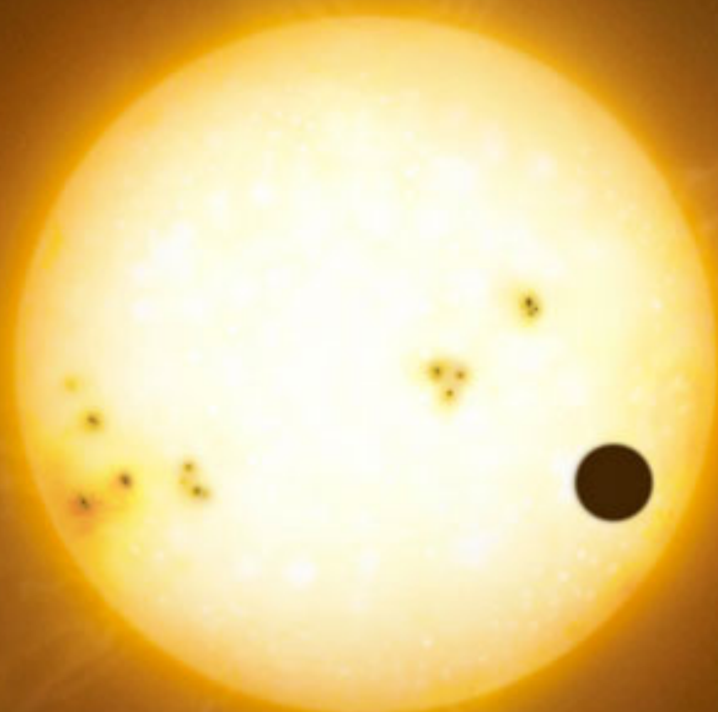
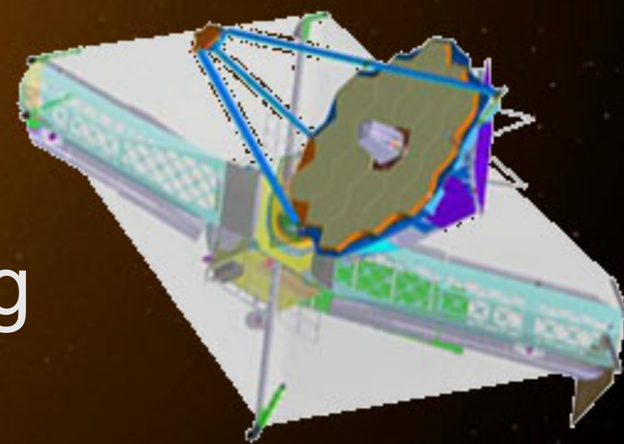
Exoplanet transit, eclipse, and phase curve observations with JWST MIRI



T Greene & MIRI Team

JWST NIRCam transit meeting

March 12, 2014



Scope of Talk

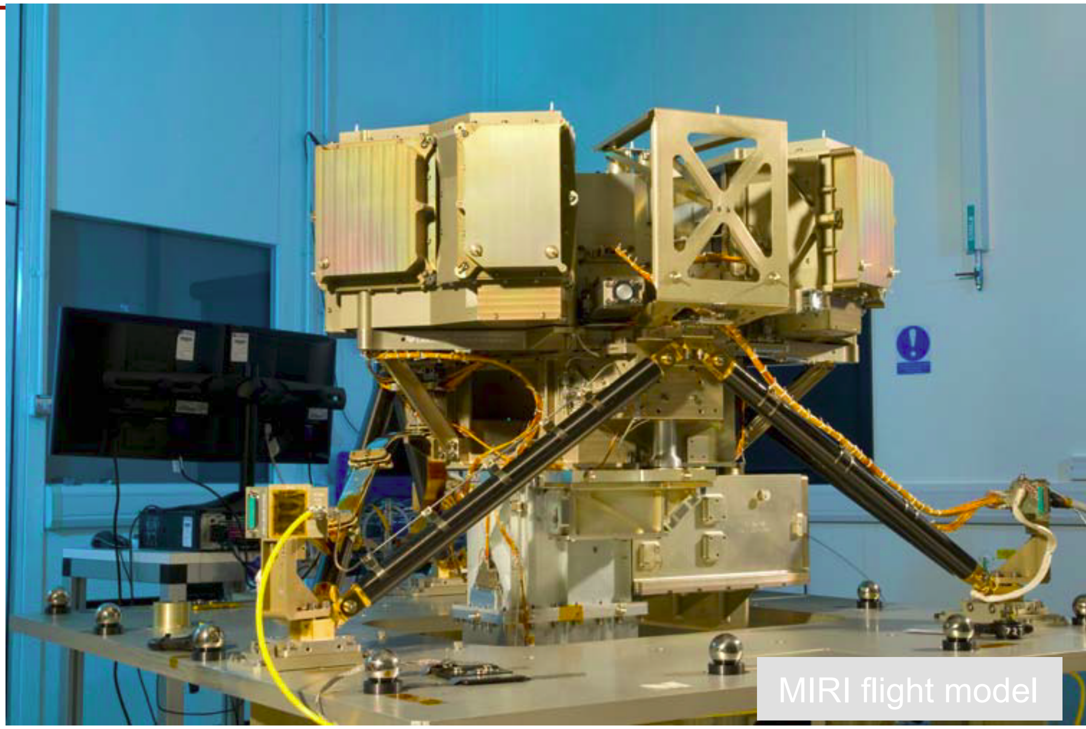
- MIRI overview
- Suggested transit modes
- Bright star limits / subarrays
- Target acquisition & pointing
- Expected performance
- Simulated spectra and potential JWST science
- Operational limitations
- Observing Examples

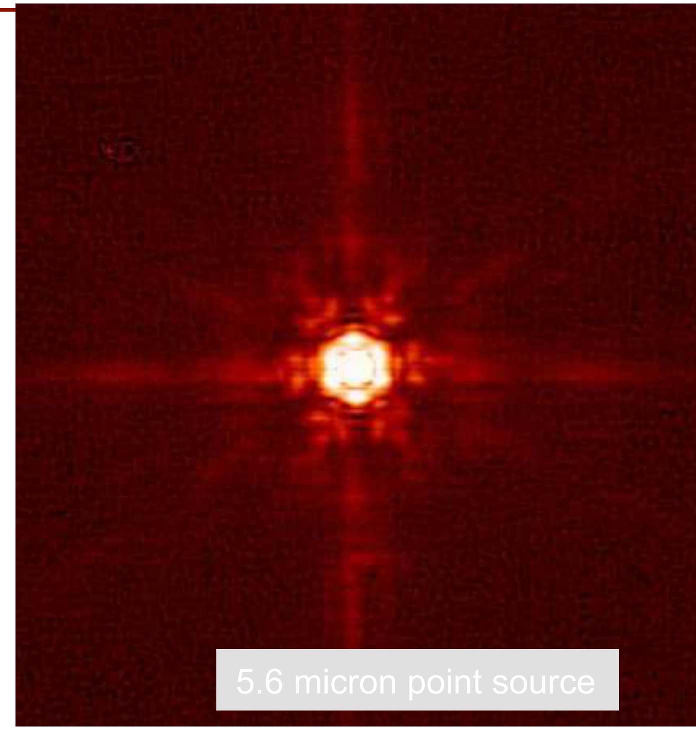
The MIRI instrument will characterize circumstellar debris disks, extra-solar planets, and the evolutionary state of high redshift galaxies

