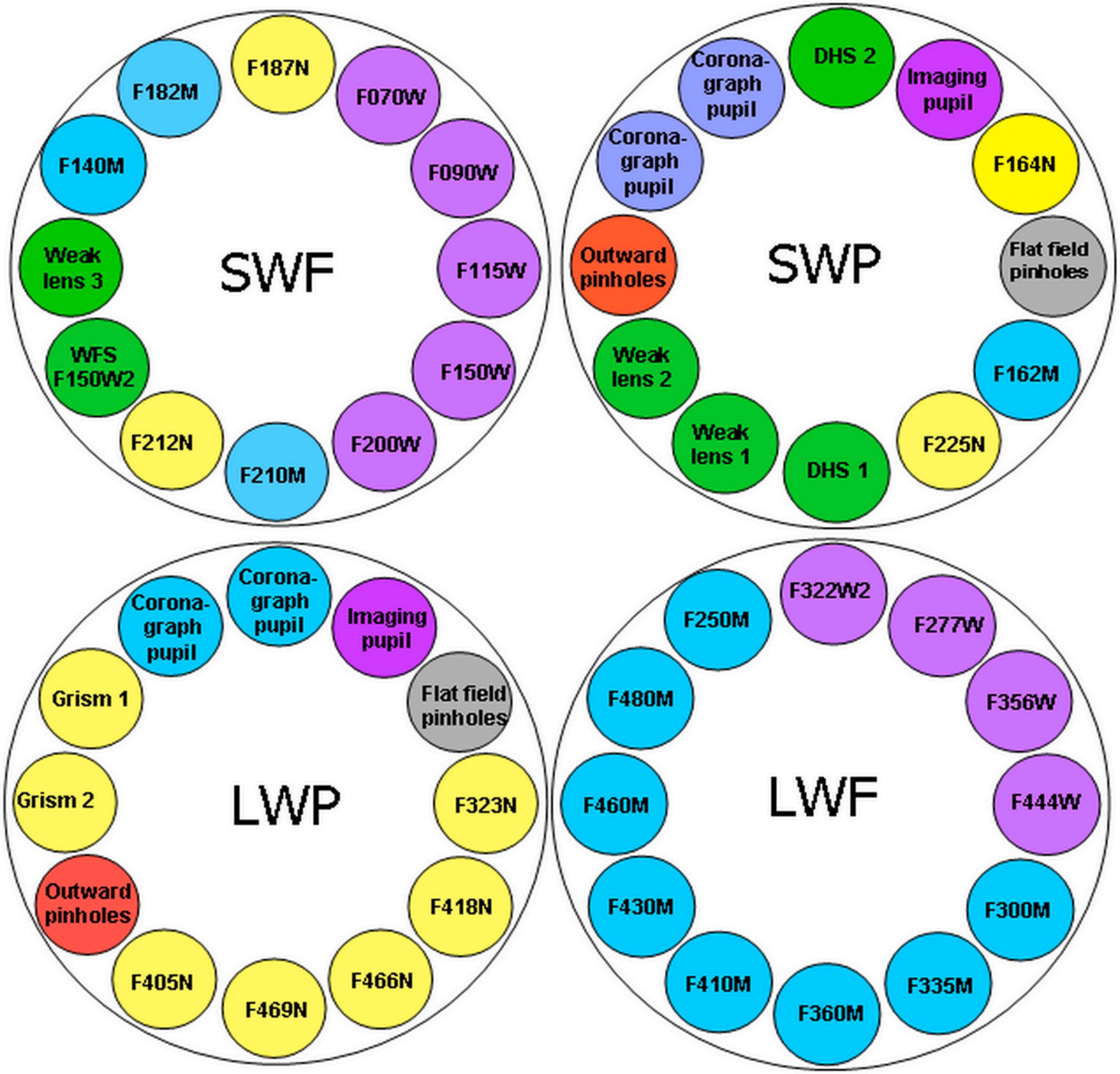


NIRCam filter details





NIRCam filter and pupil wheels



Short Wavelength side has SWF and SWP: can use those in series

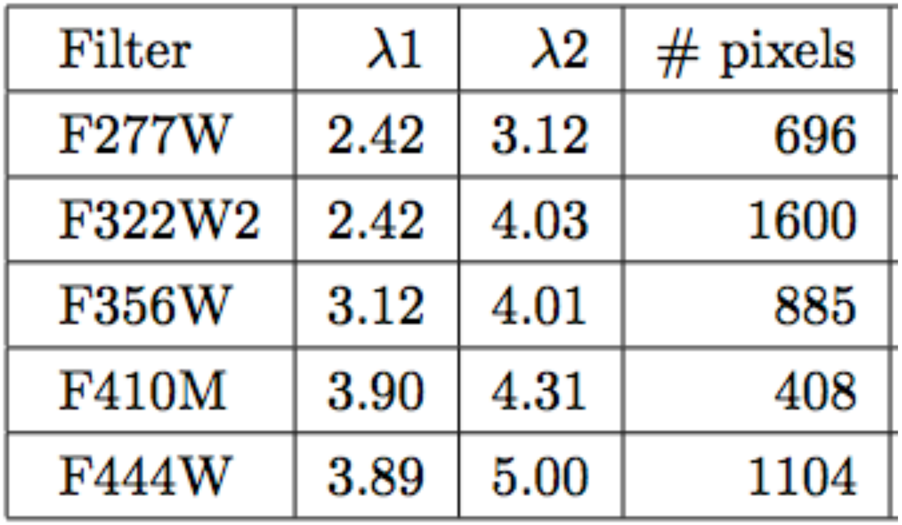
Long Wavelength side has LWF and LWP: can use those in series

