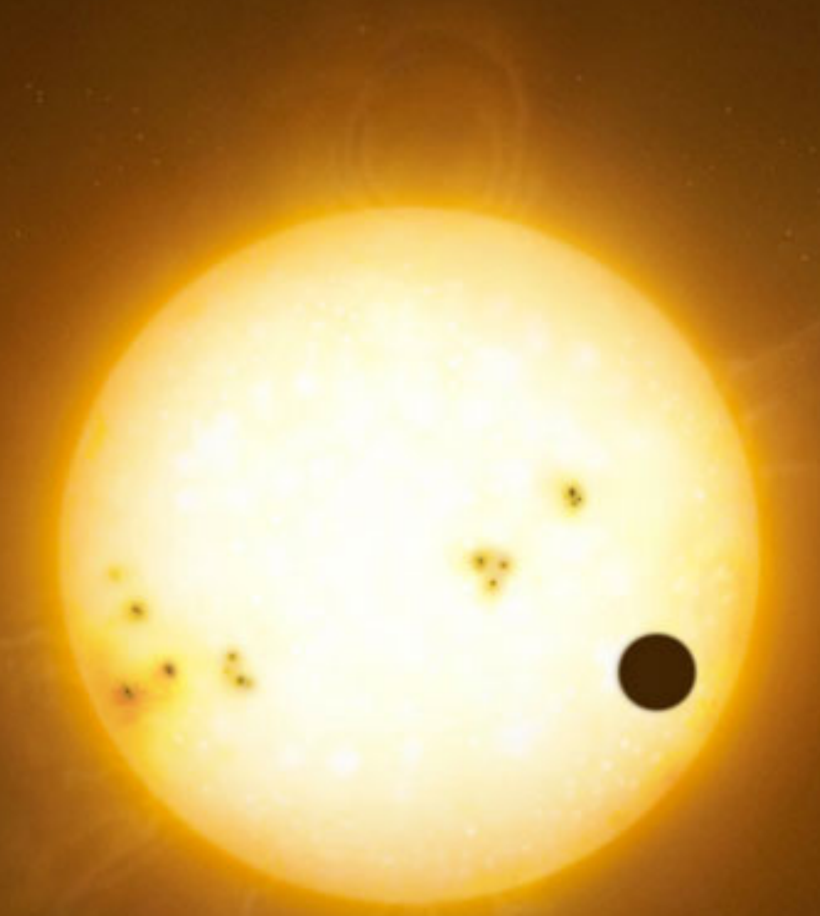
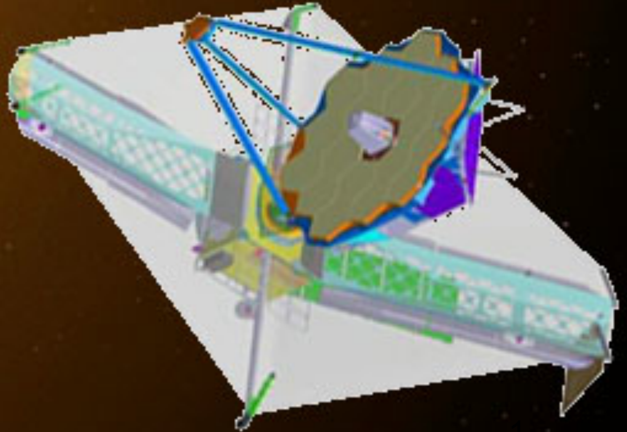
Exoplanet transit, eclipse, and phase curve observations with JWST MIRI and NIRCam



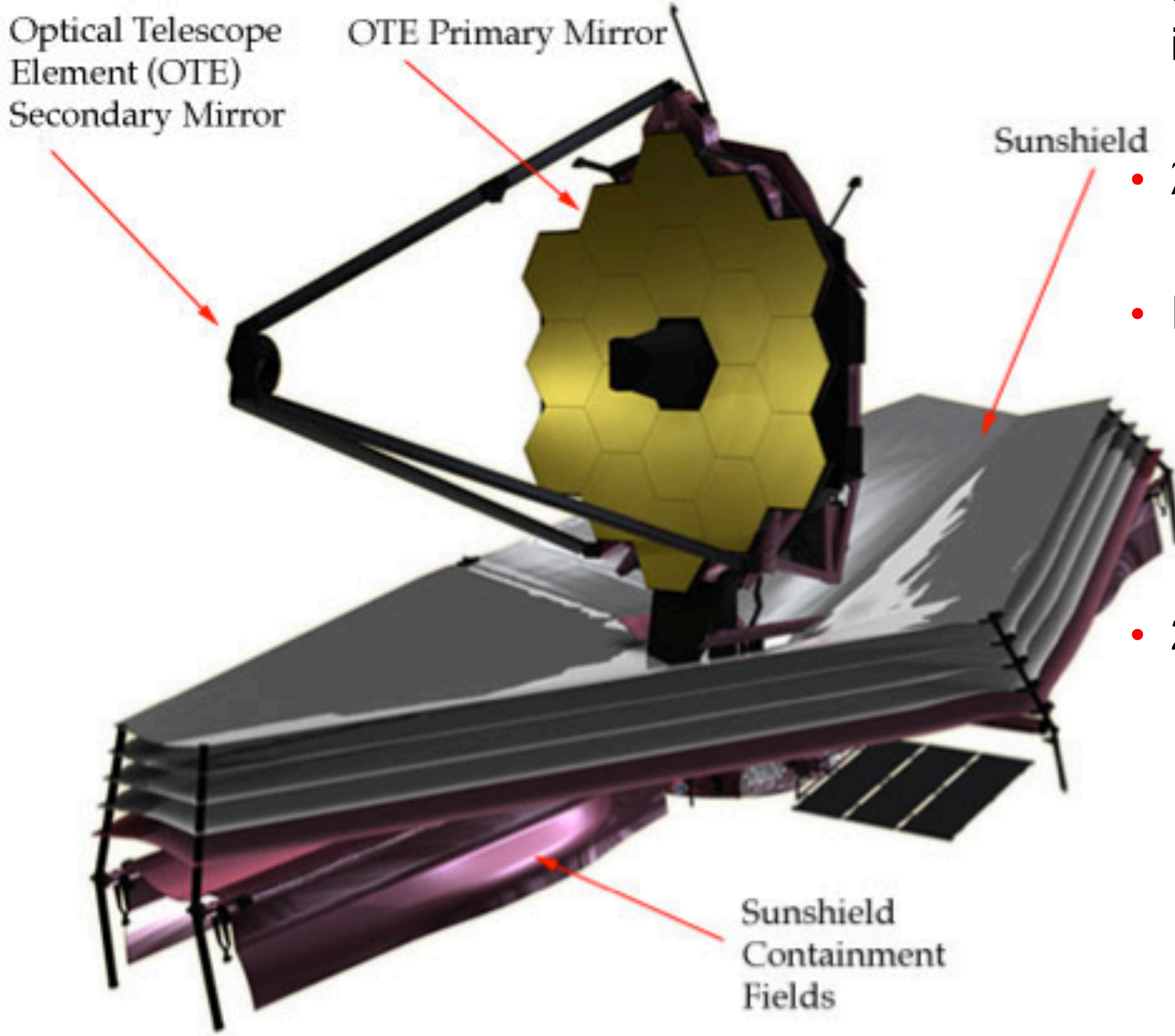
Tom Greene (NASA Ames)
ExoPAG #9
Jan 4, 2014



Scope of Talk

- JWST in a nutshell
- MIRI & NIRCam features and modes
  - Direct imaging
  - Spectroscopy
  - Subarrays and bright limits
- Observatory limits
- Systematic noise floor
- Simulated spectra and potential JWST science

JWST in a nutshell



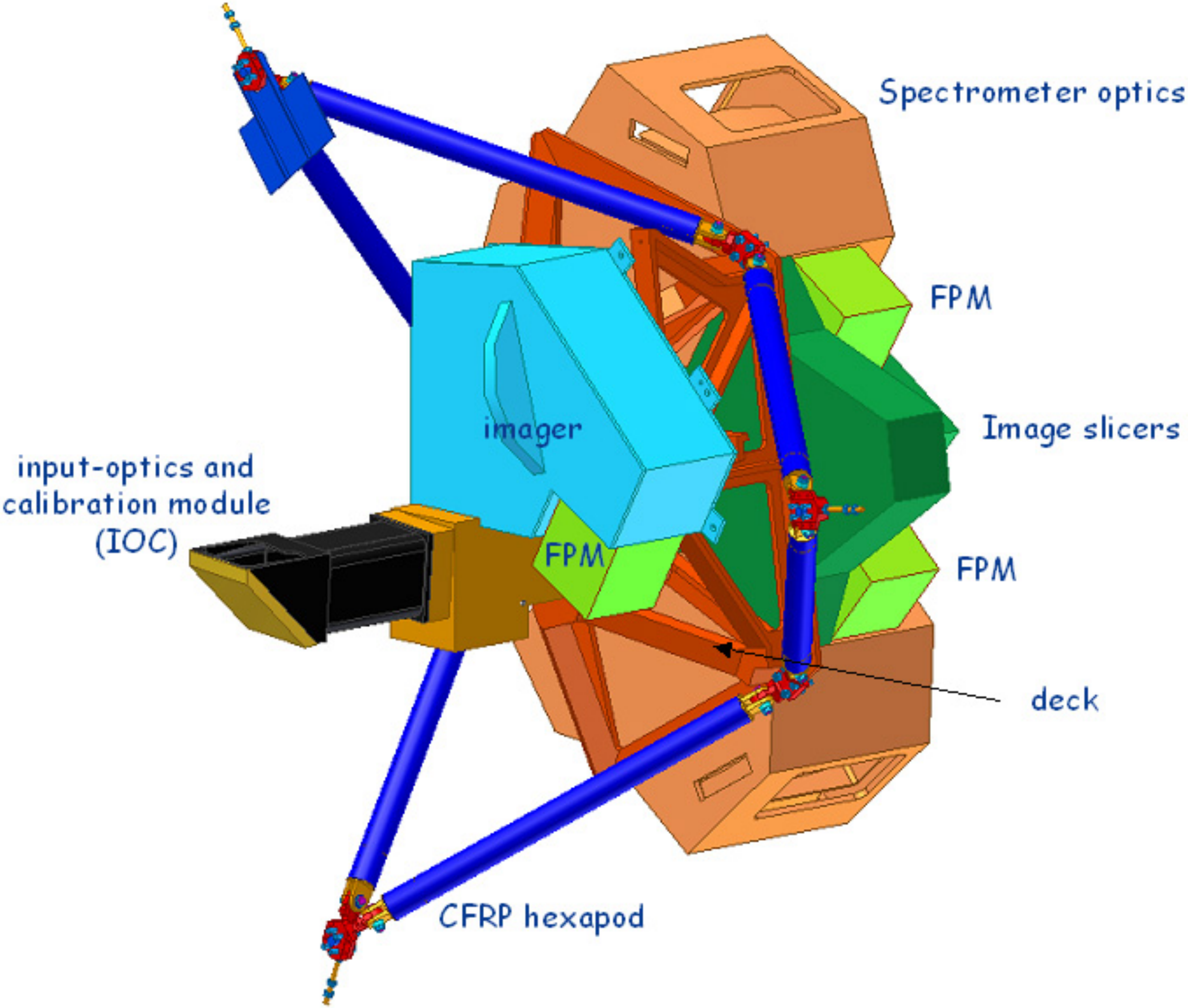
- 6.5-m primary mirror; 25 m^2 in 18 segments
  – T~40K, bkg. limited
- λ <1 - 28 μm
  - zodi-limited to 10μm
- Instruments:
  – NIRCam 0.7 – 5 μm
  – NIRSpec 0.7 – 5 um
  – MIRI 5 – 28 um
  – NIRISS/FGS .7–5(2.3) um
- 2018 launch
  – Arianne V to L2
  – 5 yr req life
  – 10 yr goal
  – No cryogens