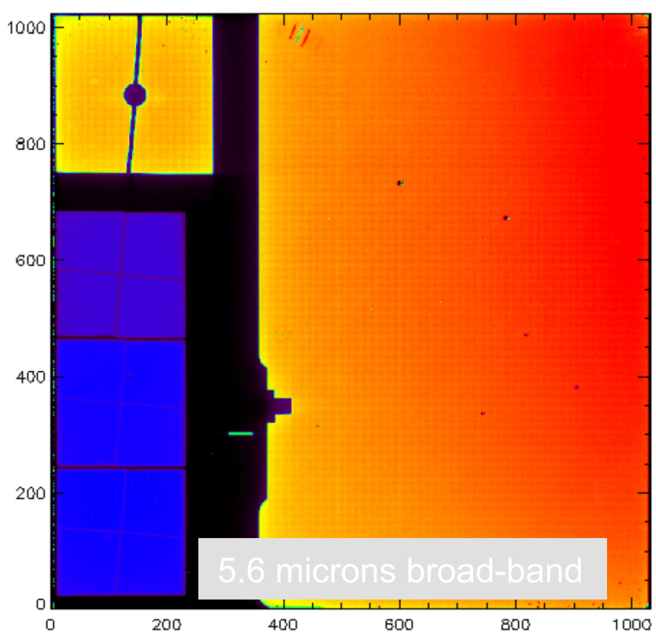
Developed by a consortium of 10 European countries and NASA/JPL

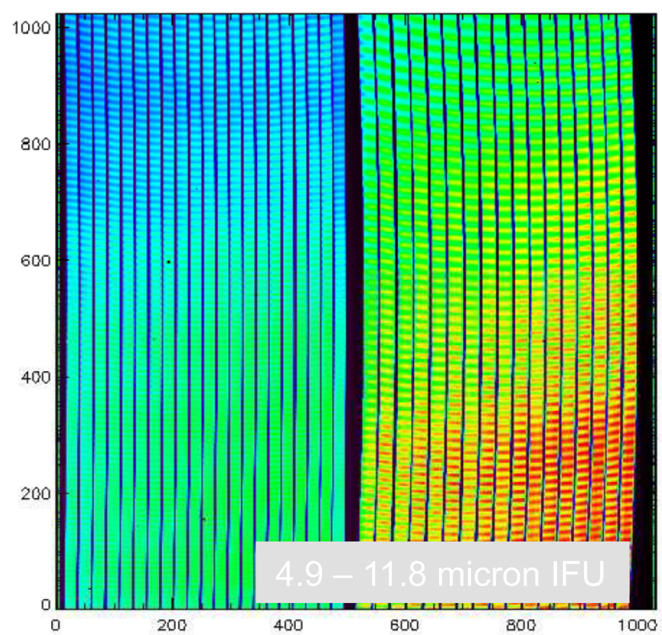
- Operating wavelength: 5 - 28 microns
- Spectral resolving power: R = 5, 70, 2000
- Broad-band imagery: 1.9 x 1.4 arc minutes FOV
- Coronagraphic imagery
- Spectroscopy:
  - R ~ 70 long slit spectroscopy 5 x 0.5 arc sec (LRS prism)
  - R ~ 2000+ spectroscopy: 3.5 x 3.5 and 7 x 7 arc sec FOV integral field units
- Detector type: Si:As, 1024 x 1024 pixel format, 3 detectors, 7 K cryo-cooler
- Reflective optics, Aluminum structure and optics

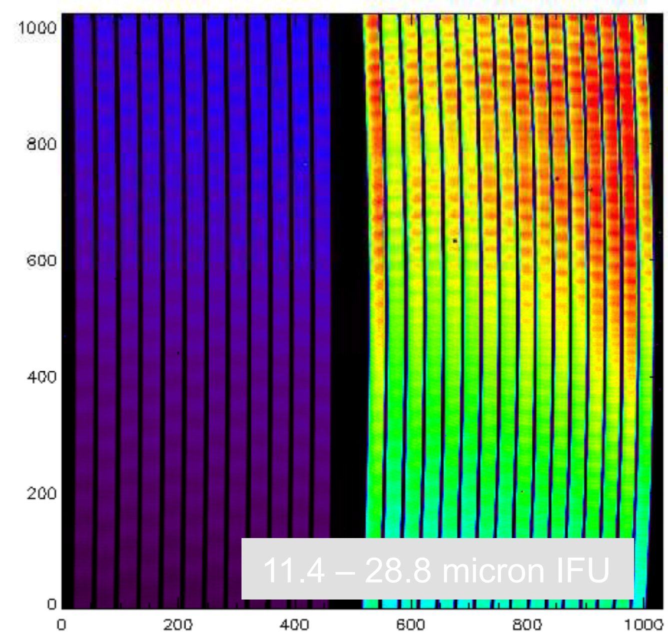
MIRI was delivered to ISIM I&T during May 2012