NIRCam 2.5 – 5 μm slitless grisms

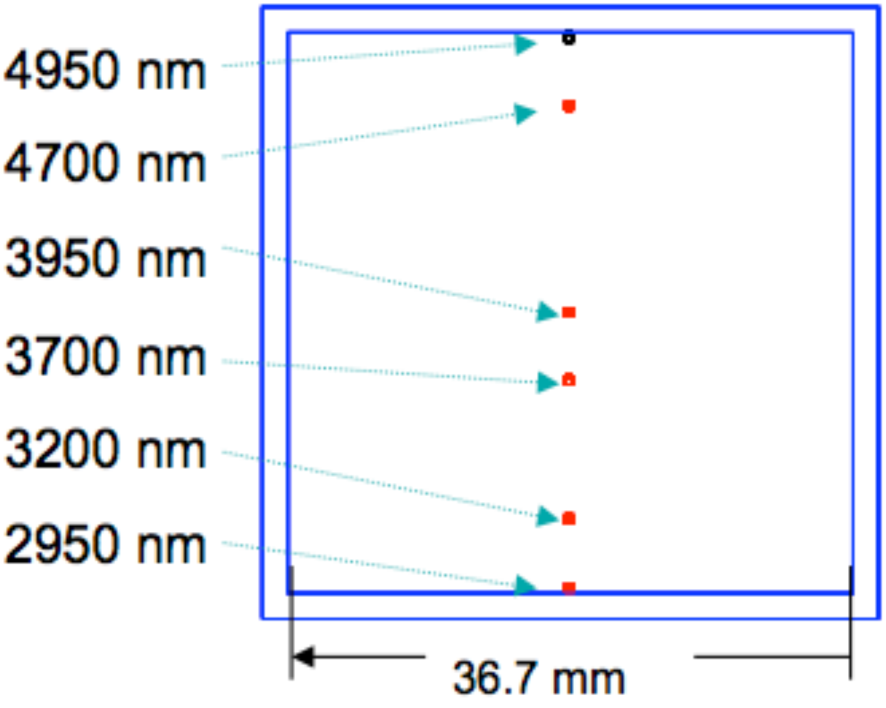
- Grisms are in the LW pupil wheel and are used in series with a LW filter
- R = 1700 @ 4 microns
  - Disp = 1000 pxls / micron
- Good spatial sampling:

– Nyquist sampled at 4 μm

Some grism filter combinations



Filter	λ1	λ2	# pixels
F277W	2.42	3.12	696
F322W2	2.42	4.03	1600
F356W	3.12	4.01	885
F410M	3.90	4.31	408
F444W	3.89	5.00	1104