The MIRI instrument will characterize circumstellar debris disks, extra-solar planets, and the evolutionary state of high redshift galaxies

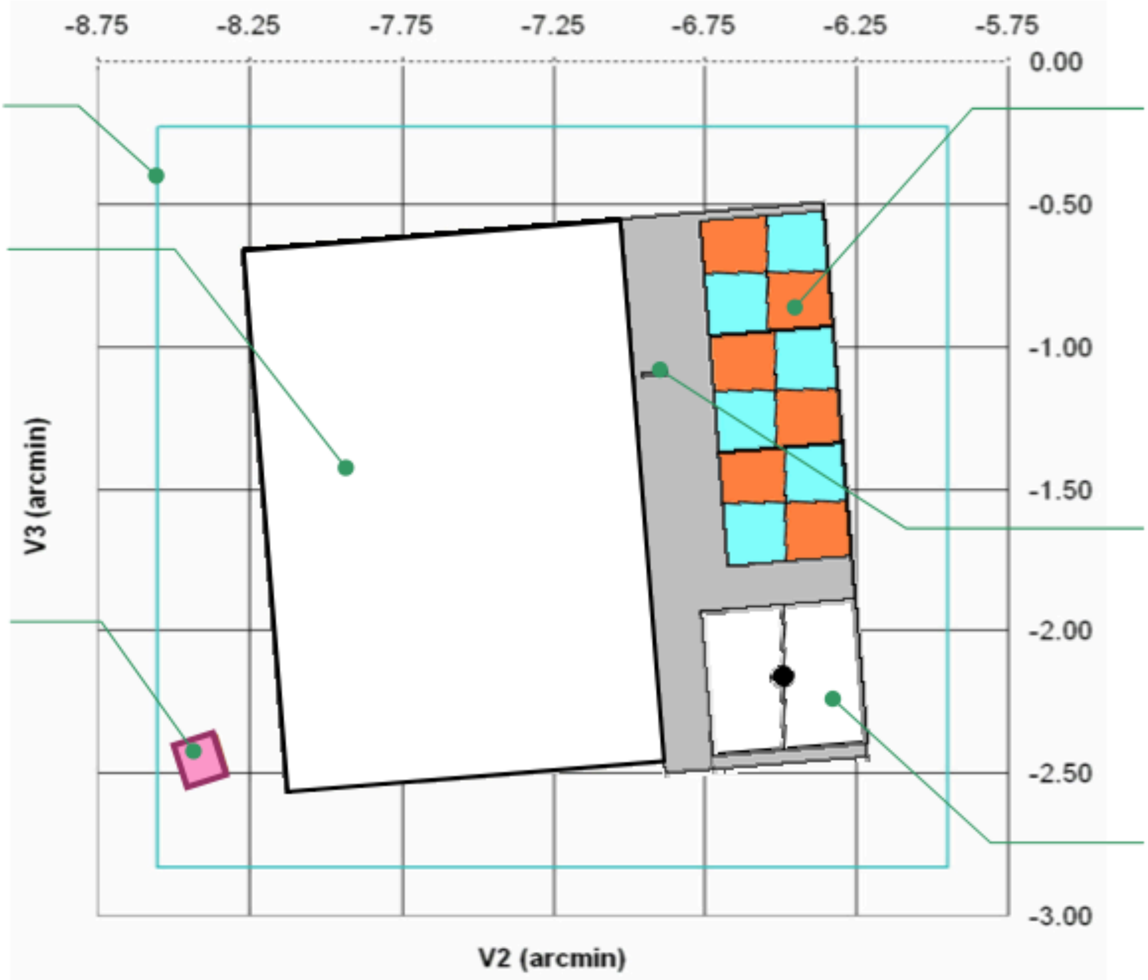
Developed by a consortium of 10 European countries and NASA/JPL

- Operating wavelength: 5 - 28 microns
- Spectral resolution: 5, 70, 2000
- Broad-band imagery: 1.9 x 1.4 arc minutes FOV
- Coronagraphic imagery
- Spectroscopy:
  - R ~ 70 long slit spectroscopy 5 x 0.2 arc sec
  - R ~ 2000+ spectroscopy: 3.5 x 3.5 and 7 x 7 arc sec FOV integral field units
- Detector type: Si:As, 1024 x 1024 pixel format, 3 detectors, 7 K cryo-cooler
- Reflective optics, Aluminum structure and optics

MIRI


Spectrometer optics
FPM
Image slicers
imager
input-optics and calibration module (IOC)
FPM
FPM
deck
CFRP hexapod

MIRI Fields of View (Requirement v Capability)



MIRI Allocation

Imager
OBA-0579 2.2'²
Cap. 1.25' x 1.88' = 2.35'²

Medium Resolution Spectrometer
OBA-0641 > 3.5" x 3.5"
Cap. 3.5" x 3.5"

4QPMs
15.5µm
11.4µm
10.65µm
OBA-0602 R ≥ 12"
Cap. 24" x 24" (R = 12")

Low Resolution Spectrometer
OBA-0622 5" x 0.6"
Cap. 5" x 0.6"

Lyot Mask 23µm
OBA-0602 R ≥ 15"
Cap. 30" x 30" (R = 15")

MIRI - Spectral Coverage

- **Imager/Coronagraph**

Name	Wavelength (μm)	Bandwidth (μm)
F560W	5.6	1.2
F770W	7.7	2.2
F1000W	10.0	2.0
F1130W	11.3	0.7
F1280W	12.8	2.4
F1500W	15.0	3.0
F1800W	18.0	3.0
F2100W	21.0	5.0
F2550W	25.5	4.0
F2550WR	25.5	4.0
F1065C	10.65	0.53
F1140C	11.4	0.57
F1550C	15.5	0.78
F2300C	23.0	4.6