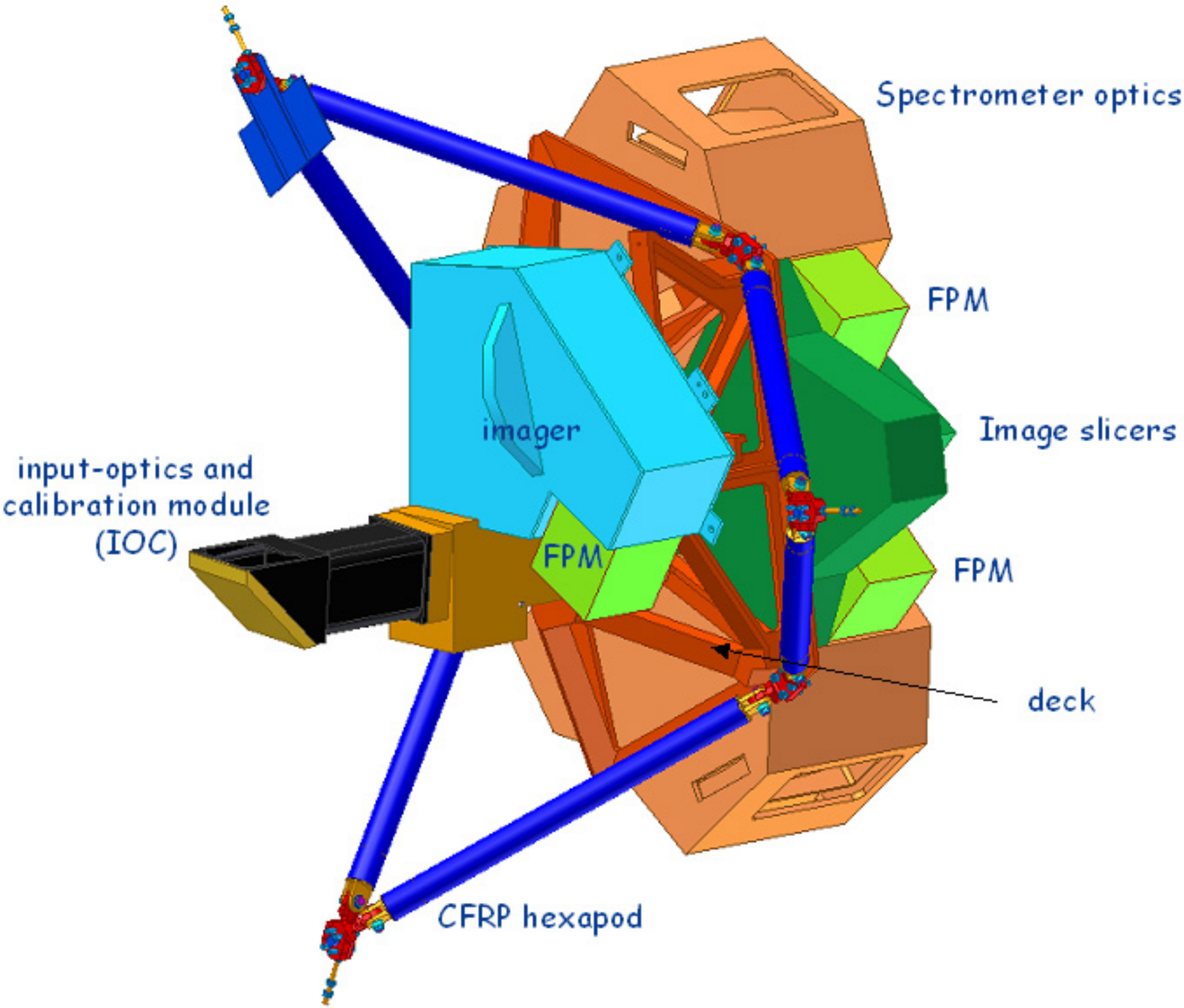








MIRI

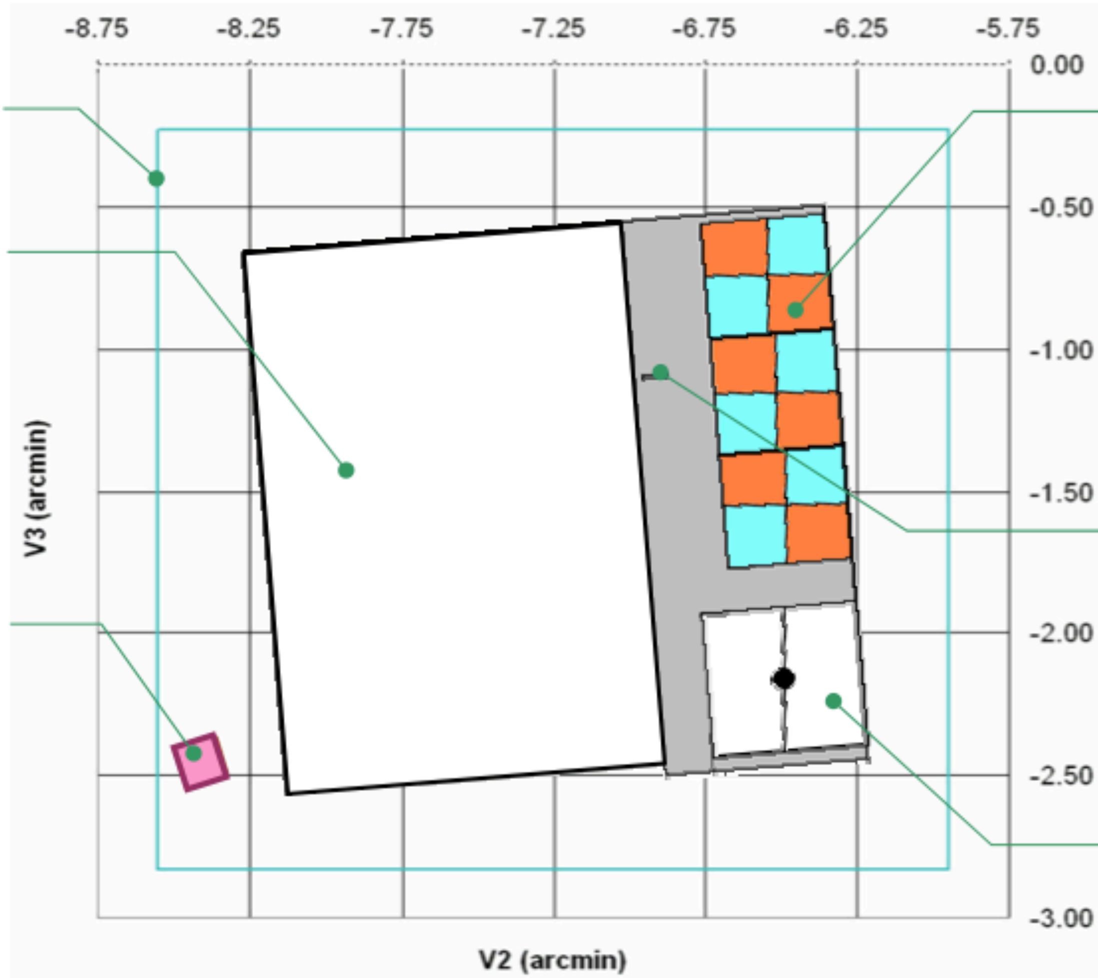

Spectrometer optics
FPM
Image slicers
imager
input-optics and
calibration module
(IOC)
FPM
FPM
deck
CFRP hexapod

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 ($R = \lambda/\Delta\lambda$) Rqmt	Spectral Resolving Power ($R = \lambda/\Delta\lambda$) Capability	Pixels per resolution element: Spectral (Rqmt >2)	Pixels per resolution element: Spatial
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

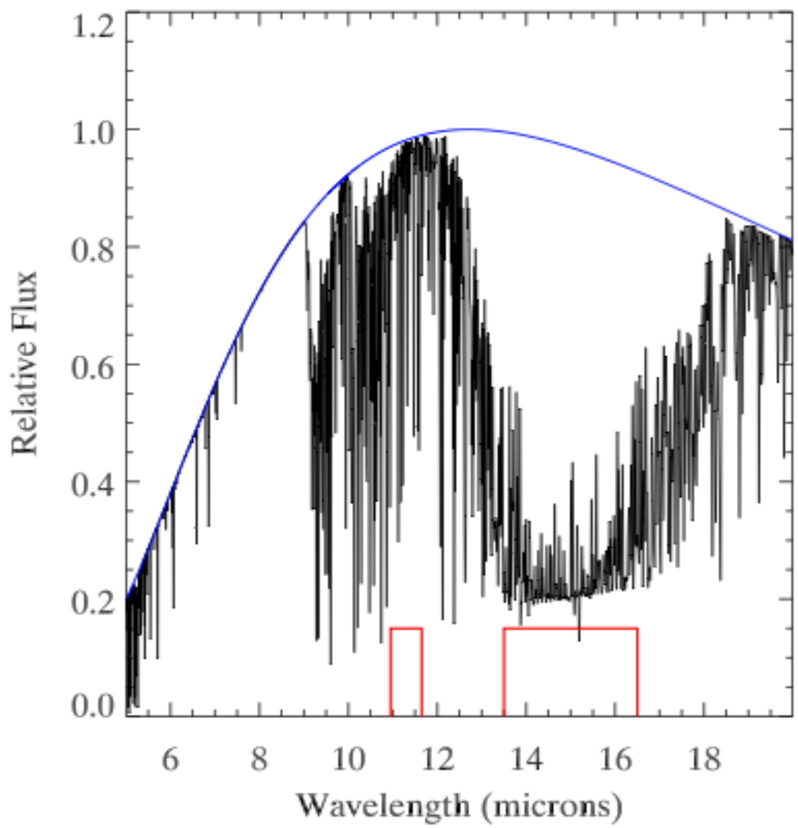
Waivers approved by MIRI Science Team (MIRI-RW-00009-ATC) "..the spectrometer is capable of doing the expected science programs with no significant compromise.."

Example MIRI transit modes

Application	Mode	Filter	Comment
Transmission spectra R~100 of bright big planets (H_2O, CH_4 to complement nIR)	LRS	prism	HD 189733, HD 209458, WASP-12
Emission spectra R~100 of cool-warm planets	LRS	prism	HD 189733, HD 209458, WASP-12
Phase curve of cool ~500K planets	Imager	F770W	GJ 436, HD80606
Emission of warm planets, down to 2Re @ 400K	Imager	F1500W F1130W	Continuum, On-Off filters for CO_2
Silicate emission of fainter planets: MRS has much lower background than LRS	MRS	Band2 B+C	10.0 – 11.8 um

- MIRI Imager & LRS are Nyquist sampled at ~7 microns wavelength
- How large should LRS extraction box be spatially?
- MRS has ~200 mas spaxels. How many to extract? Precision Issues with source drift / jitter: light lost between spaxels?