LW FPA size 36.7 X 36.7 mm

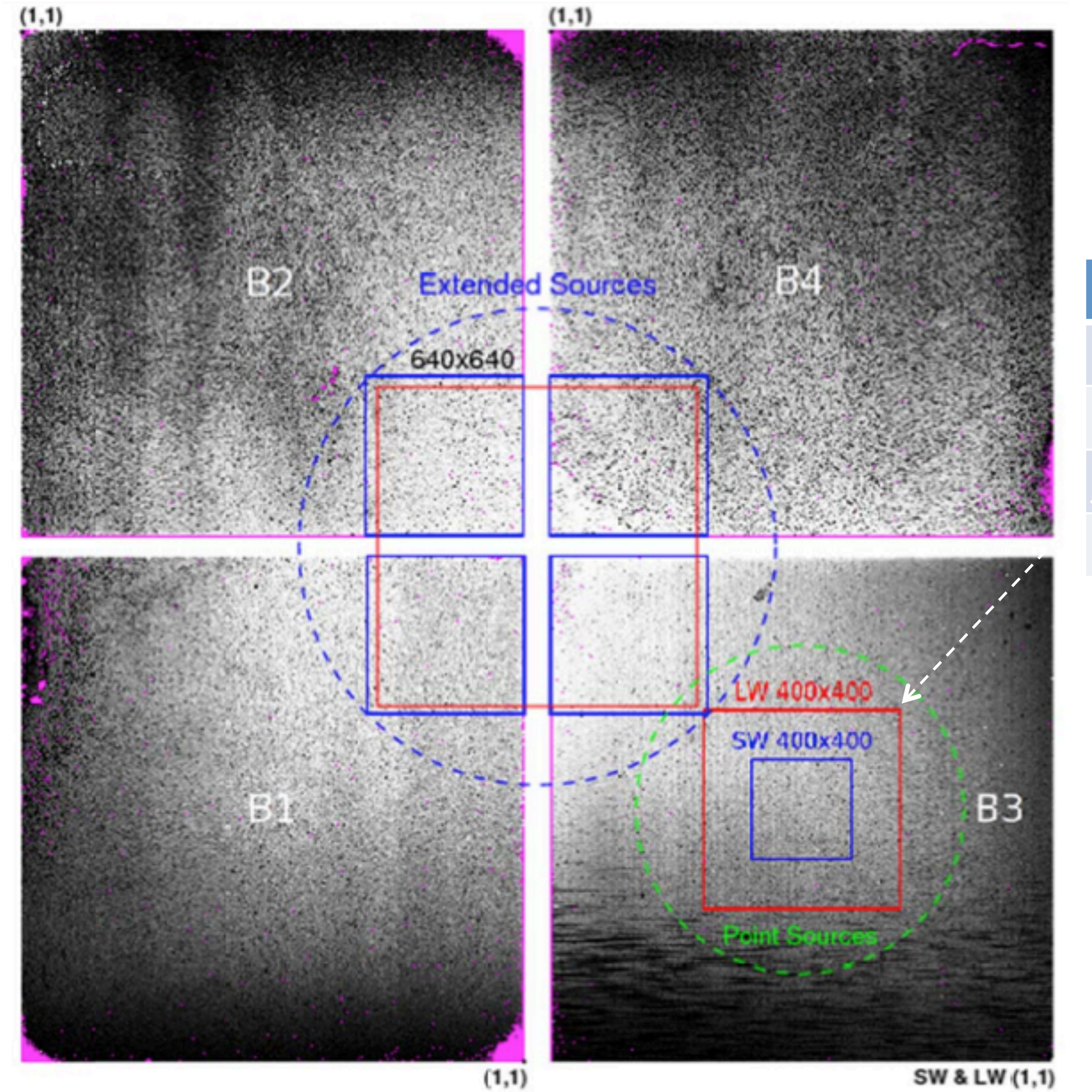
Center Field Dispersion by Grism

- 2 grisms per module in perpendicular orientations

Sample NIRCam transit modes

Application	Filter	Pupil	Subarray
Faint imaging transit confirmation (e.g., Kepler followup KOI-02311.01 K=11.0 mag)	SW and LW	Imaging	64 x 64
Highest precision imaging: small planet / bright star (TESS-001, K = 5.5 mag)	F200W	WL8	160 x 160
Phase curve imaging	SW or LW	Imaging	Set by brightness
Spectroscopy (R ~ 1700): H_2O & CH_4 High precision / fine sampling / high R	F322W2 2.4- 4.0	Grism	2048 x 64
Spectroscopy (R ~ 1700): CO_2 & CO High precision / fine sampling / high R	F444W: 3.9- 5.0	Grism	2048 x 64

NIRCam Subarray Layout



Point Source Subarrays

Use	Size	Tf(s)	dmag
Bright	64x64	0.049	5.82
WL8	160x160	0.277	3.95
Pt src	400x400	1.65	2.01
Grism	2048x64		

Current NIRCam bright limits

		Brightest Observable with subarray	Brightest Observable with subarray
Mode	**Disperser/Filter**	**G0**	**M5**
Imaging	F356W	8.721	8.958
Imaging	F444W	7.857	8.200
Imaging	F200W+WL8	6.149	6.080
Imaging	F200W only	9.279	9.210
Grism	F322W2	5.080	5.180
Grism	F444W	2.740	3.080
Grism	F356W	4.040	4.270

- Values are for 2 frames per integration to 80% full well
- Imaging with 64 x 64 subarrays (2”x2” or 4”x4”)
- Grism subarray bright limits for 4 outputs (stripe mode); 1.5 mag fainter for 1 output
- 2 Frame integrations have low (33 or 67%) duty cycle: pixel resets, not efficient!

FYI: Full frame imaging bright limits are K ~ 15 - 14 mag for SW – LW M & W filters
Data rate is not an issue if using 1 output subarrays

Acquisition

- 7 mas JWST pointing allows acquisition to a fraction of a pixel (1 pixel = 32 mas SW; 64 mas LW)
- Based on Spitzer, will choose source location sweet spots for imaging and spectroscopy
- Imaging Acquisition:
  - Acquire in science subarray / filter combo
  - Can acquire a bright star in N filter then offset for F200W+WL8
- Spectroscopic Acquisition
  - Acquire bright star in 64 x 64 subarray LW N filter
  - Configure grism, then filter, then offset

Pointing Knowledge during Observations

- Imaging:

  - Use science data to determine pointing and do any de-correlation

  - Can get simultaneous SW and LW photometric data

- Spectroscopy:

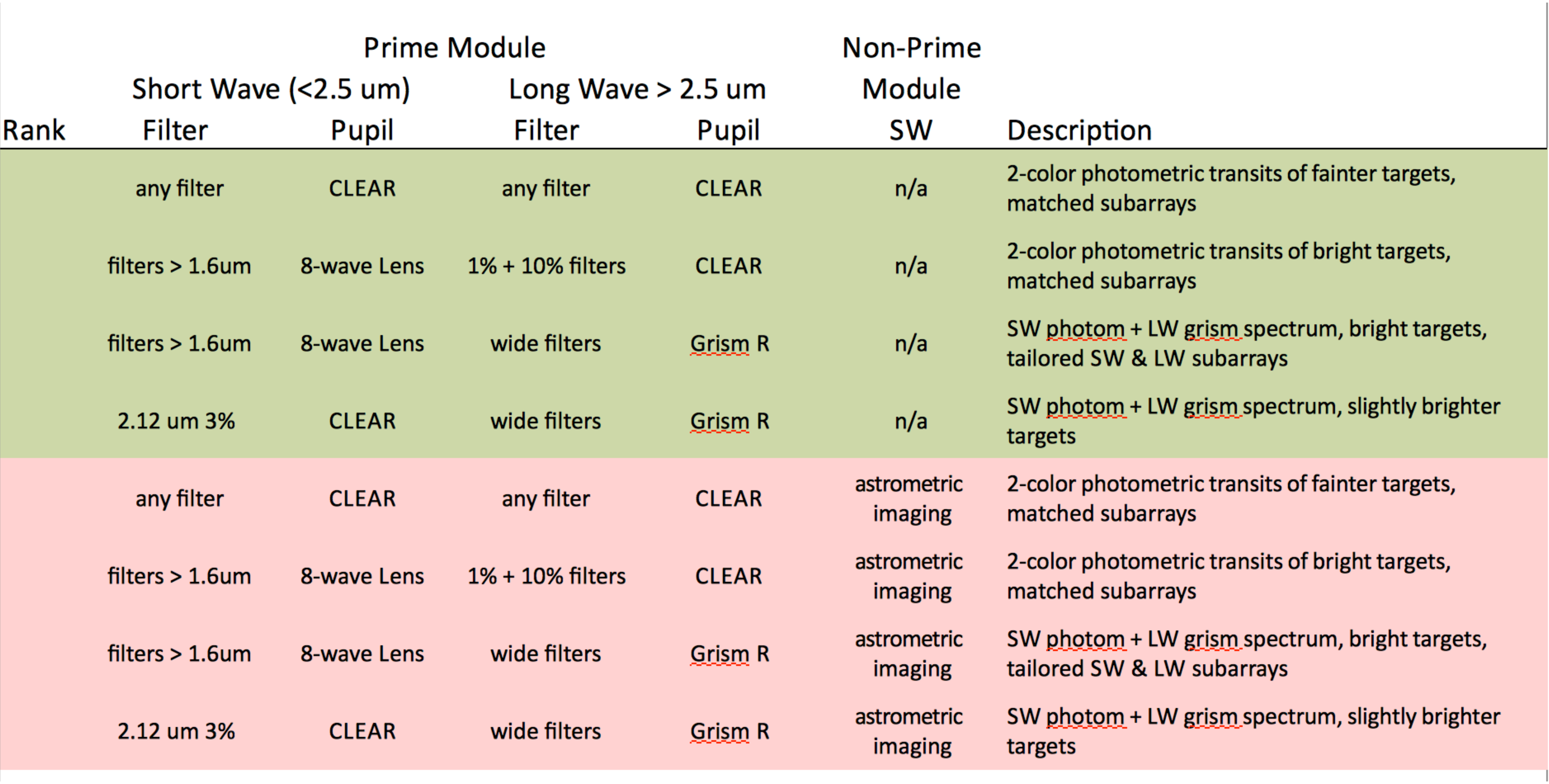
  - Possible to use SW side of module to image the target to record pointing during exposures BUT will have to use grism subarray:

    All detectors in a module must use same subarray config

      Will need to use WL4 lens or N filter to image bright stars

  - Bright grism targets may saturate when imaged in SW:
    use N filter or with WL+8

NIRCam transit mode summary



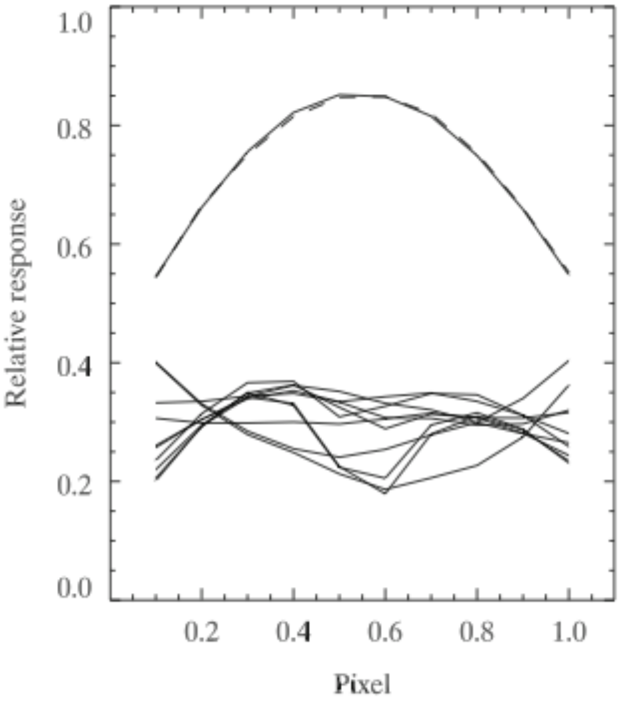
	Prime Module				Non-Prime	
	Short Wave (<2.5 um)		Long Wave > 2.5 um		Module	
Rank	Filter	Pupil	Filter	Pupil	SW	Description
	any filter	CLEAR	any filter	CLEAR	n/a	2-color photometric transits of fainter targets, matched subarrays
	filters > 1.6um	8-wave Lens	1% + 10% filters	CLEAR	n/a	2-color photometric transits of bright targets, matched subarrays
	filters > 1.6um	8-wave Lens	wide filters	Grism R	n/a	SW photom + LW grism spectrum, bright targets, tailored SW & LW subarrays
	2.12 um 3%	CLEAR	wide filters	Grism R	n/a	SW photom + LW grism spectrum, slightly brighter targets
	any filter	CLEAR	any filter	CLEAR	astrometric imaging	2-color photometric transits of fainter targets, matched subarrays
	filters > 1.6um	8-wave Lens	1% + 10% filters	CLEAR	astrometric imaging	2-color photometric transits of bright targets, matched subarrays
	filters > 1.6um	8-wave Lens	wide filters	Grism R	astrometric imaging	SW photom + LW grism spectrum, bright targets, tailored SW & LW subarrays
	2.12 um 3%	CLEAR	wide filters	Grism R	astrometric imaging	SW photom + LW grism spectrum, slightly brighter targets

NIRCam Systematic Noise Estimates

- Variable PSF and image jitter will induce spectrophotometric errors due to non-uniform intra-pixel detector response and residual flat field errors
- Use of slitless grisms will eliminate any systematic noise due to jitter-induced slit losses
- HST WF3 IR grism is used in spatial scanning mode to spread light onto many pixels, achieves ~ 30 ppm precision

Deming et al. 2009 PASP

FIG. 8.—Intrapixel sensitivity variation for a representative NIRSpec detector pixel, from engineering measurements of the flight detector. The upper traces show the average variation in the dispersion direction (*solid line*), and the spatial direction (*dashed line*). The lower traces divide the pixel into 10 strips parallel to the spectral dispersion, and they show the difference from a parabolic fit of response vs. distance from pixel center. The differences have been amplified by a factor of 4, and offset by 0.3, for clarity of presentation.