- **Low Resn. Spectrometer**

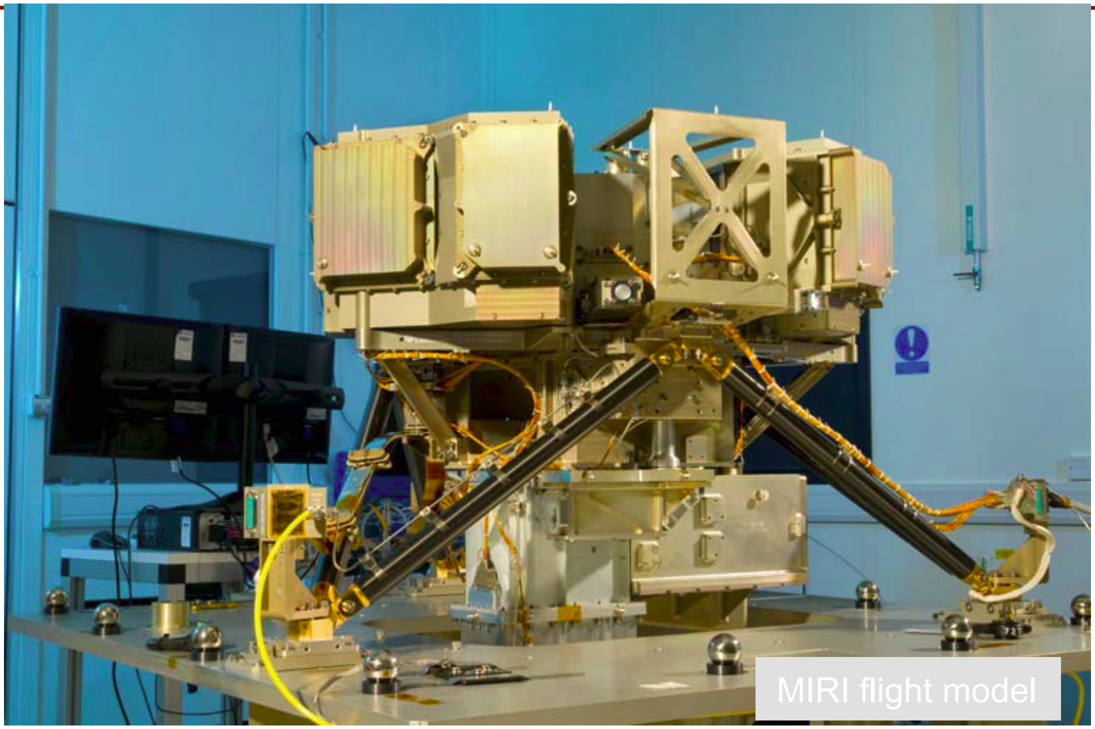
5 to 10 μm, R = 100 at 7.5 μm

- **Medium Resolution Spectrometer**

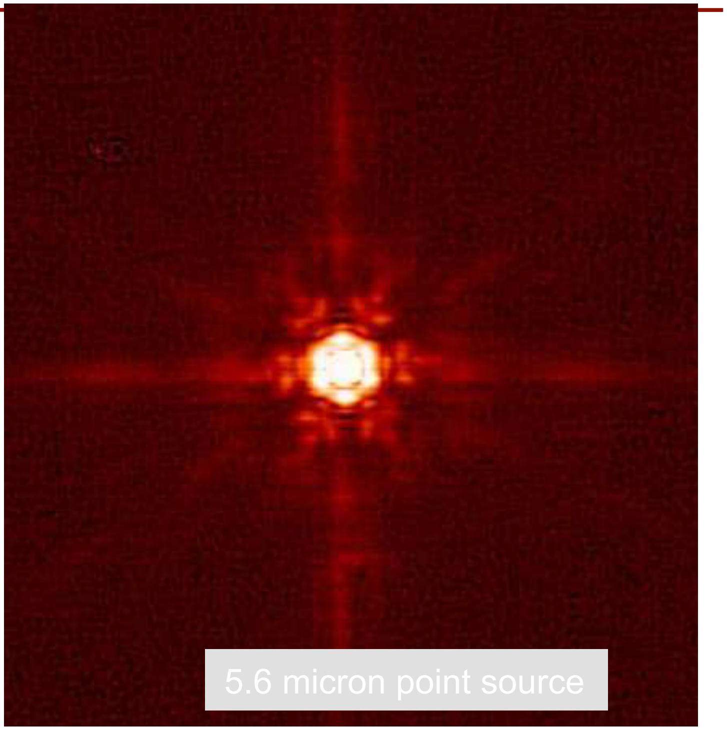
Sub-band	Wavelength Coverage [μm]	Spectral Resolving Power		Pixels per resolution element	
		(R = λ/Δλ)		Spectral (Rqmt >2)	Spatial
		Rqmt	Capability		
1A	4.9 - 5.8	> 2400	5180 - 6430	0.9 - 1.1	1.1 - 1.7
1B	5.6 - 6.7		4800 - 6600	0.9 - 1.2	1.2 - 1.6
1C	6.5 - 7.7		4770 - 6480	0.9 - 1.3	1.2 - 1.5
2A	7.5 - 8.8		2040 - 5590	1.1 - 3.1	1.2 - 1.7
2B	8.6 - 10.2		1770 - 5310	1.1 - 3.7	1.3 - 1.9
2C	10.0 - 11.8	> 1600	1600 - 5000	1.2 - 4.1	1.5 - 2.2
3A	11.5 - 13.6		3070 - 5900	1.0 - 2.1	1.6 - 2.0
3B	13.3 - 15.7		2390 - 5510	1.1 - 2.2	1.9 - 2.3
3C	15.3 - 18.1	> 800	2150 - 5040	1.2 - 2.5	2.2 - 2.6
4A	17.6 - 21.0		2190 - 2510	1.7 - 2.1	2.2 - 2.7
4B	20.5 - 24.5		1950 - 2210	1.9 - 2.4	2.6 - 4.0
4C	23.9 - 28.6		1860 - 1950	2.2 - 2.7	3.1 - 3.7

Waivers approved by MIRI Science Team (MIRI-RW-00009-ATC) "..the spectrometer is capable of doing the expected science programs with no significant compromise.."

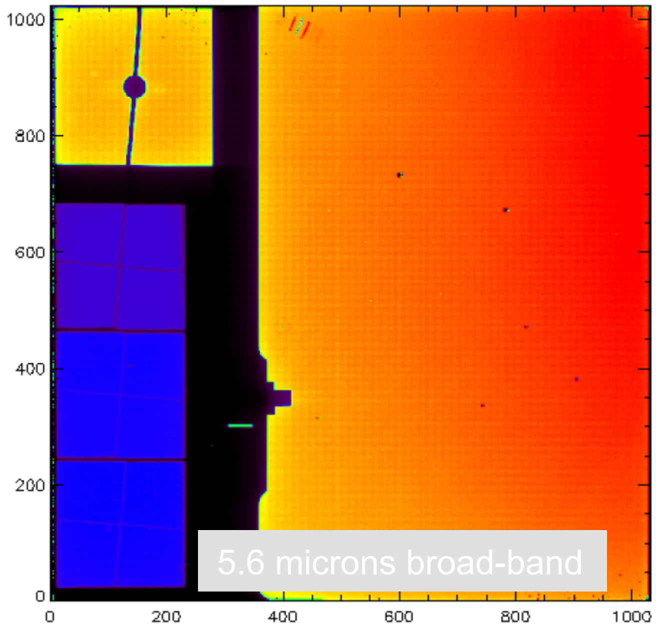
MIRI was delivered to ISIM I&T during May 2012



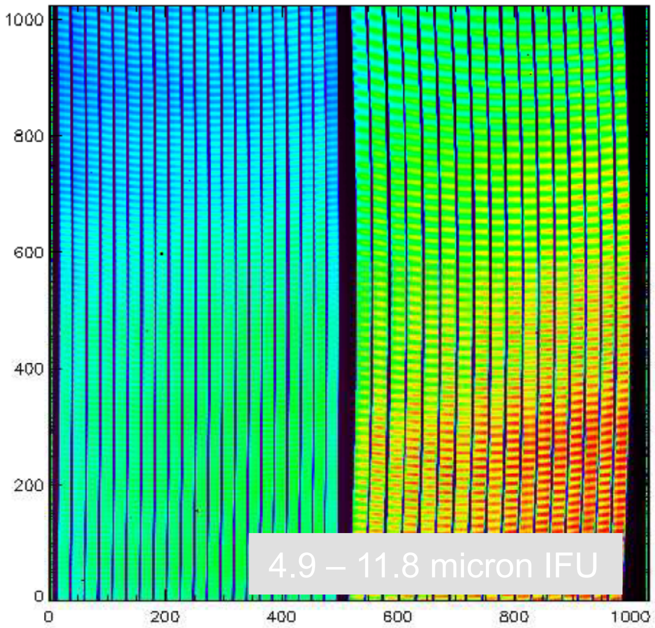
MIRI flight model



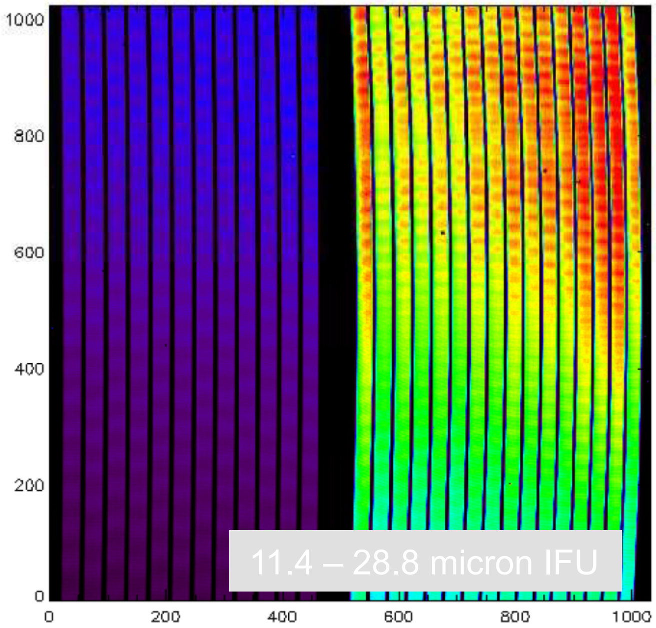
5.6 micron point source



5.6 microns broad-band



4.9 – 11.8 micron IFU



11.4 – 28.8 micron IFU

MIRI Imager / LRS Subarrays

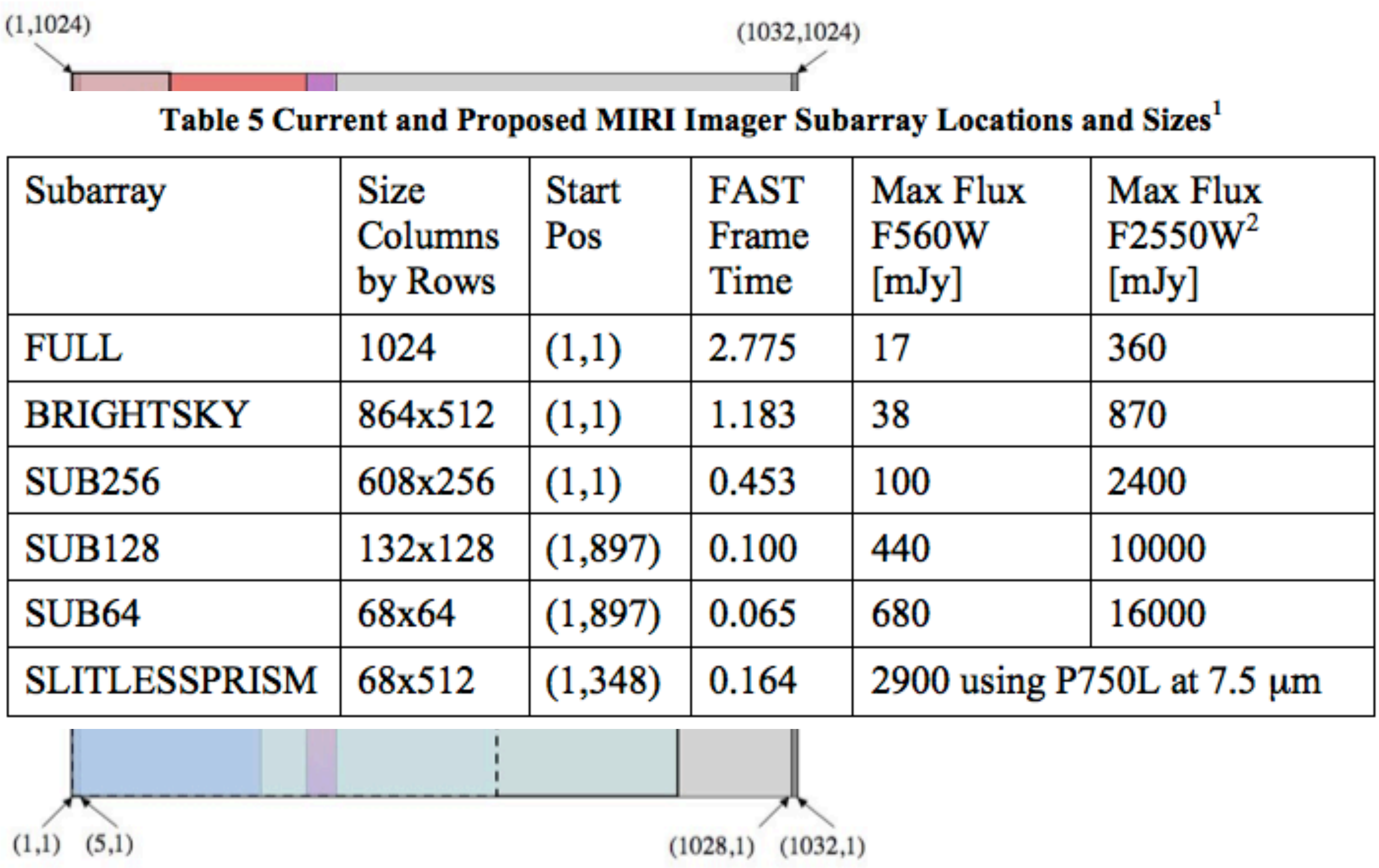
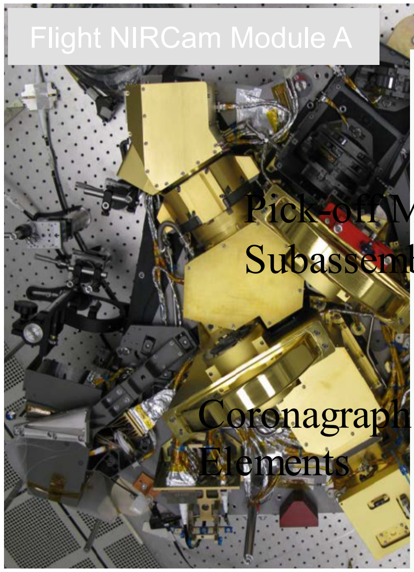