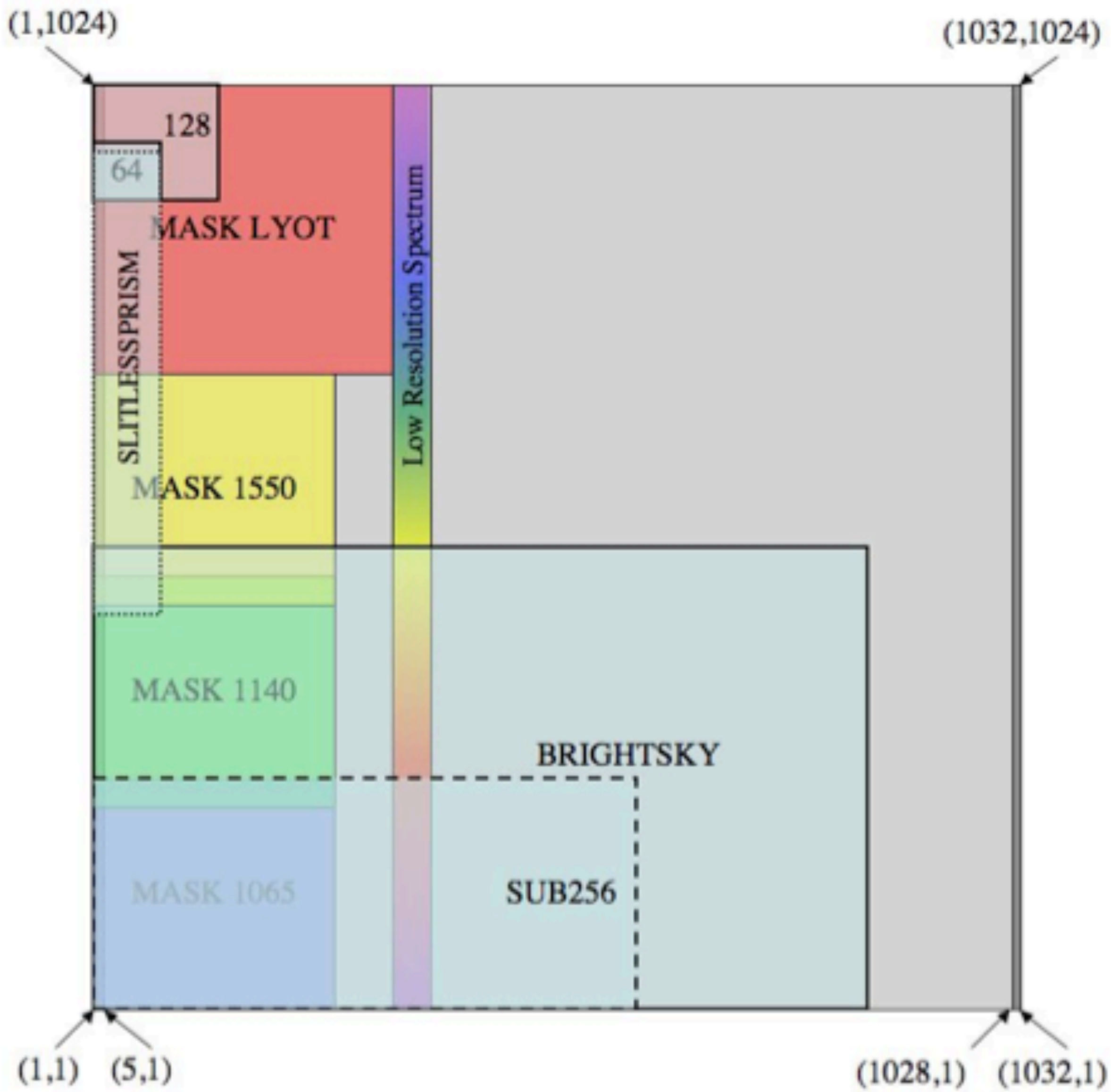
MIRI detection of CO_2 in Super-Earth emission?



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

MIRI Imager / LRS Subarrays

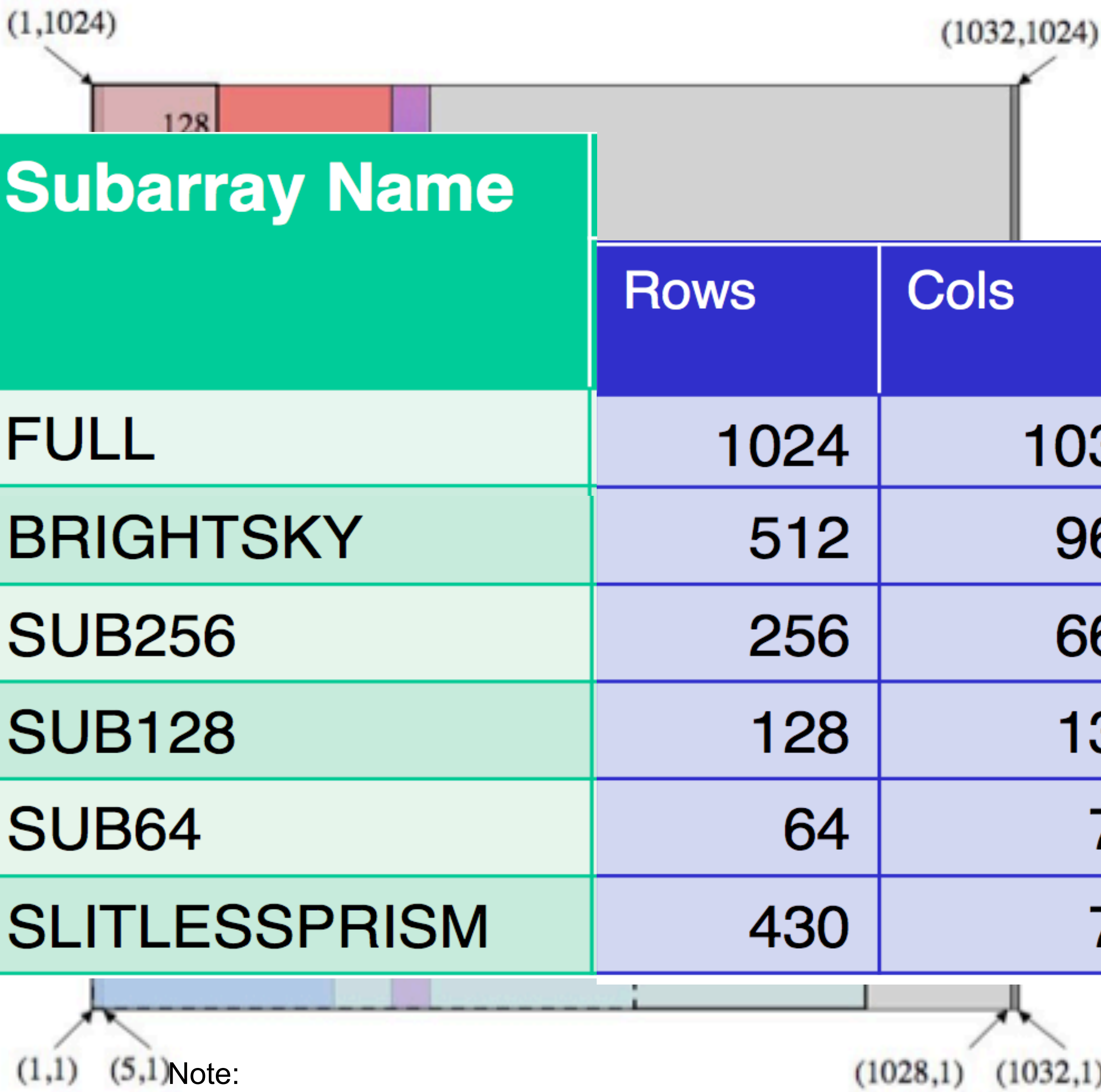


Must step through detector columns to address a subarray, so all are placed on left side (starting at column 1)