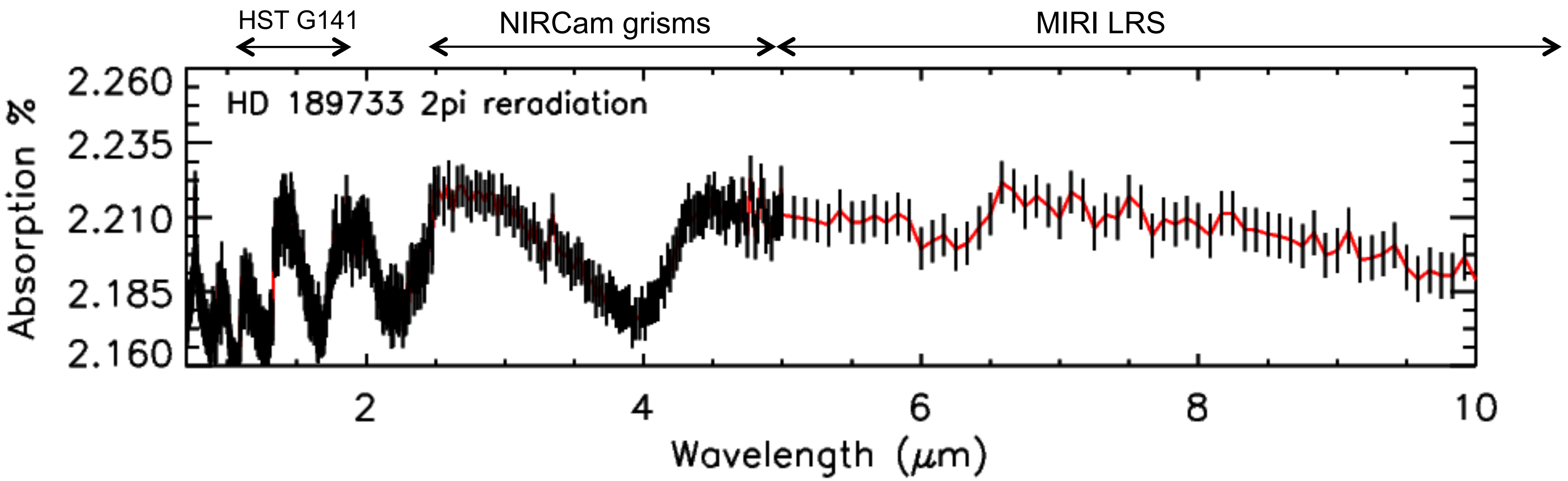
Systematic Noise Limits

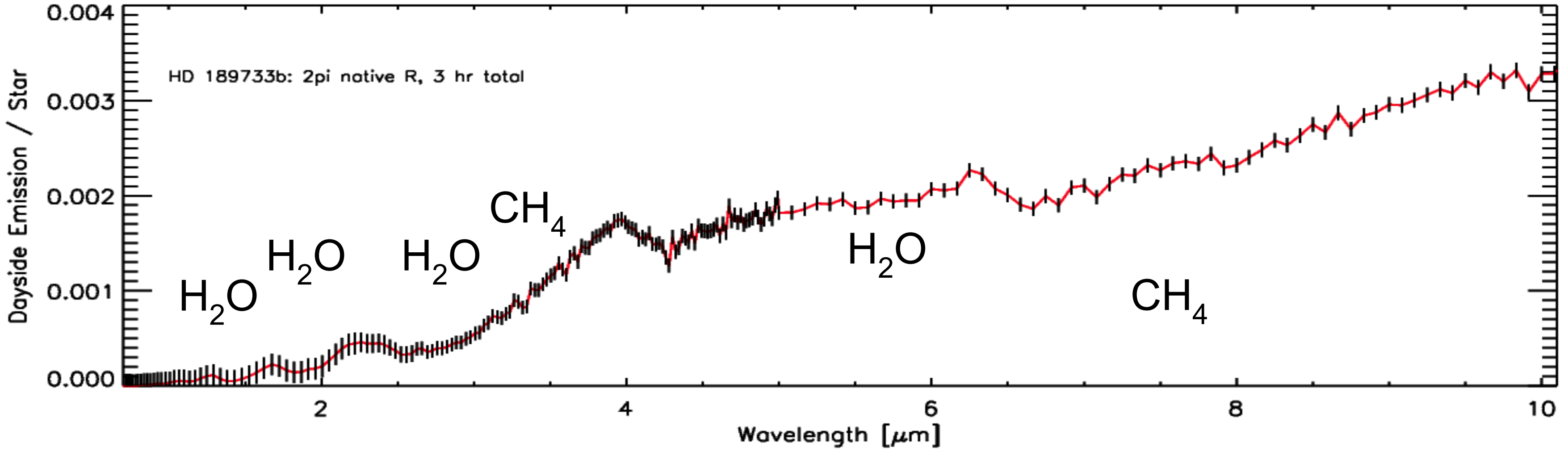
- Expect a systematic noise floor to emerge when photon SNR is high: jitter, PSF changes, detector systematics
- NIRCam (+ NIRISS + NIRSpec) detectors are similar to HST WFC3; expect similar <35 ppm noise floor
  - Nyquist sampling at 2.0 and 4.0 microns wavelength
  - Validated by independent modeling
  - Some precision testing to be done before launch:
    - ISIM CV2 test: differential with FGS (Marcia's talk)
    - Detector testbeds