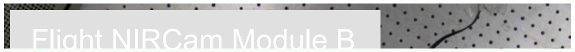
Table 5 Current and Proposed MIRI Imager Subarray Locations and Sizes[1]

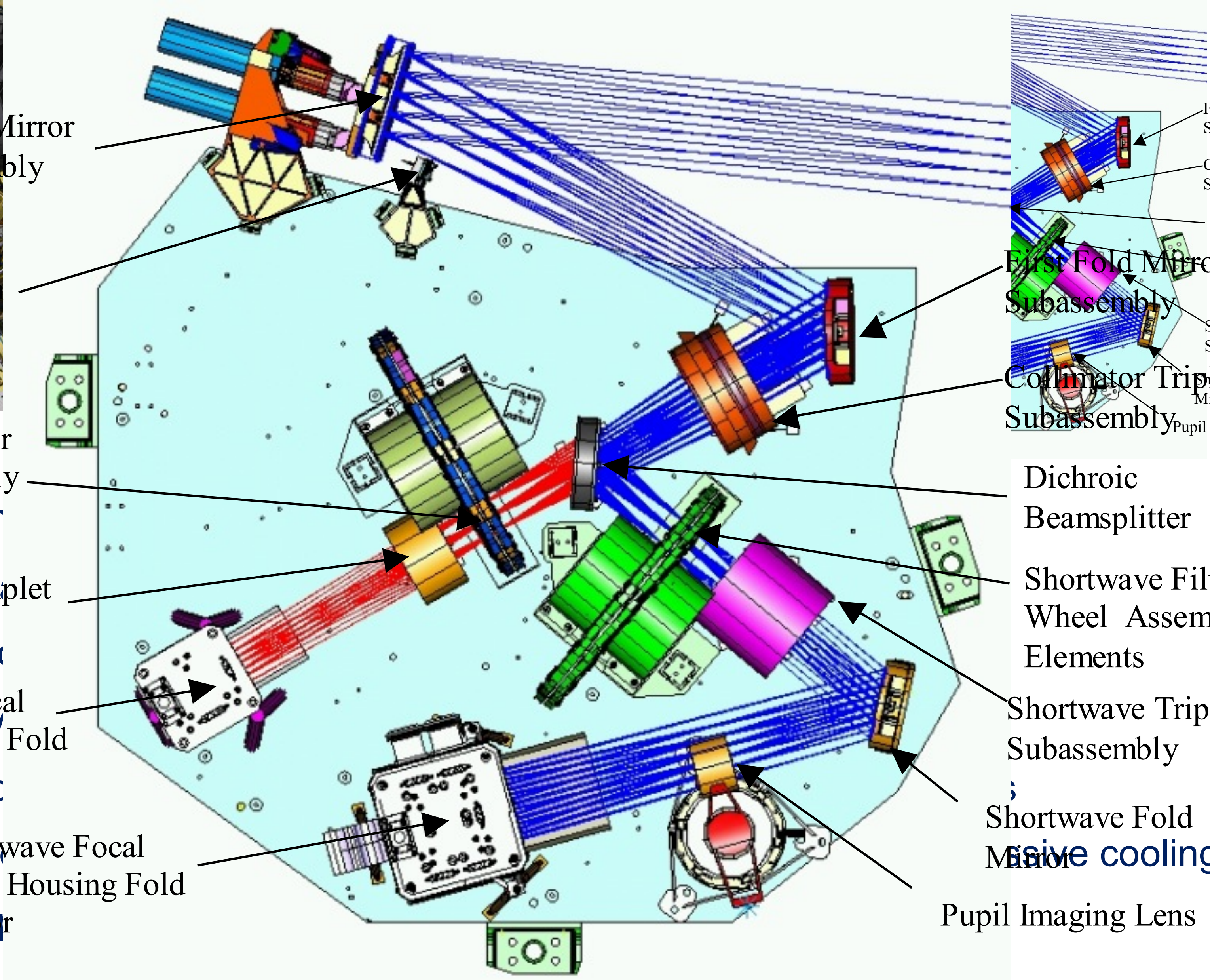
Subarray	Size Columns by Rows	Start Pos	FAST Frame Time	Max Flux F560W [mJy]	Max Flux F2550W[2] [mJy]
FULL	1024	(1,1)	2.775	17	360
BRIGHTSKY	864x512	(1,1)	1.183	38	870
SUB256	608x256	(1,1)	0.453	100	2400
SUB128	132x128	(1,897)	0.100	440	10000
SUB64	68x64	(1,897)	0.065	680	16000
SLITLESSPRISM	68x512	(1,348)	0.164	2900 using P750L at 7.5 µm	

Note: Fastest readouts will have low (~50%) efficiencies

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







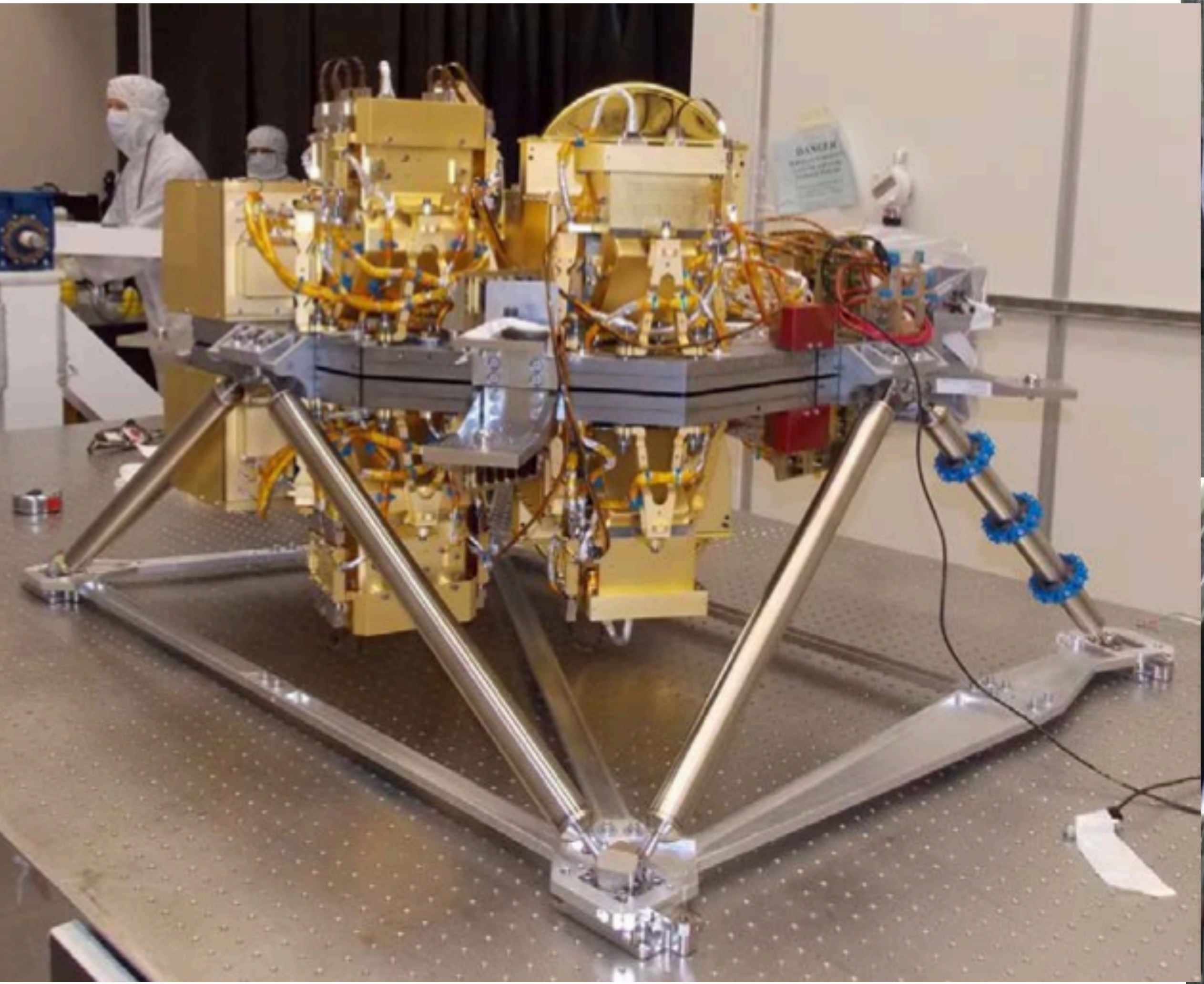
Developed by th

- Operating
- Spectral reso
- Field of view
- Angular reso
- Detector typ
- Refractive op

sive cooling

Supports telescope wavefront sensing

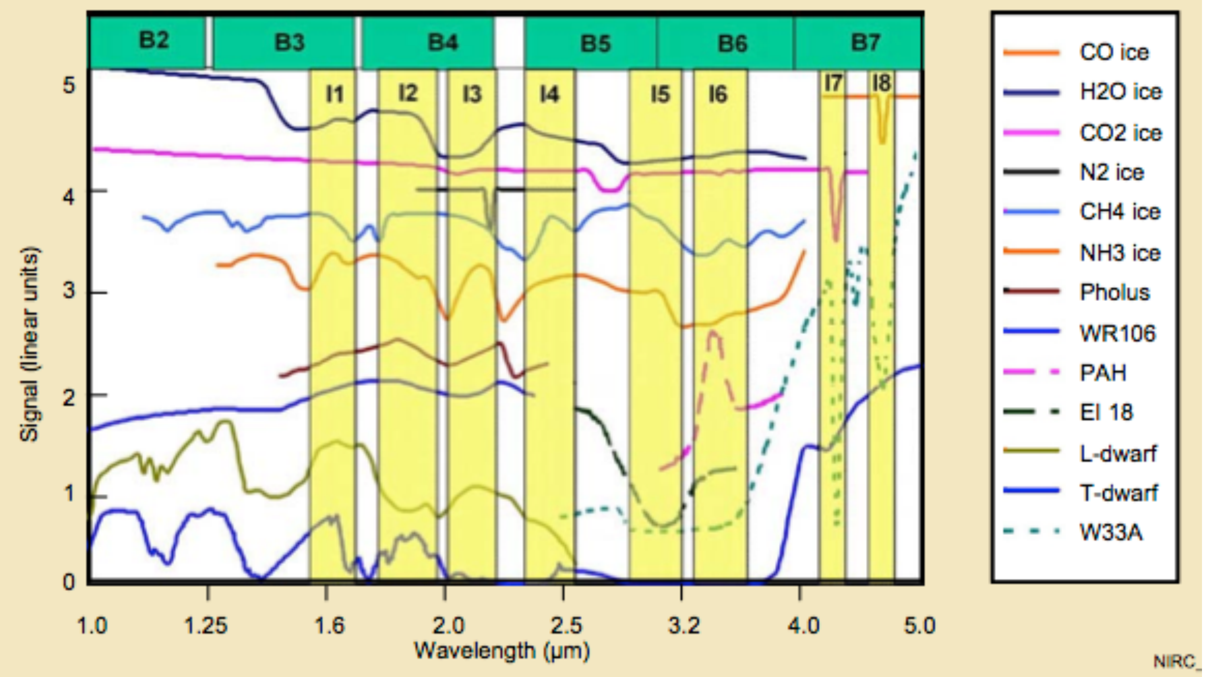
NIRCam consists of 2 identical modules with adjacent FOVs