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

MIRI Imager / LRS Subarrays

Coronagraph subarrays not listed



Subarray Name	Rows	Cols	Row Start	t_{Frame} [sec]
FULL	1024	1032	1	2.775
BRIGHTSKY	512	968	37	1.316
SUB256	256	668	37	0.492
SUB128	128	136	889	0.101
SUB64	64	72	779	0.066
SLITLESSPRISM	430	72	521	0.150

Note:
1. These are the “new” recently modified subarrays (2014)
2. Fastest readouts will have ‘reasonably high’ efficiencies due to resetting row pairs
3. Subarray frame times to be ~10% slower with new focal plane electronics

Current MIRI bright limits

		Brightest Observable with subarray	Brightest Observable with subarray
Mode	Disperser/Filter	G0 (K mag)	M5 (K mag)
Imaging	F770W	5.86	6.28
Imaging	F1130W	3.31	3.75
Imaging	F1500W	3.43	3.86
Spectrograph	Band2C	3.74	4.09
LRS	PRISM	4.41	4.83

- All mags are for 2 frame integrations to 80% full well

  New focal plane electronics will slow readouts by ~10% (0.1 mag fainter limits)

- Imaging mode uses 64 x 72 subarray
- LRS uses SLITLESSPRISM 430 x 72 subarray
- MRS Band 2C is full frame

Acquisition

- 7 mas JWST pointing allows acquisition to a fraction of a pixel (1 pixel = 110 mas imager/LRS; >180 mas MRS)
- Based on Spitzer, will choose source location sweet spots for imaging and spectroscopy
- Imaging Acquisition:

  - Acquire with neutral density filter or science subarray / filter combo

- LRS Spectroscopic Acquisition

  - Acquire bright star in 64 x 64 subarray

  - Configure prism, then offset to SLITLESSPRISM subarray

- MRS Spectroscopic Acquisition

  - Acquire star in Imager near MRS (ND filter if needed)

  - Offset to MRS, configure DGWs (A / B / C)

Pointing Knowledge during Observations

- Imaging:

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

- Spectroscopy:

  - Take image before and after MRS exposure

  - No plans to use imager during MRS observations, but theoretically possible

  - Can use guider centroid data to reconstruct pointing

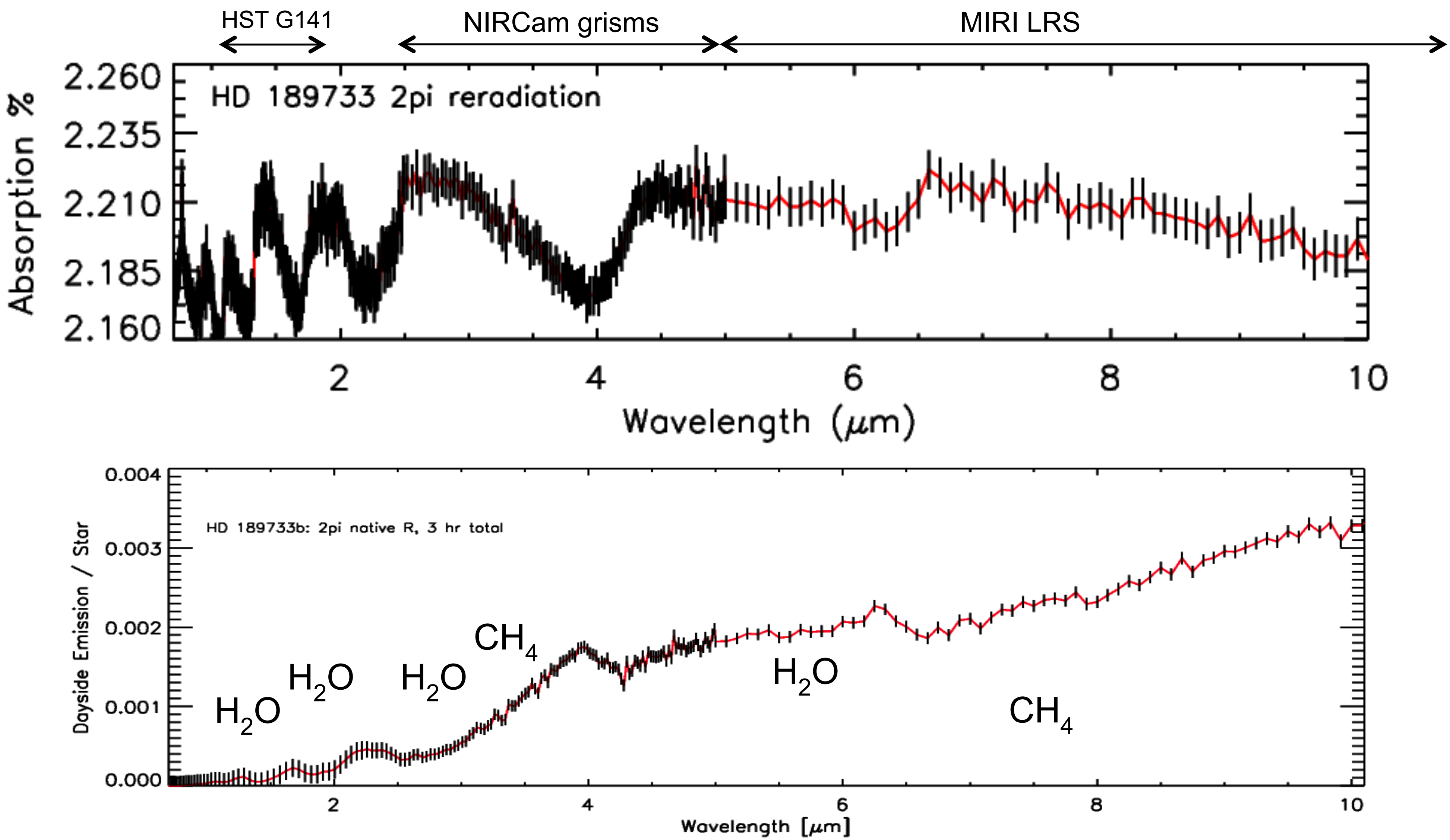
Systematic Noise Limits

- Expect a systematic noise floor to emerge when photon SNR is high: jitter/ slice losses, PSF changes, detector drifts
- MIRI detectors are similar to Spitzer IRAC 5.8 & 8.0 μm ; expect similar noise floor (expect <100ppm, in progress)
  - Imager: Nyquist sampling at 7 microns wavelength
  - MRS is spatially undersampled. Issue or not?
  - Photometric stability testing of imager has yielded ~100 ppm precision when expert reduction techniques applied.
- Working on implementing noise reduction techniques in MIRI data pipeline to achieve Spitzer-type performance