JWST Spectral Simulations

- Transmission and emission models from J. Fortney group
- Semi-realistic model of telescope and instrument wavelength-dependent resolution and throughput
  - Includes reflections, grating functions, filter values or guesses
- Photon noise and systematic noise floor added in quadrature
  - Detector noise not included explicitly (just in noise floor). Need to determine extraction apertures for imaging and spectroscopy
- Systematic noise is difficult to predict but major causes can be modeled / predicted (I just put in values)
  - May have large wavelength dependencies for some instruments
- Next: do retrievals on simulations to determine what science issues can be addressed with JWST data

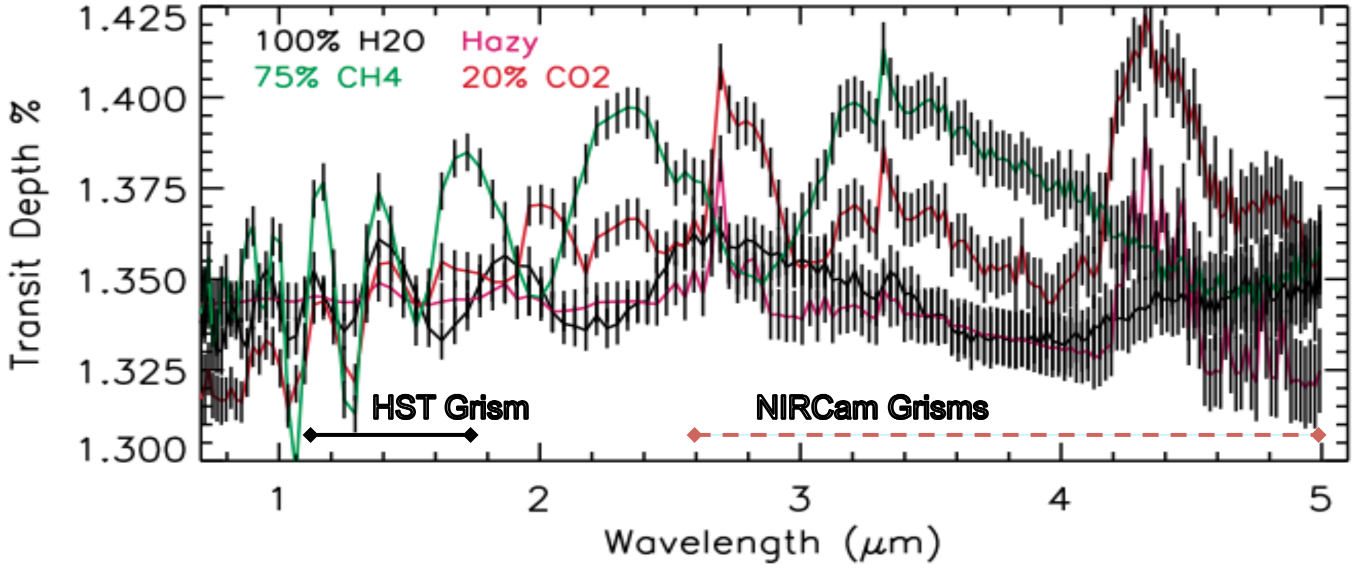
HD 189733b Gas Giant



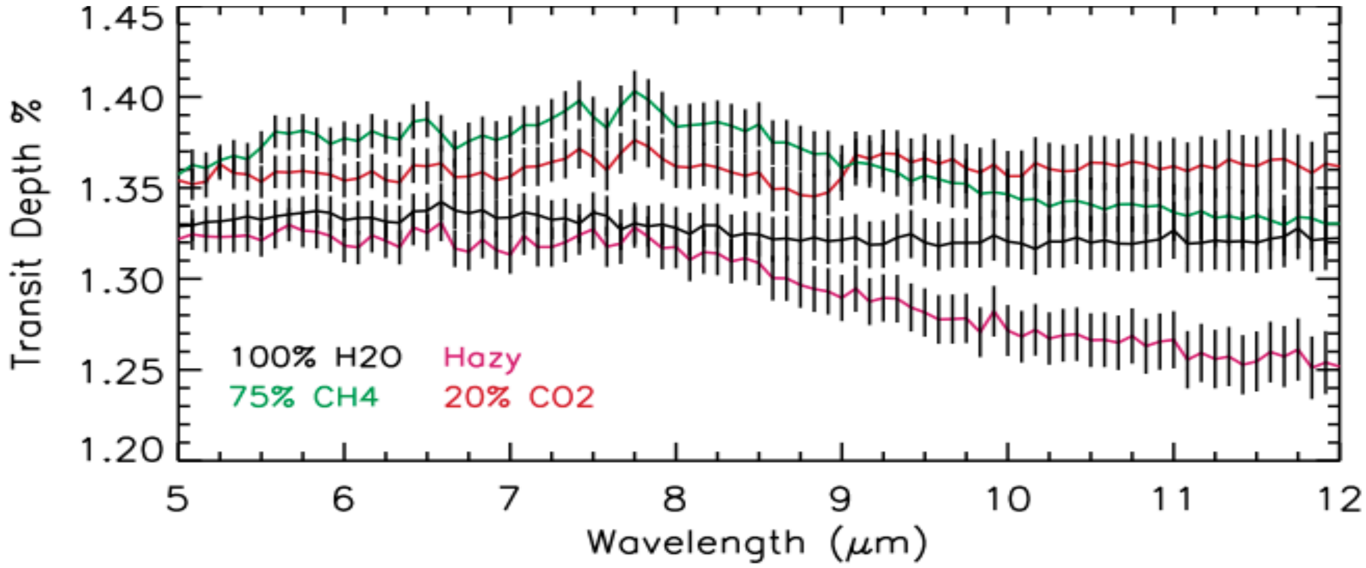


- Only 1 transit (top) or eclipse (bottom) plus time on star for each (1 NIRSPec + 1 MIRI)
- Multiple features of several molecules separate compositions, temperature, and distributions (J. Fortney group models + JWST simulation code)