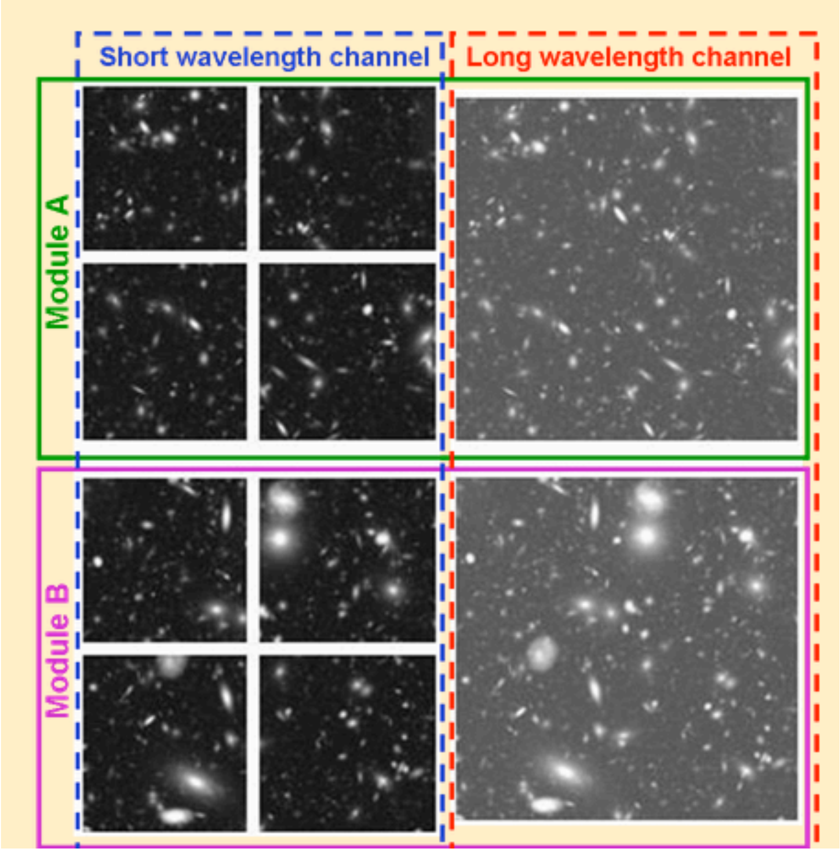


Integrated NIRCam Flight Model

NIRCam Modules A & B In Test Chamber

NIRCam filters and modes

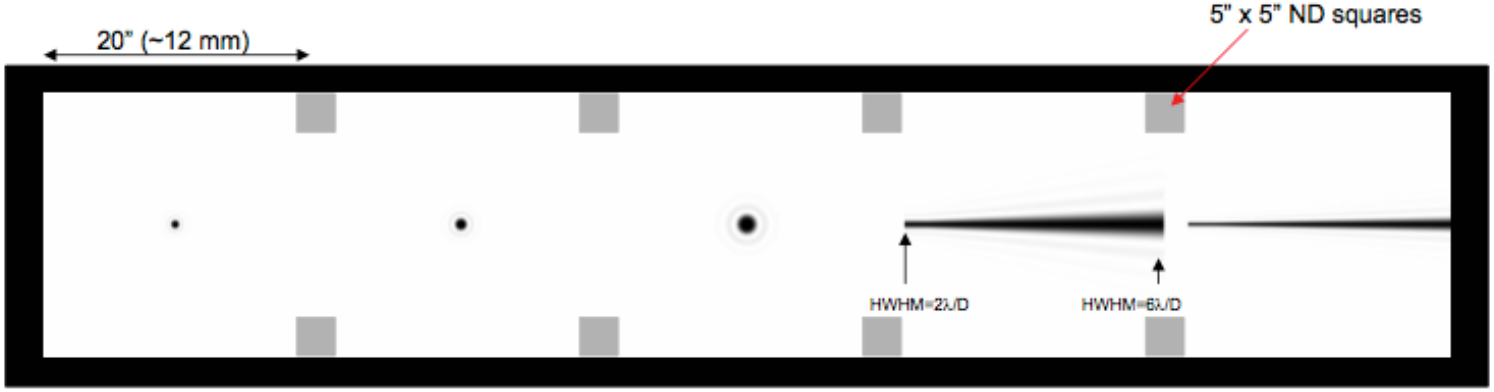




NIRCam Wide, Medium and some Narrow filters (top).
NIRCam also has SW weak lenses to spread out light;

On-sky layout (right);

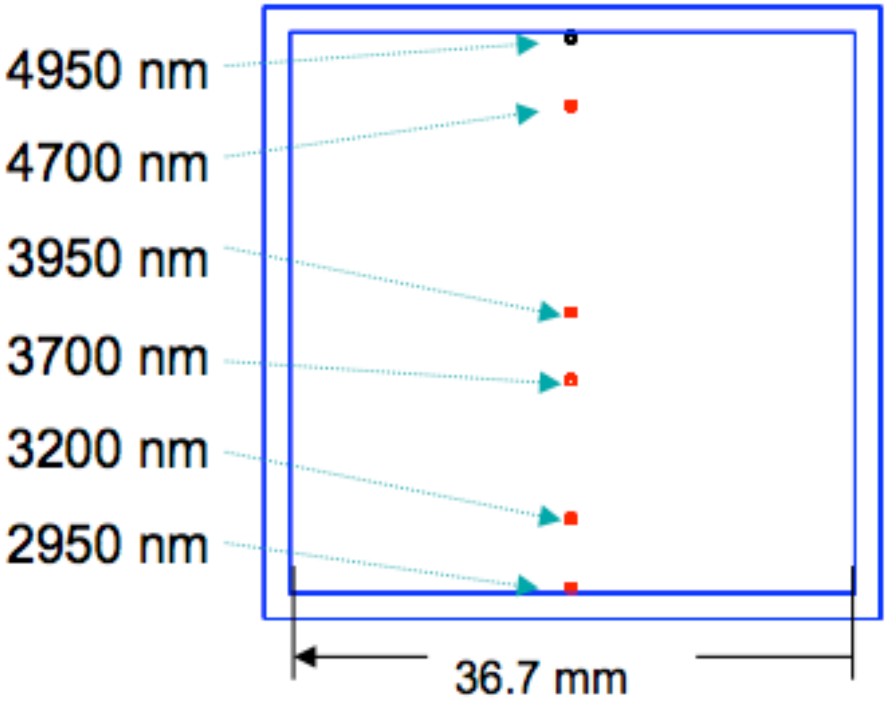
Coronagraphic masks (right)



HWHM = 0.40" (6λ/D @ 2.1 μm)	HWHM = 0.64" (6λ/D @ 3.35 μm)	HWHM = 0.82" (6λ/D @ 4.3 μm)	$HWHM_c$ = 0.58" (4λ/D @ 4.6 μm)	$HWHM_c$ = 0.27" (4λ/D @ 2.1 μm)

NIRCam 2.5 – 5 μm slitless grisms

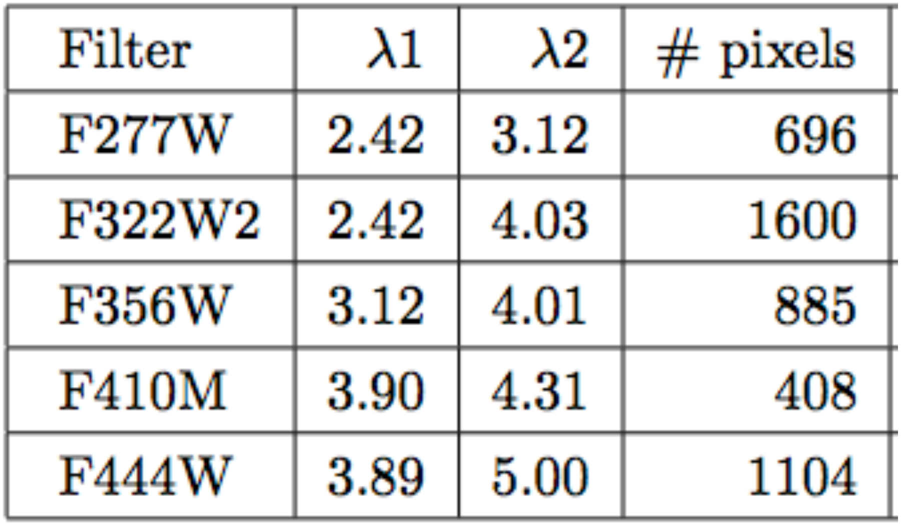
- Grisms are in the LW pupil wheel and are used in series with a LW filter
- R = 1700
- Good spatial sampling:
  - Nyquist sampled at 4 μm



LW FPA size 36.7 X 36.7 mm

Center Field Dispersion by Grism

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

- 2 grisms per module in perpendicular orientations

Preliminary NIRCam subarrays / bright limits

- Point source imaging subarrays of 64 x 64, 160 x 160, and 400 x 400 pixels LW & SW
  - Bright limit K~ 9 mag (G2 V) with wide filter in 64 x 64 subarray depending on wavelength
  - 8 wave weak lens gives K ~ 4 mag saturation limit for SW photometry with 160 x 160 pixel subarray
- 2048 x 64 grism subarray allows K ~ 3 - 5 mag bright limit for G2V star at $\lambda \sim 3$ μm (depending on spectral orientation: 1 or 4 outputs used)
- 1024 x 32 grism subarray also possible for up to 1.5 mag brighter objects: complete spectrum except for W2 filters