JWST Spectral Simulations

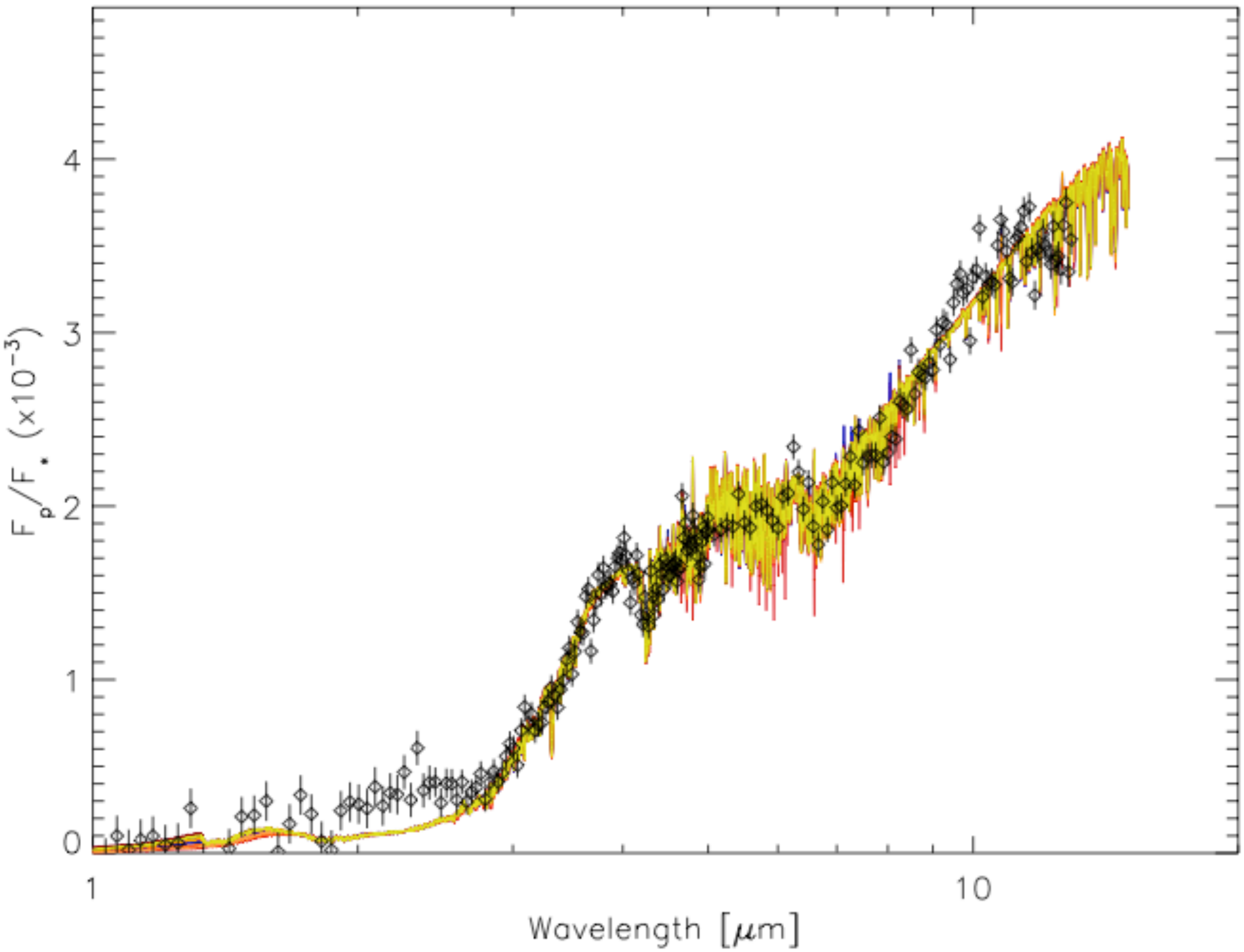
- Transmission and emission models from J. Fortney group
- Semi-realistic model of telescope and instrument wavelength-dependent resolution and throughput
  - Includes reflections, grating functions, filter values or guesses
- Photon noise and systematic noise floor added in quadrature
  - Detector noise 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
- Need to incorporate background noise in extracted LRS spectra: important for K > ~7.5 mag stars

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)

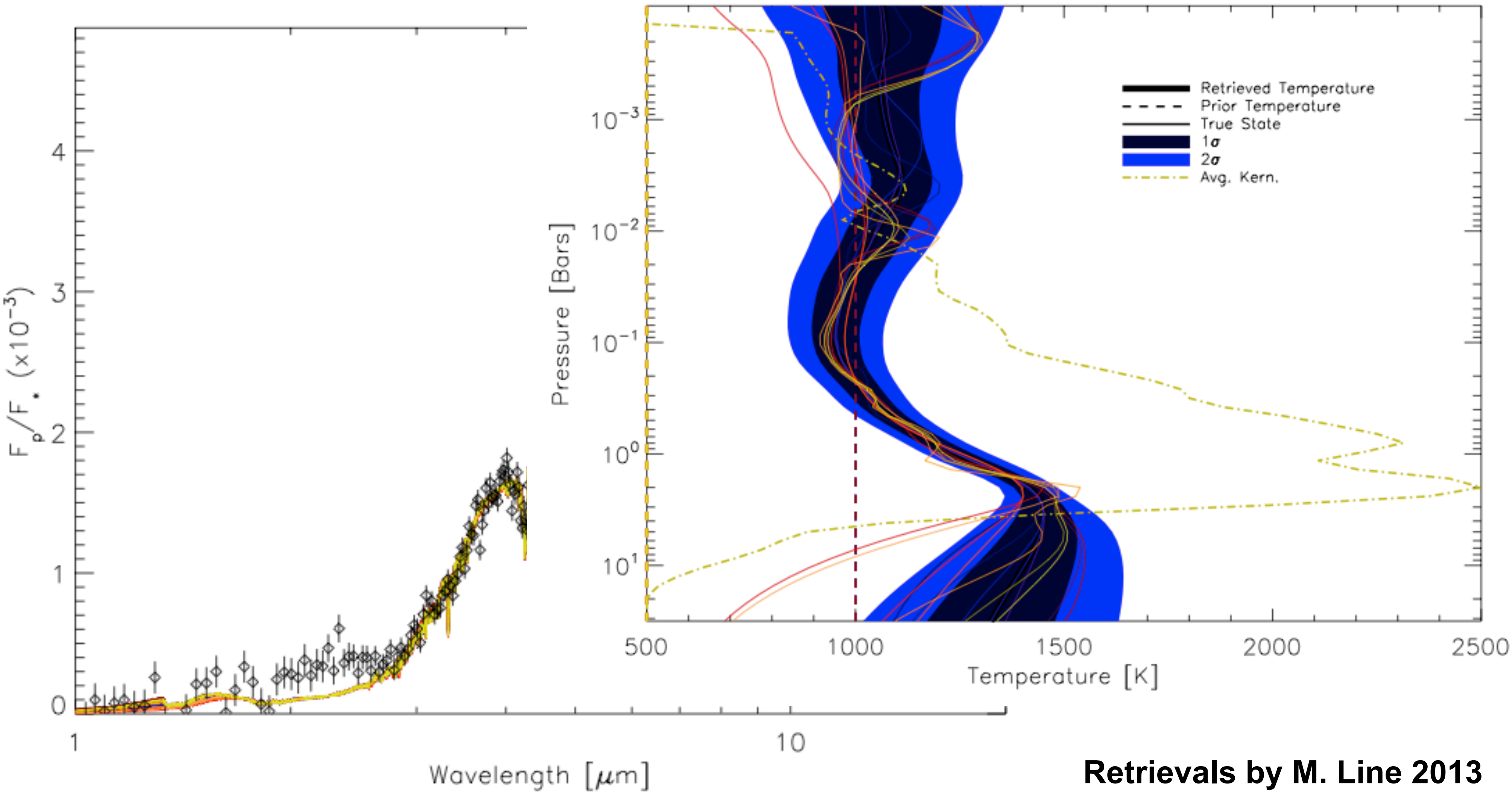
Retrieval from HD 189733b emission simulation