GJ 1214b transmission spectra simulations (with noise floor)



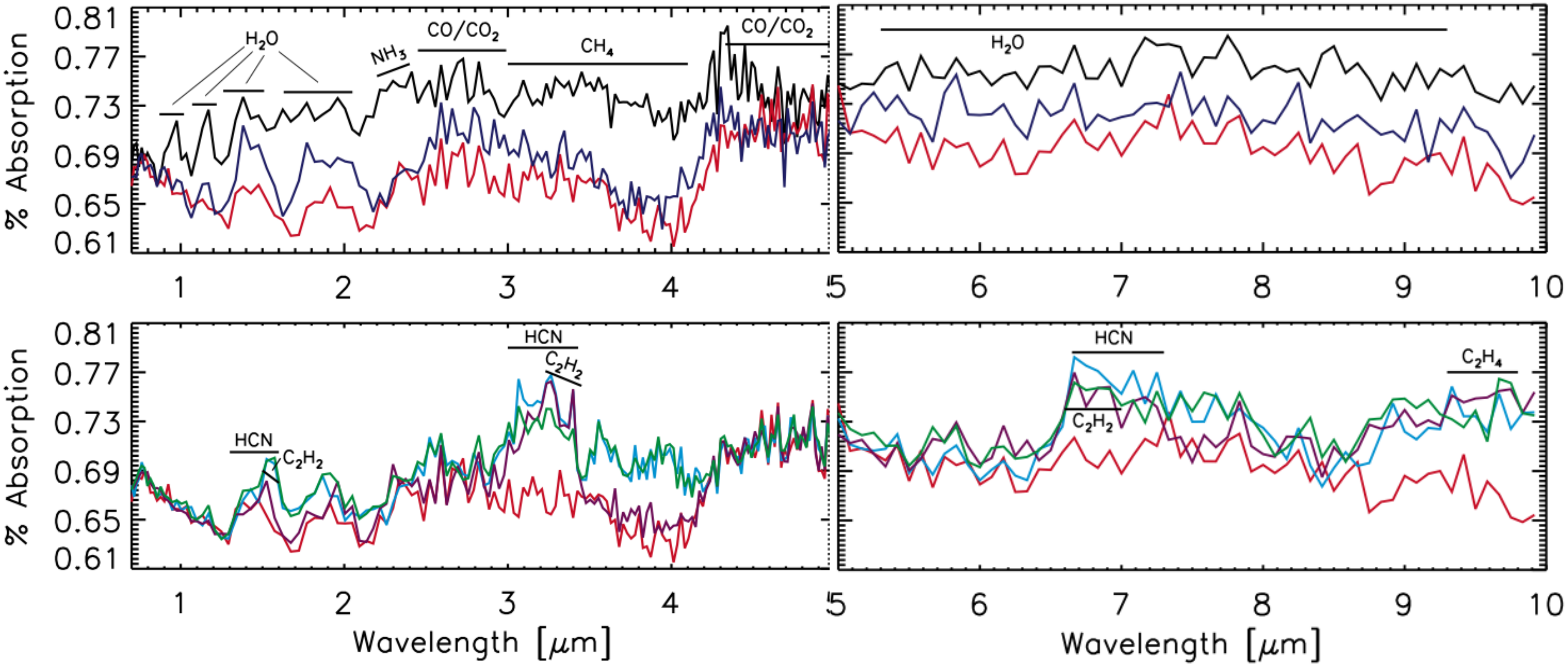
NIRSpec prism simulation also covers NIRISS and NIRCam. NIRCam grism range (red line) is very useful for identifying components



MIRI LRS spectrum is also useful for identifying components

- Simulated *single transit* model absorption spectra distinguish between different low density atmosphere models for low mass planets like GJ 1214b (*Fortney et al. 2013)*.