JWST Observational Constraints

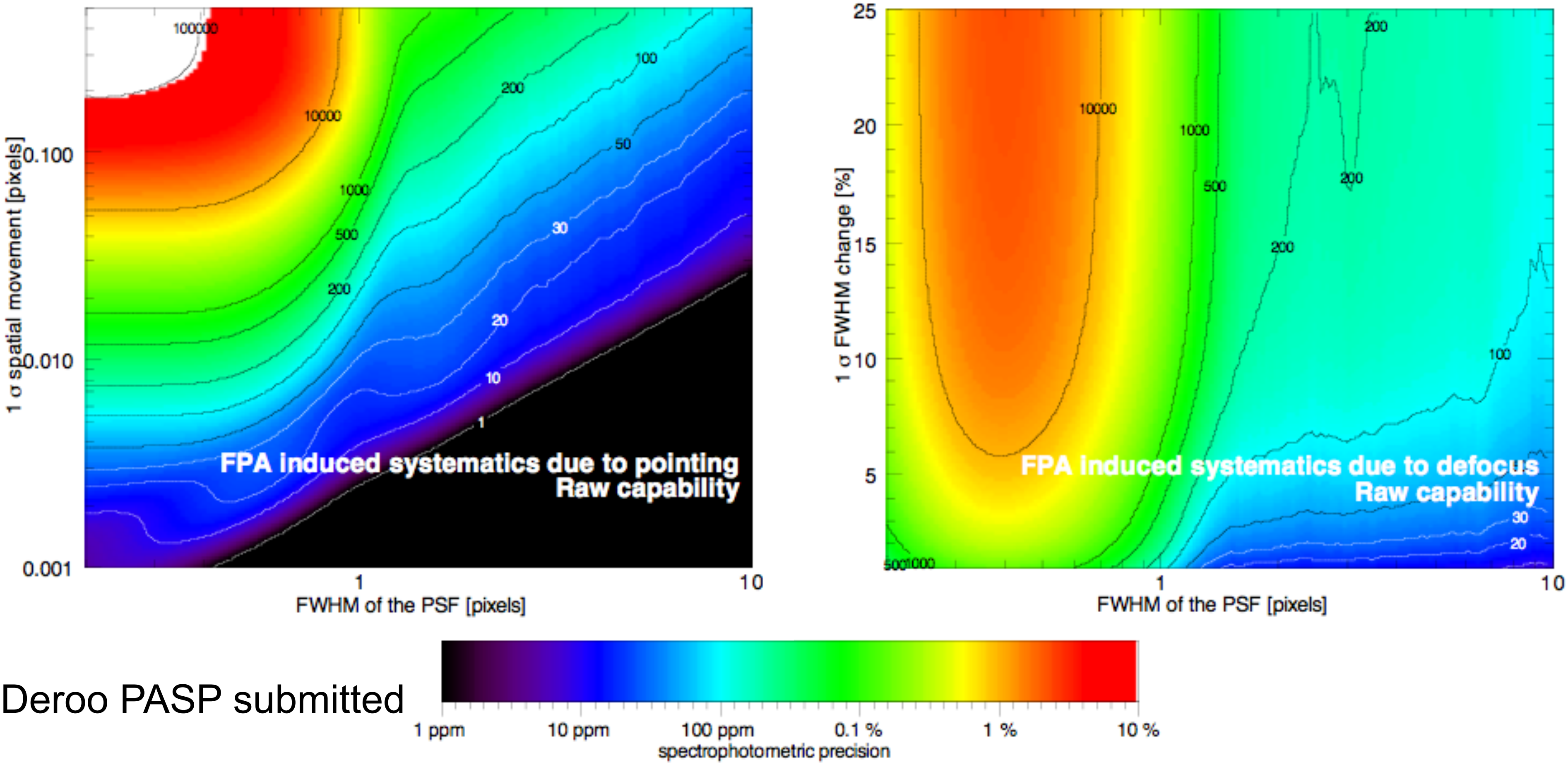
- JWST instantaneous field of regard is limited
  Sun angles between 85 and 135 degrees (35% of sky; CVZ > 5d)
  Two 50-day visibility windows per year near ecliptic
- Absolute pointing (7 mas 1 sigma requirement) limits spectrophotometric precision of multiple visits, particularly with HgCdTe detectors (NIRCam, NIRISS, NIRSpec)
- Pointing jitter (7 mas 1 sigma requirement) limits spectrophotometric precision of a single observation / visit.
- JWST has a 1E4 second exposure limit due to required moves of the high gain antenna.
  - Currently planning to allow observations through this limit, but expect pointing jump of 100 mas for 1 minute duration.
- Must observe a single field at a fixed roll angle for up to 10 days continuously BUT:
  - Maximum visit duration is 1 day for momentum dump: need new guide star acq; BAD for phase curves!

Systematic Noise Limits

- Expect a systematic noise floor to emerge when photon SNR is high
- NIRCam (+ NIRISS + NIRSpec) detectors are similar to HST WFC3; expect similar ~35 ppm noise floor
  - Validated by independent modeling
- MIRI cryogenic (7K) CMOS detectors are less stable; more like Spitzer IRAC band 3 and 4
  - Still working on optimal noise reduction strategy, hoping for ~50 ppm noise floor in single / few visits

Systematic Noise Estimate Models

- Focus and pointing drifts are likely the biggest impact for JWST when the PSF is undersampled.
  - Will impact MIRI MRS but not a serious issue for NIRCam SW or LW at λ > 3 μm.
- NIRCam grism, MIRI LWS (& NIRISS GR700XD) all have no slit losses and suffer minimal impact from undersampling

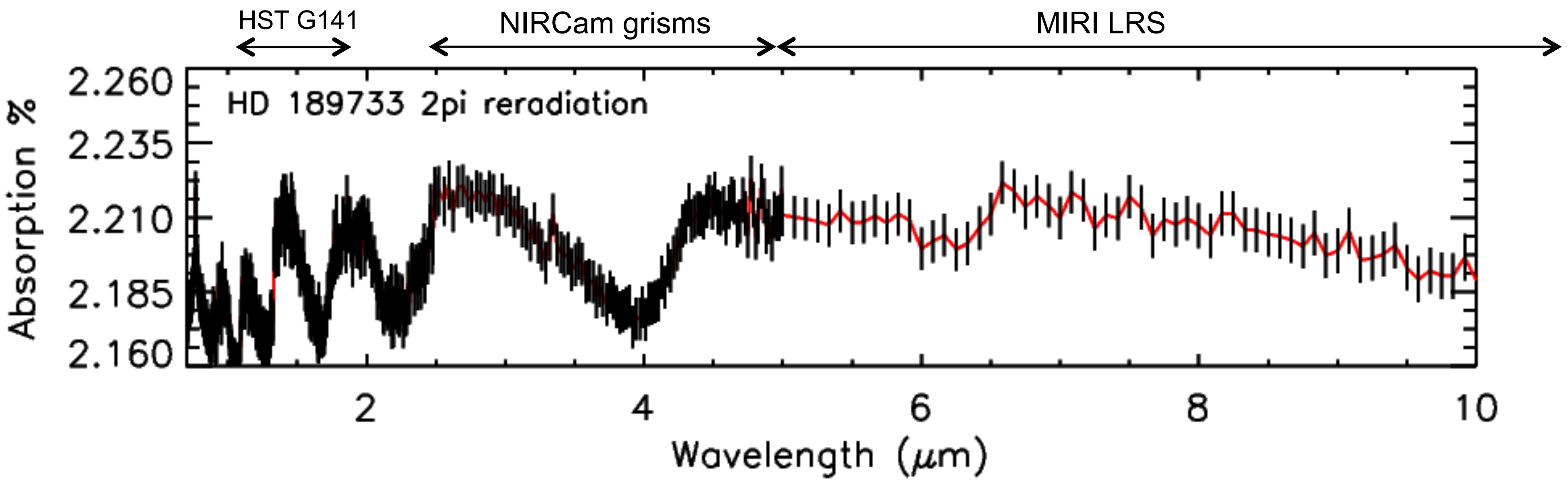


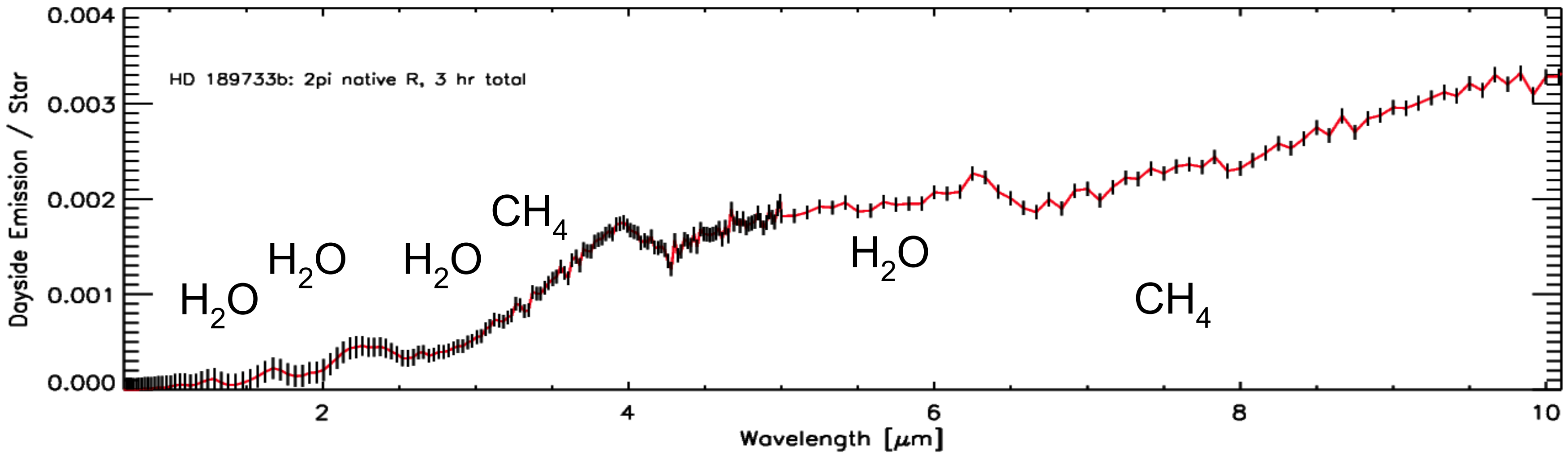
P. Deroo PASP submitted

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, filters
  - Use actual instrument models or guesstimates
- Photon noise and systematic noise floor added in quadrature
- Systematic noise is difficult to predict but major causes can be modeled / predicted
  - Different for each instrument and mode
  - May have large wavelength dependencies for some instruments (Deroo sub. PASP)
- Do retrievals on simulations to determine what science issues can be addressed with JWST data