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

Retrieval from HD 189733b emission simulation



Retrievals by M. Line 2013

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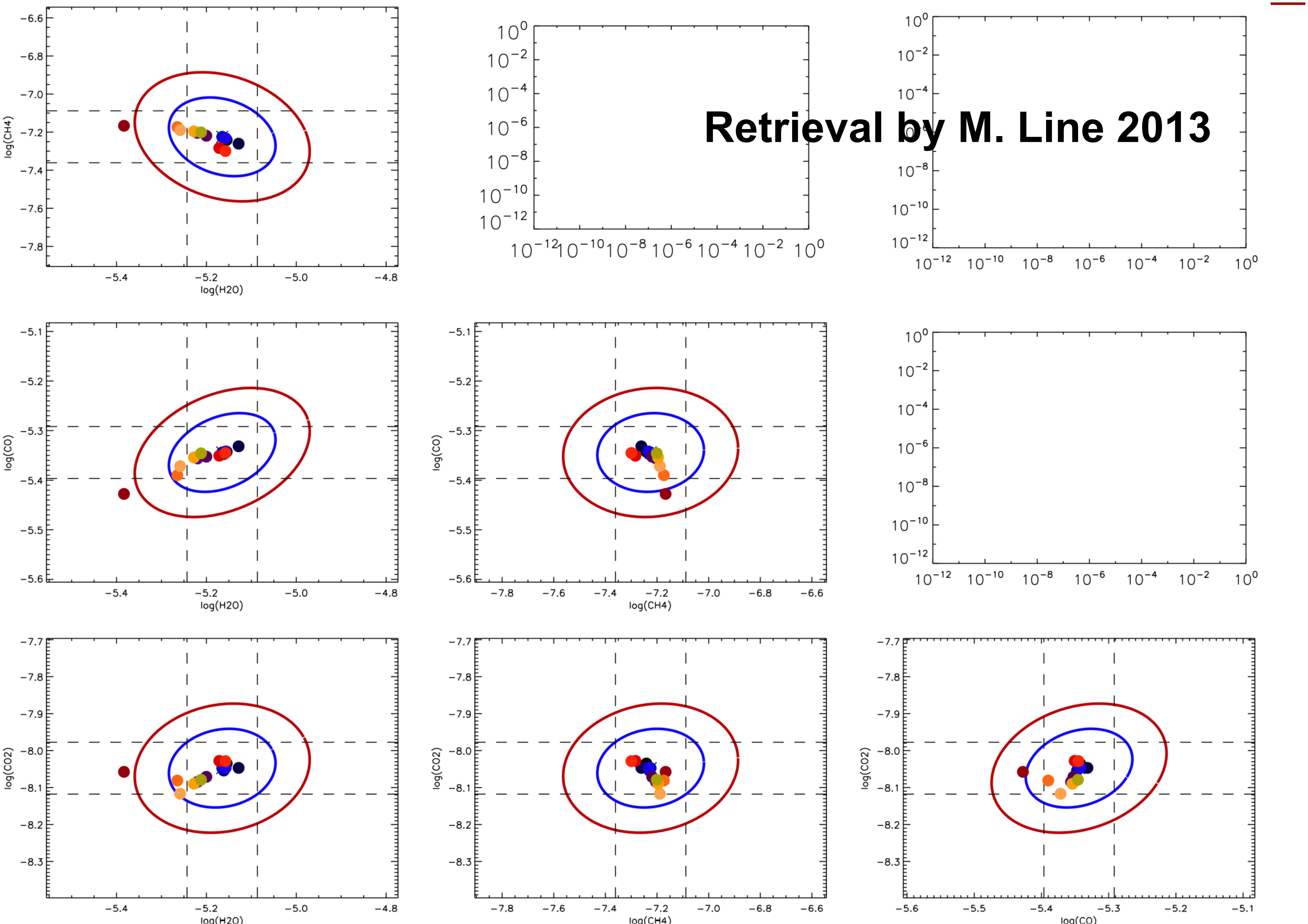
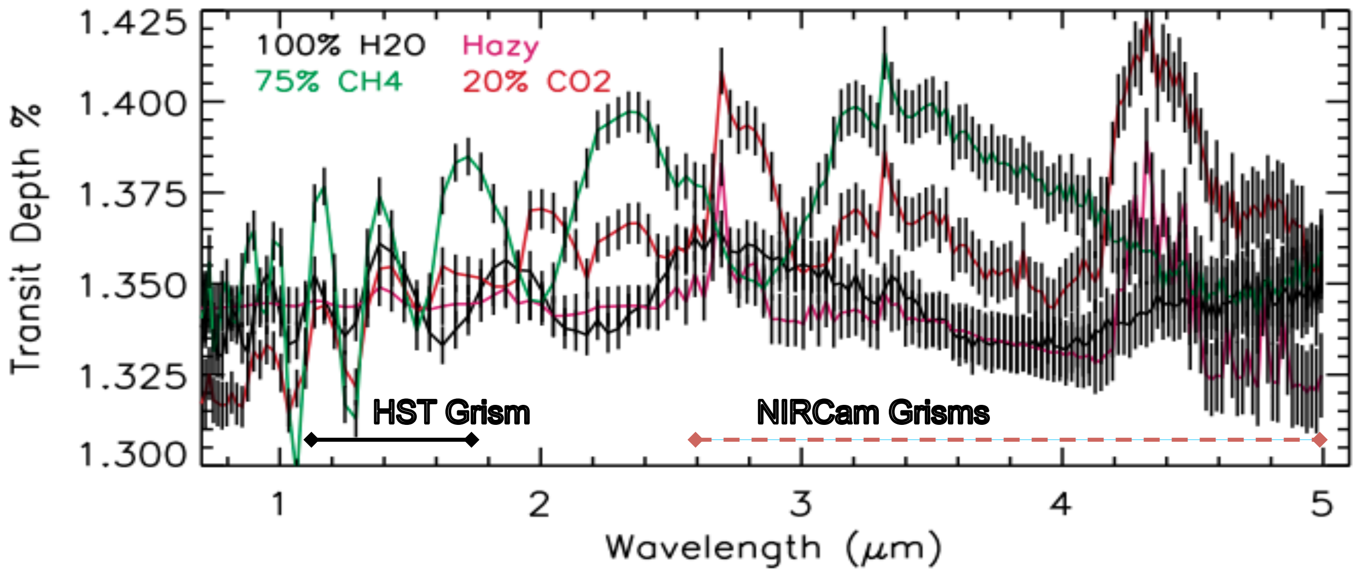
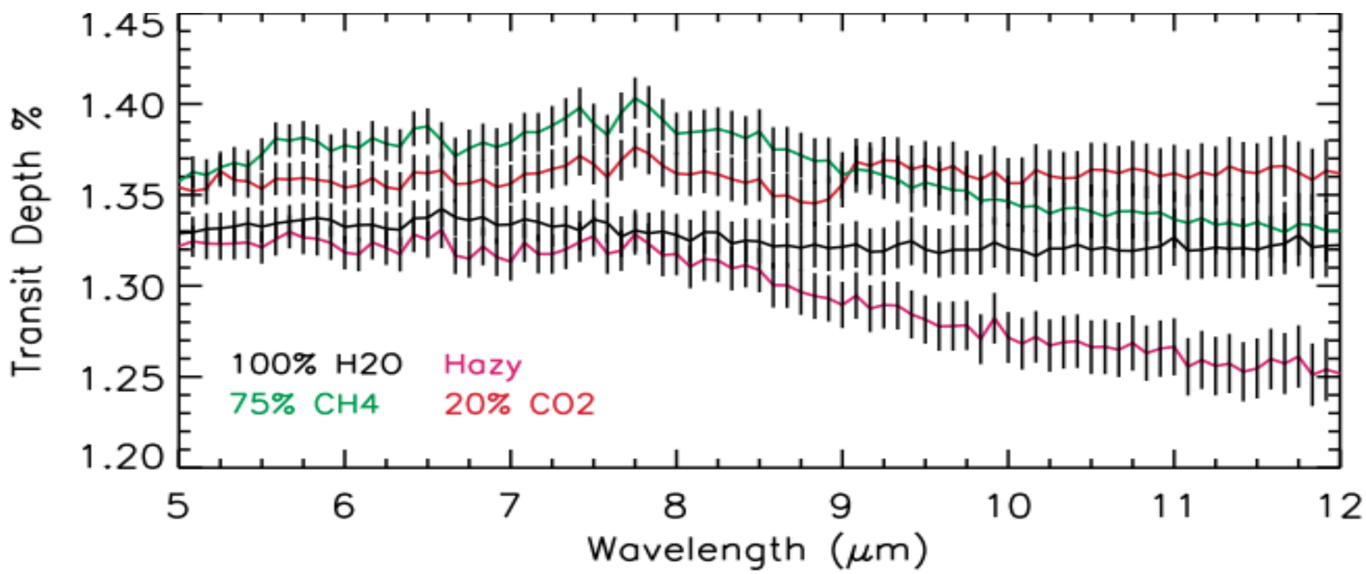
HD 189733b composition