GJ 436b (warm Neptune) transmission spectra simulations



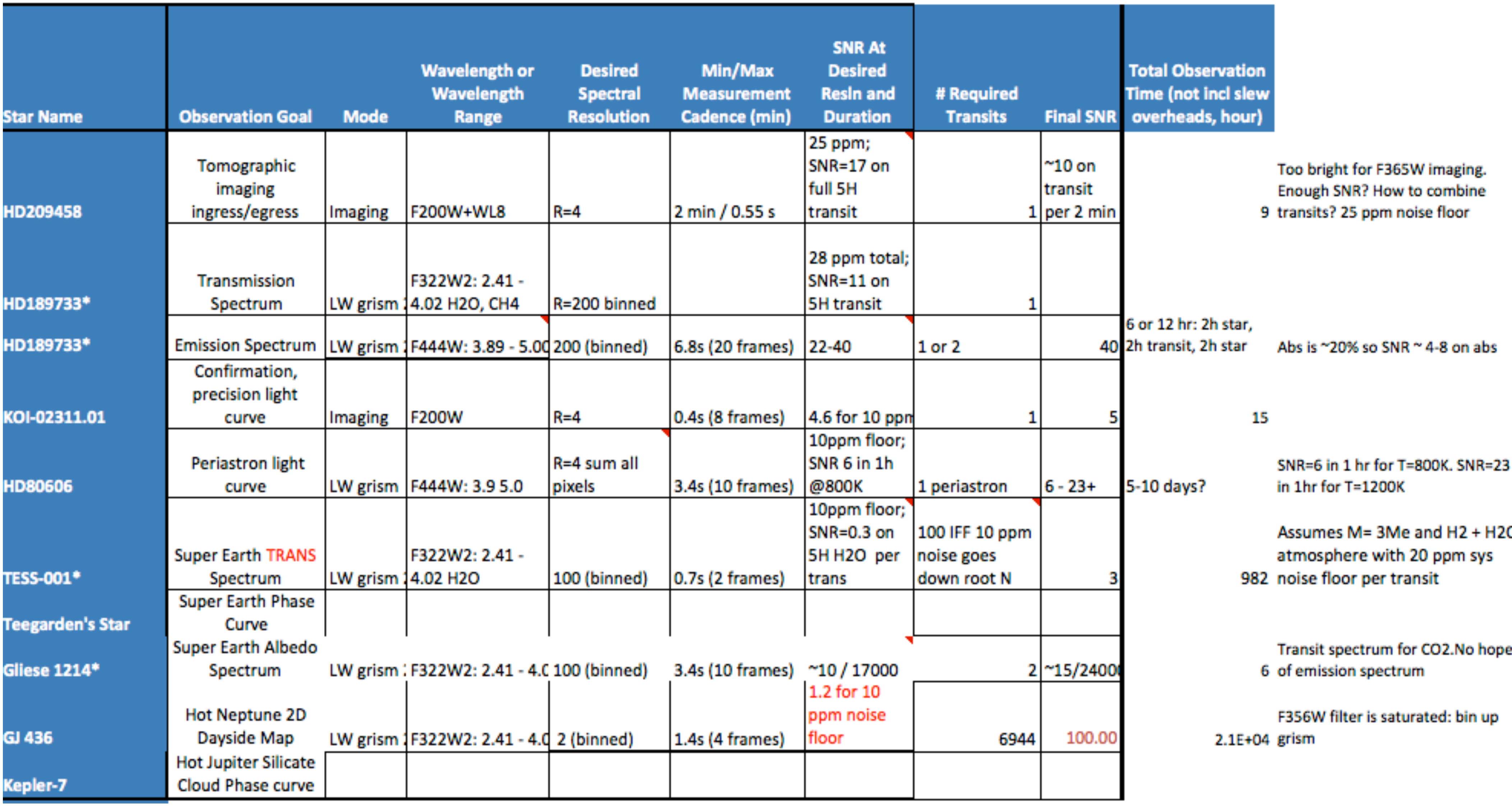
- Simulated single transit model absorption spectra distinguish between equilibrium 30X solar (black), reduced CH4 & H2O (blue, red) or non-equilibrium chemistries where H2O and CH4 are absent in favor of higher order hydrocarbons HCN, C2H2, and other molecules (purple, cyan and green curves). 1 transit each: 30 min star + 30 min in-transit integration time. Noise has been added (*Shabram et al. 2011)*.

NIRCam Transit Observing Limitations

- Pointing jitter (7 mas 1 sigma requirement) limits spectrophotometric precision of a single observation / visit
  - F200W + WL8 least affected
  - Binned grism data less affected than in-focus imaging

- NIRCam exposure limit of 65,535 integrations:
  - 6480 s (1.8 hr) for 64 x 64 subarray w/2 frames (BAD!)
    - About 2/3 of JWST exposure limit
  - 4.5E4 s (12.4 hr) for 2048 x 64 grism subarray w/2 frames
    - A bit shorter than observatory momentum dump interval

Sample NIRCam Observations



Star Name	Observation Goal	Mode	Wavelength or Wavelength Range	Desired Spectral Resolution	Min/Max Measurement Cadence (min)	SNR At Desired Resln and Duration	# Required Transits	Final SNR	Total Observation Time (not incl slew overheads, hour)	
HD209458	Tomographic imaging ingress/egress	Imaging	F200W+WL8	R=4	2 min / 0.55 s	25 ppm; SNR=17 on full 5H transit	1	~10 on transit per 2 min	9	Too bright for F365W imaging. Enough SNR? How to combine transits? 25 ppm noise floor
HD189733*	Transmission Spectrum	LW grism	F322W2: 2.41 - 4.02 H2O, CH4	R=200 binned		28 ppm total; SNR=11 on 5H transit	1			
HD189733*	Emission Spectrum	LW grism	F444W: 3.89 - 5.0	200 (binned)	6.8s (20 frames)	22-40	1 or 2	40	6 or 12 hr: 2h star, 2h transit, 2h star	Abs is ~20% so SNR ~ 4-8 on abs
KOI-02311.01	Confirmation, precision light curve	Imaging	F200W	R=4	0.4s (8 frames)	4.6 for 10 ppm	1	5	15	
HD80606	Periastron light curve	LW grism	F444W: 3.9 5.0	R=4 sum all pixels	3.4s (10 frames)	10ppm floor; SNR 6 in 1h @800K	1 periastron	6 - 23+	5-10 days?	SNR=6 in 1 hr for T=800K. SNR=23 in 1hr for T=1200K
TESS-001*	Super Earth TRANS Spectrum	LW grism	F322W2: 2.41 - 4.02 H2O	100 (binned)	0.7s (2 frames)	10ppm floor; SNR=0.3 on 5H H2O per trans	100 IFF 10 ppm noise goes down root N	3	982	Assumes M= 3Me and H2 + H2 atmosphere with 20 ppm sys noise floor per transit
Teegarden's Star	Super Earth Phase Curve									
Gliese 1214*	Super Earth Albedo Spectrum	LW grism	F322W2: 2.41 - 4.0	100 (binned)	3.4s (10 frames)	~10 / 17000	2	~15/2400	6	Transit spectrum for CO2.No hope of emission spectrum
GJ 436	Hot Neptune 2D Dayside Map	LW grism	F322W2: 2.41 - 4.0	2 (binned)	1.4s (4 frames)	1.2 for 10 ppm noise floor	6944	100.00	2.1E+04	F356W filter is saturated: bin up grism
Kepler-7	Hot Jupiter Silicate Cloud Phase curve									