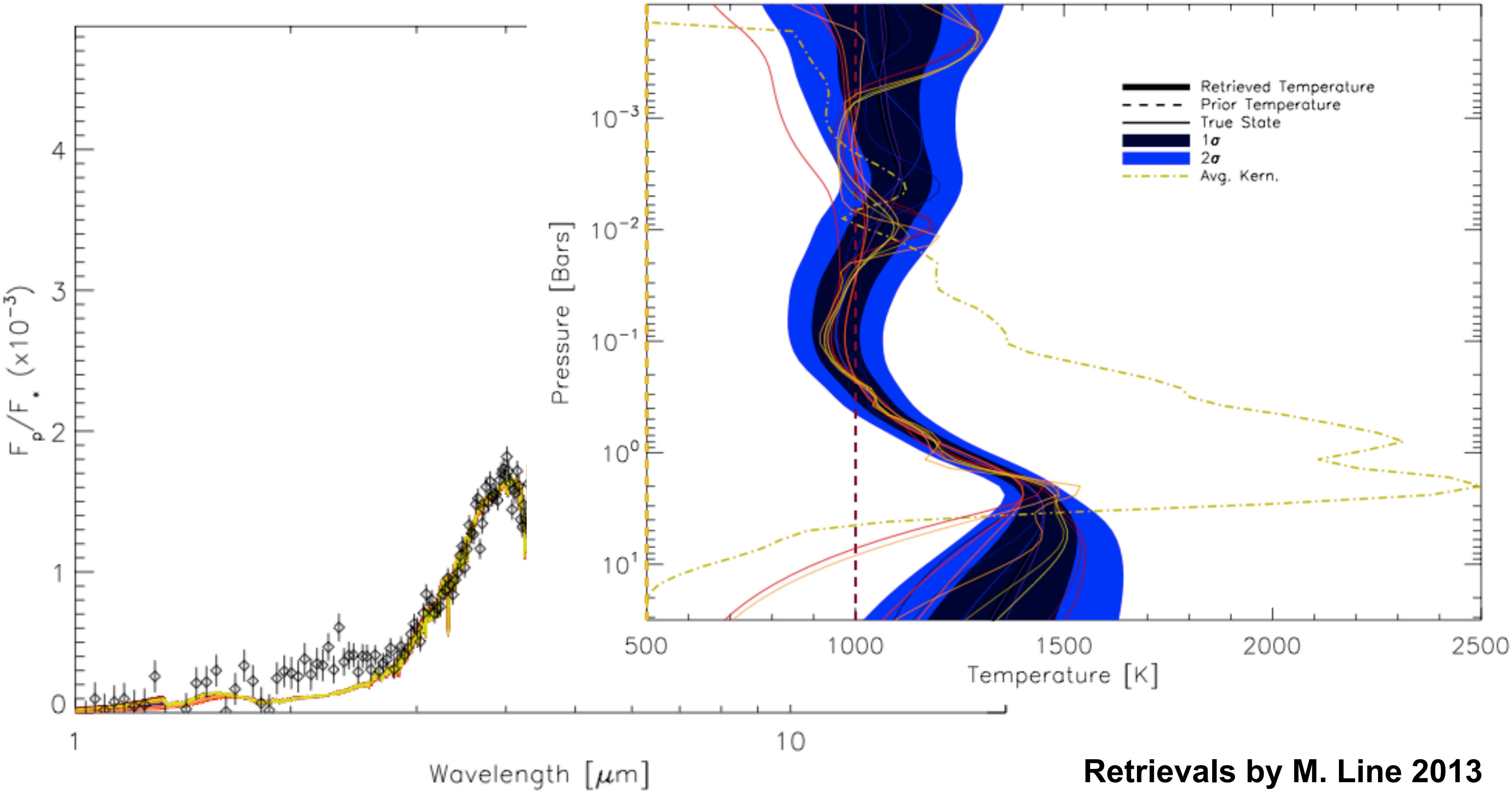
HD 189733b Gas Giant





- 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)

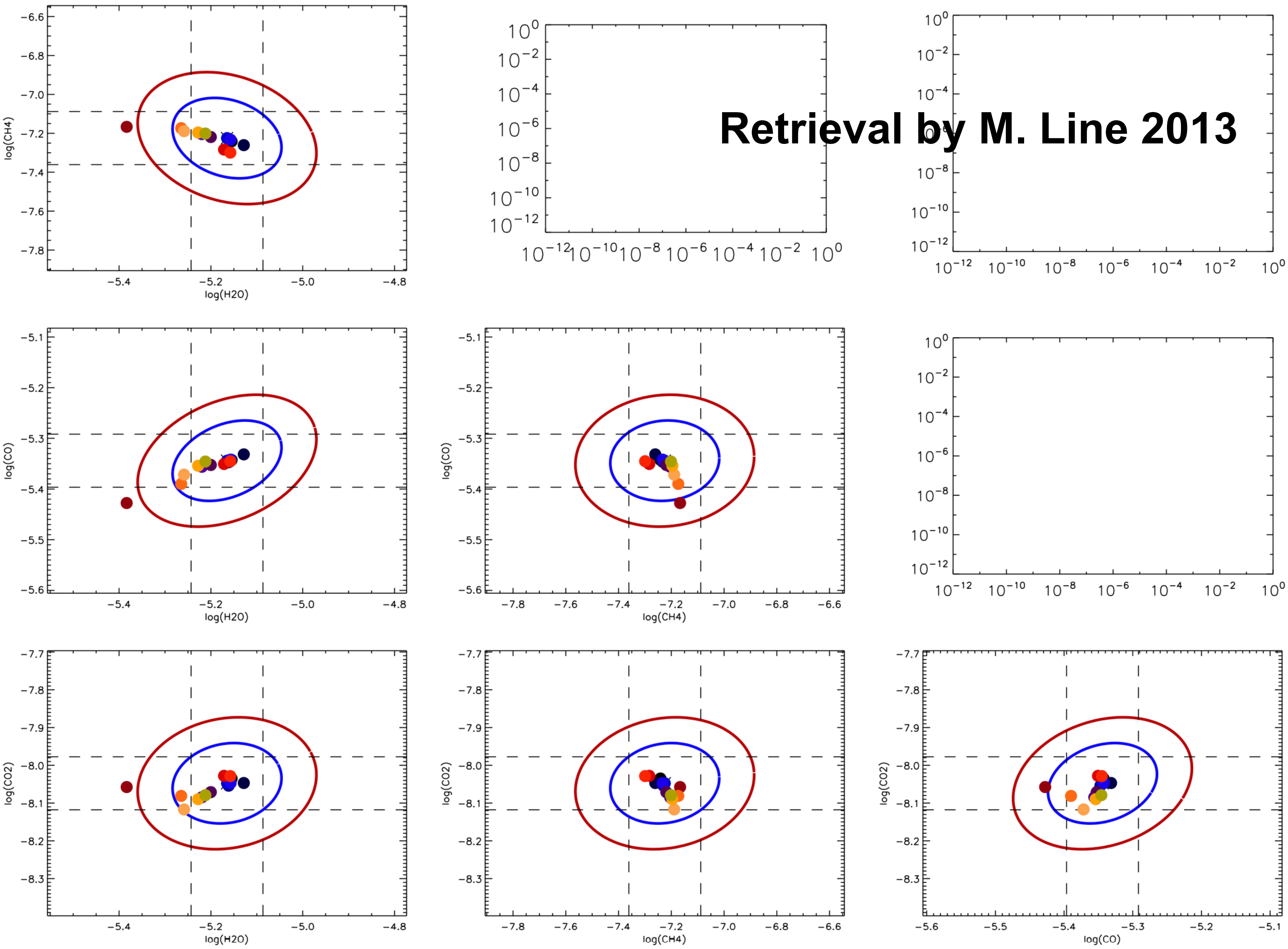
Retrieval from HD 189733b emission simulation



Retrievals by M. Line 2013

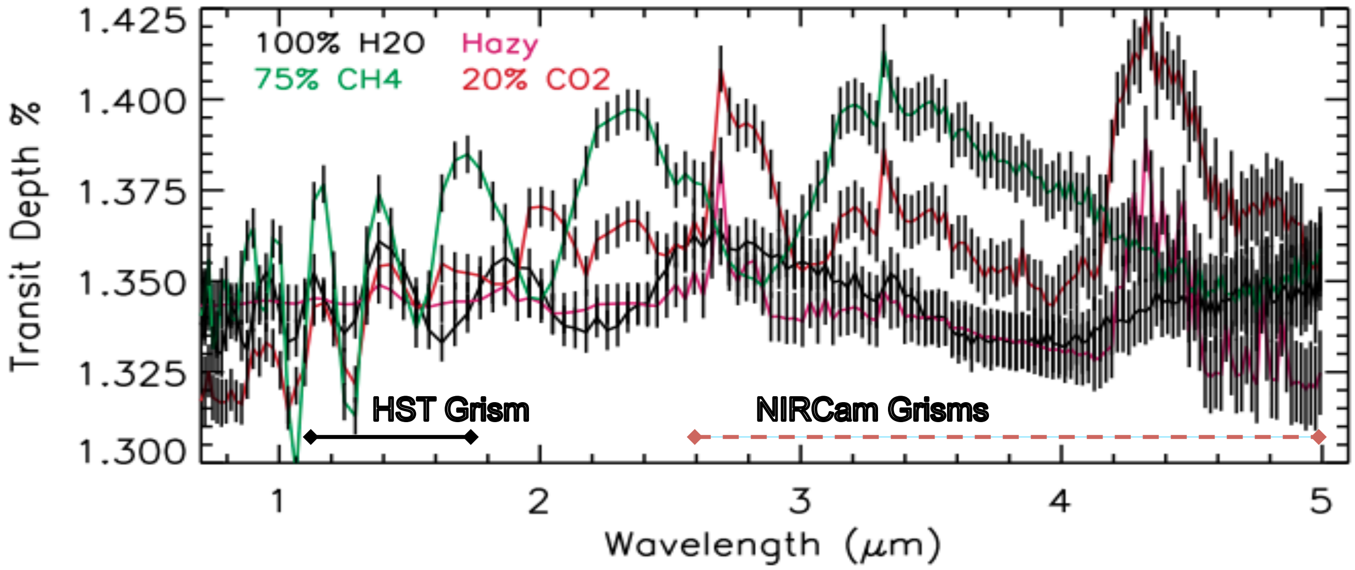
- Simulations of Fortney et al. emission model, initial retrieval by M. Line
- Different model for simulation and retrieval; slightly different star / planet parameters to simulate errors