GJ 1214b transmission spectra simulations (with noise floor)



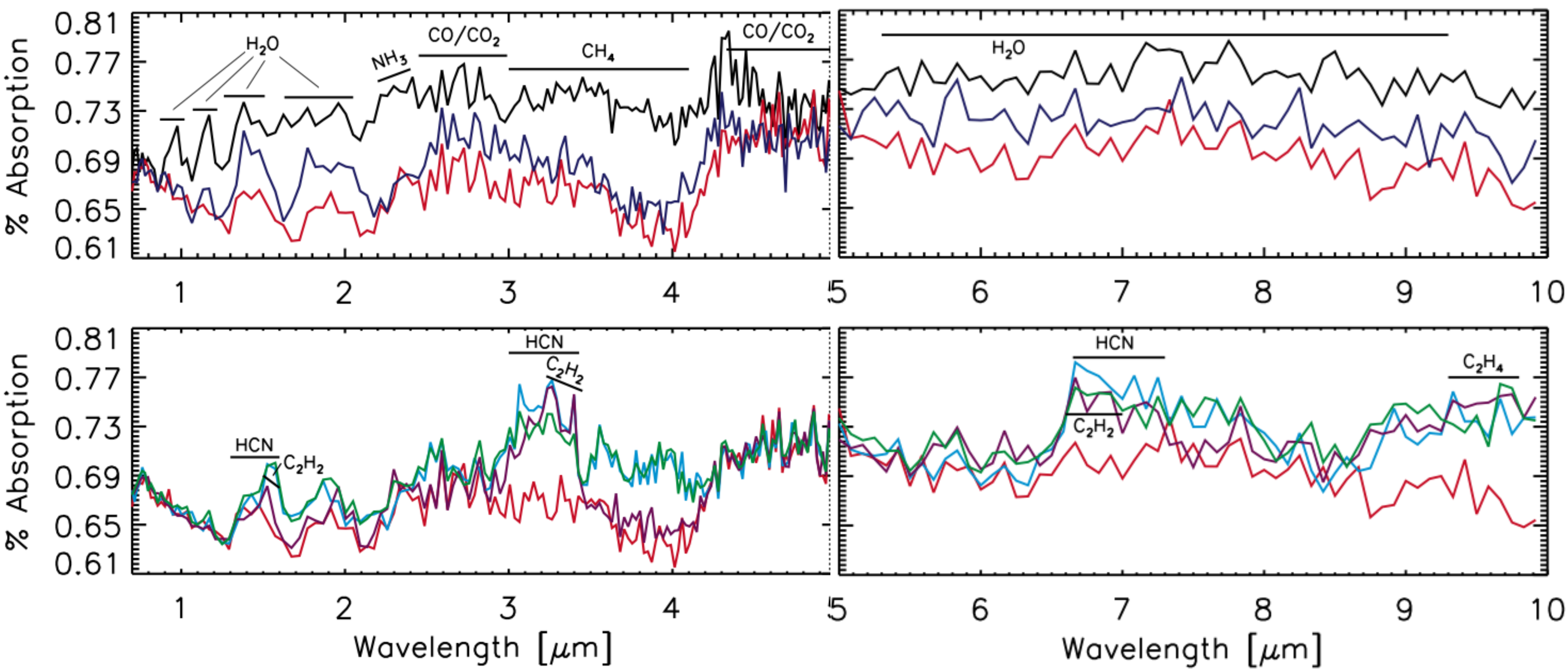
NIRSpec prism simulation also covers NIRISS and NIRCam. NIRCam grism range (red line) is very useful for identifying components



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)*.

- **Need about 100 ppm 1 sigma to discriminate usefully.**

MIRI Observing Limitations

- Pointing jitter (7 mas 1 sigma requirement) limits spectrophotometric precision of a single observation / visit
  - MRS may be biggest issue: light lost between slices?
  - Detector drifts likely to be bigger issue: good intrapixel response and filters and LRS > 10 microns are very well sampled
- MIRI exposure limit 2^16-1 integrations:
  - 2.4 hour limit with 64x64 subarray 2 frame integrations
    - Comparable to JWST exposure limit (2.8 hr)
  - 5.5 hr limit with SLITLESSPRISM subarray 2 frame integrations

  - MIRI operational constraint of 1000 frames per integration (related to background & cosmic rays) is not an issue for transits

Sample MIRI Observations

MIRI

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	Imager	F770W: 6.6 - 8.8	3.5	2 min of 0.132 s	SNR = 17 on full disk	1	~9	9	Enough SNR? How to combine eclipses? 50 ppm noise floor. WASP-12 is a bit higher SNR
HD189733*	Emission Spectrum	LRS	LRS: 5 - 14	100	0.3 s (2 frames)	26 on planet	2	37	12	50 ppm noise floor
KOI-02311.01	Confirmation, precision light curve									
HD80606	Periastron light curve									
TESS-001*	Super Earth Spectrum									
Teegarden's Star	Super Earth Phase Curve	Imager	F1500W: 13.5-16.5	5	5.26s (80 frames)	SNR = 1.2 in 1 hr; 50 ppm		3 in 6 hr if root N noise	288	SNR = 11 over 140hr with 50 ppm floor per 1 hr exp. Higher SNR than F770W
Gliese 1214*	Super Earth Albedo Spectrum								a lot	
GJ 436	Hot Neptune 2D Dayside Map	Imager	F770W: 6.6 - 8.8	3.5	1.5d of 0.132 s	SNR = 3.3in 1hr with 50ppm limit	0.6 Period	~30/1 hr	38	SNR = 3.3/1 hr with 50 ppm noise SNR=6.6/1 hr with 25 ppm noise
Kepler-7	Hot Jupiter Silicate Cloud Phase curve	MRS/Ch2	7-12 micron	15	~1000s ints	SNR = 5 on planet / 1 hr	1 phase curve for Band2C; 3 for 7.4-11.8 um	0.5 - 1.5 PC (2.5 - 7.5d)	120 - 360 hr	50 ppm noise floor not an issue: photon + dark SNR= 6300 in 1 hr