HD 189733b composition

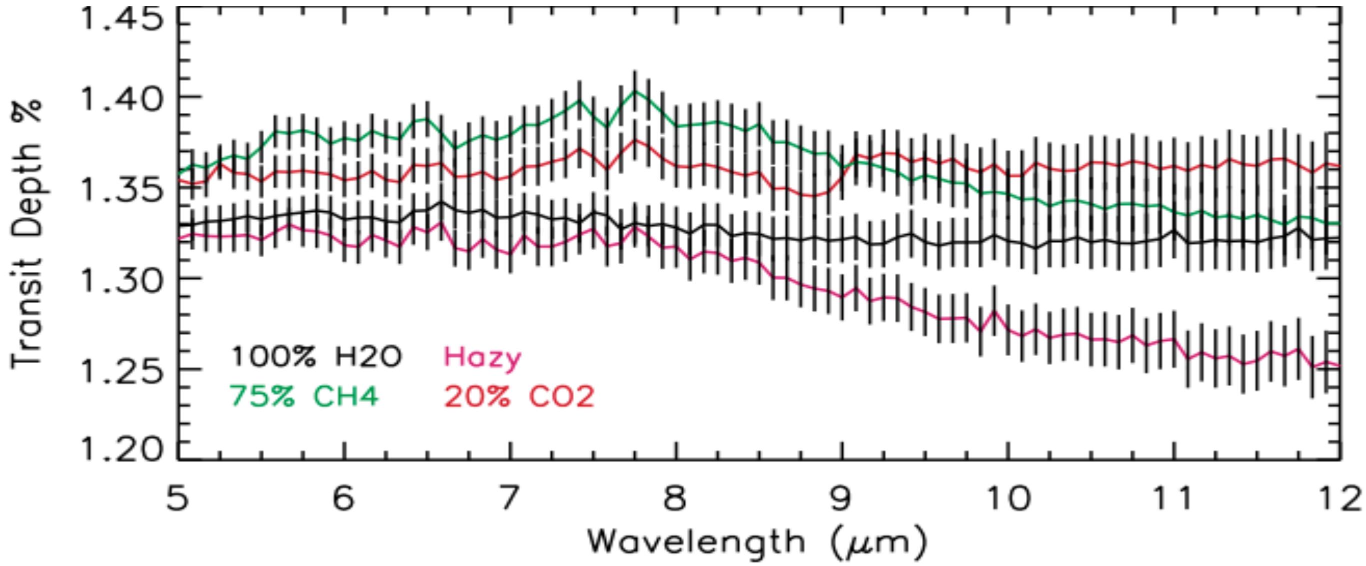


Retrieval by M. Line 2013

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)*.

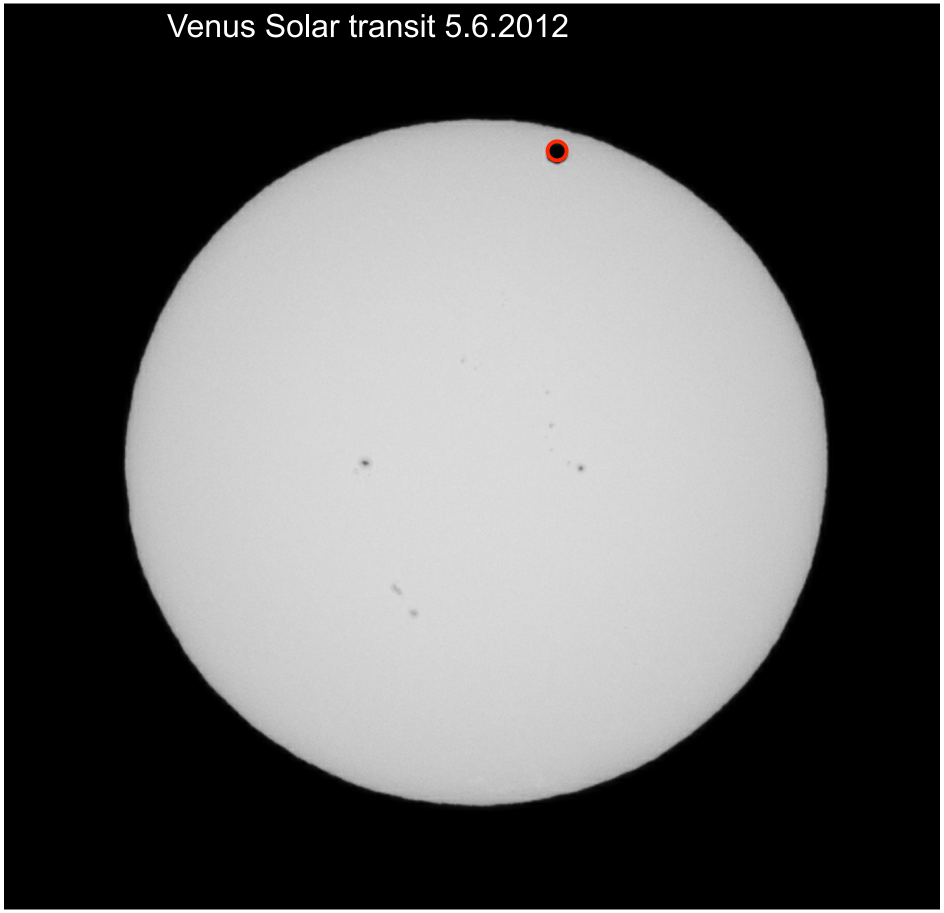
What are the optimum JWST targets?

- Ideally we need planets transiting / eclipsing IR bright but small stars
  - Star SNR ~ sqrt(signal) and transit depth ~ $(R_{pl} / R_*)^2$

    Photon-limited SNR about 2.5x better than HST (just sqrt area)
  - If stable, M stars are ideal hosts for transmission & emission
  - Most Kepler planets are too distant for spectroscopy
- Large radius planets with large atmospheric scale heights kT/(µg) will have high SNR transmission spectra
  - Nearby gas giants, ice giants, mini-Neptunes will be good
  - Also good emission spectra SNR for hot Jupiters
- Can characterize nearby mini-Neptunes found by TESS
- JWST cannot do it all: not enough time to do all transiting planets; not optimized for high precision so co-adding many weak spectra may not be productive

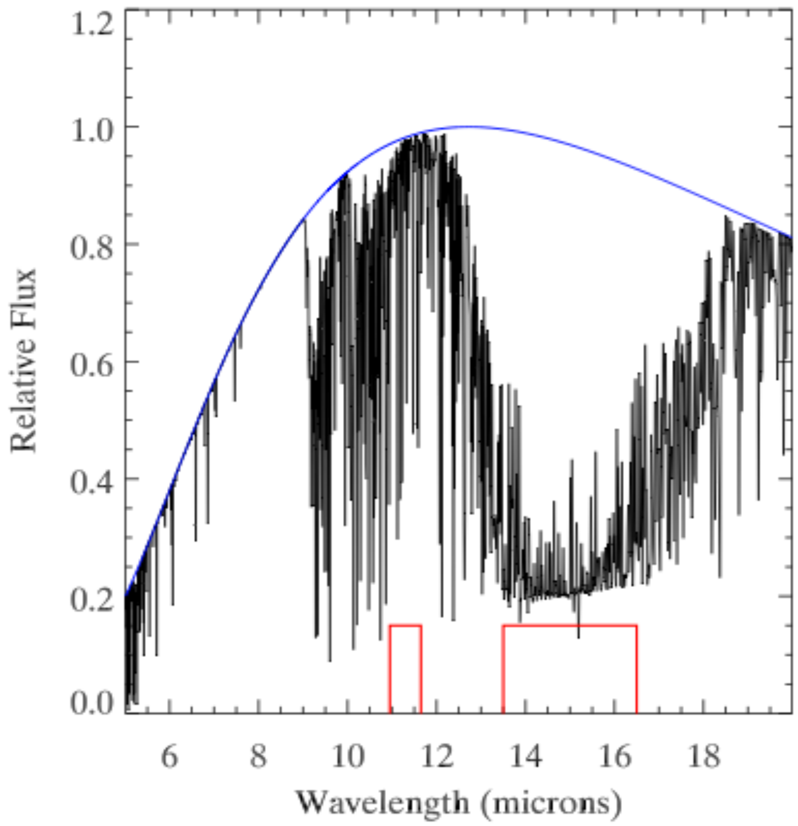
Earth transit facts of life

- Earth disk area is ~ 1E-4 of a G2V star or 1E-3 of M3V (GJ 581)
- Absorbing area of Earth atmosphere is $A \sim 2\pi R_e 5H$, $H = kT_e/\mu g \sim 8$ km, so $A \alpha T_e/\mu\rho$ and $A/Ae \sim 0.01$
- Therefore a completely absorbing spectral line would have a signal (Area) of ~1E-5 relative to M3V star
- Detecting a 100% absorption at SNR=3 requires precision of 3 ppm
- Would require co-addition of ~100 transits to get 1E11 photons per spectral element, but systematic noise must be > 20x lower than HST
- Super-Earths? Remember $A \alpha T_e/\mu\rho$ Area is independent of radius R
- ***Direct imaging is best for Earths!***



The disk of Venus against the Sun is about the size of Earth transiting an M3-5 dwarf. The red annulus is much larger than the absorbing limb of the Earth atmosphere. Notice the star spots. Photo by H. Chapman.

MIRI detection of CO_2 in Super-Earth emission?



Deming et al. (2009) showing Miller-Ricci (2009) Super-Earth Emission spectrum and MIRI filters

- JWST MIRI filters (red boxes, left) may detect deep CO2 absorption in Super-Earth emission observations if hosts ar enearby M dwarfs.
- Modeling shows that modest S/N detections possible on super-Earth planets around M stars IF data co-add well (Deming et al. 2009).

- Could detect CO2 feature in ~50 hr for ~300-400K 2 R_e planet around M5 star at 10 pc: IF the data SNR improves with co-additions

Some Conclusions

- Expect exquisite JWST spectra of gas and ice giants
  - Determine abundances, temperature profiles, and energy transport in hot Jupiters with little degeneracy using transit & eclipse spectra and phase observations.
  - Good SNR transmission spectra in SINGLE TRANSITS for hot Jupiters over 0.7 – 12+ microns
- Expect photon-limited SNR ~ 2.5x better than HST WF3 G141 with a similar systematic noise floor
  - But much better science than HST: more planets, larger wavelength range
- Possibly detect CO_2 absorption in Super-Earths, but Earth-like planets are otherwise too difficult
- There is plenty of exoplanet spectroscopy to do:
  - JWST will provide good SNR spectra of a few dozen gas giant, ice giant , and nearby mini-Neptune planetary atmospheres over its 5 year mission
  - Statistical survey of giant planet atmospheres with a dedicated mission. Wavelength coverage & low systematic noise are as important as aperture