Transit Spectroscopy with NIRISS

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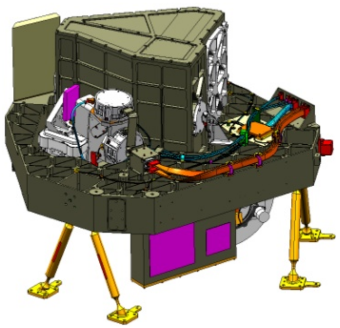
FGS/NIRISS PI



Collaborators

- David Lafrenière, UdeM (NIRISS exoplanet team lead)
- Loic Abert, UdeM
- Etienne Artigau, UdeM
- Mike Meyer, ETH, Switzerland
- Ray Jayawardhana, Toronto
- ….

Outline

- NIRISS overview
- Transit spectroscopy capability
- Simulations
- Performance limitations

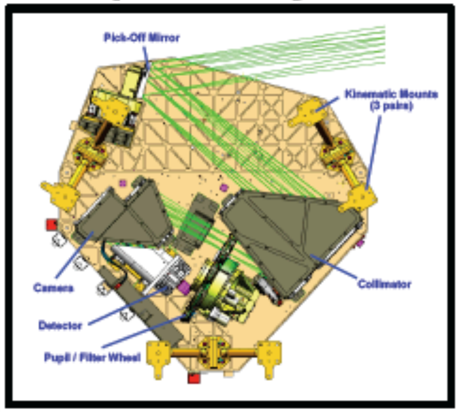
FGS/NIRISS overview

- Two instruments in one box provided by CSA
- FGS (Fine Guidance Sensor)
  - Provides fine guiding to the observatory
  - 0.6-5 μm IR camera. No filters, single optical train with two redundant detectors each with a FOV of 2.3’x2.3’
    - Noise equivalent angle (one axis): 3.5 milliarcsec
    - 95% sky coverage down to J_{AB}=19.5
- NIRISS (Near-Infrared Imager and Slitless Spectrograph)
  - 0.7-5 μm IR camera.
  - Four observing modes
  - Main science drivers
    - First Light: high-z galaxies
    - Exoplanet detection and characterization


CAUTION
ATTENTION
TRIP HAZARD
RISQUE DE TREBUCHER
COM DEV
COM DEV

The Near-Infrared Imager and Slitless Spectrograph (NIRISS)

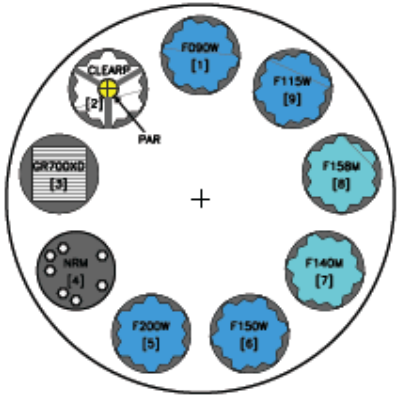
Optical Layout



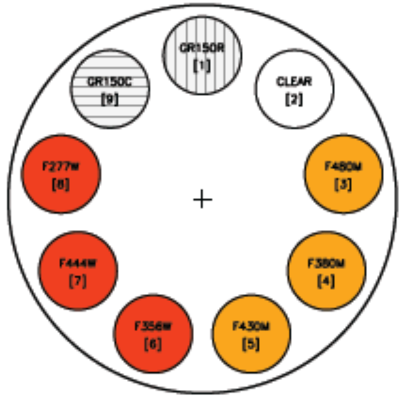
At a glance:

Detector	Teledyne HAWAII-2RG HgCdTe with 5.2µm cutoff 2048 × 2048 pixels
Field of View	2.2′ × 2.2′
Plate scale	0.065 arcsec / pixel
Pupil Wheel	"Blue" filters Grism GR700XD Aperture Mask NRM
Filter Wheel	"Red" filters Grisms GR150C,R

Pupil Wheel



Filter Wheel



Observing Modes

Imaging

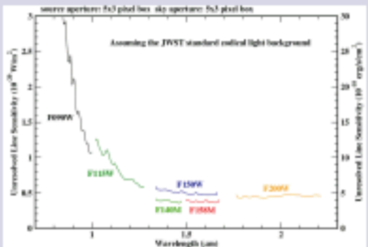
Point-Source Sensitivity:
S/N=10 in 10 ks

Filter	nJy	m(Vega)
F090W	11.28	28.28
F115W	11.22	28.06
F150W	9.19	27.83
F200W	7.81	27.54
F277W	6.63	27.09
F356W	6.89	26.56
F444W	12.29	25.49

"R" Wide-Field Slitless Spectroscopy "C"

GR150{R,C} grisms + "Blue" Filters
Resolving Power (1st order): ~150
Spectral coverage (1st order): 0.8 – 2.2 µm
{Row, Column} orientations provide orthogonal dispersion directions on the detector to mitigate blending. Blocking filters isolate wavelengths of interest.

Fiducial sensitivity (unresolved line):
5 ×10^{-18} erg/s/cm² with S/N=10 in 10 ks



Single-Object Slitless Spectroscopy

GR700XD grism + CLEAR
Three cross-dispersed orders
Spectral coverage 0.6 – 2.5 µm
Resolving Power (1st order): 300 – 800
The orders are broadened in the cross-dispersion direction by 30 – 40 pixels.

Subarray readout formats through 1 or 4 pre-amps optimize SOSS for **exoplanet transit spectroscopy.** No slit losses; target acquisition provides repeatability.

Estimated J-band bright limits (G2 V star):

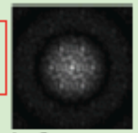
Subarray	1 pre-amp	4 pre-amps
2048 × 256	8.2	6.7
2048 × 80	6.9	5.5

Aperture Masking Interferometry

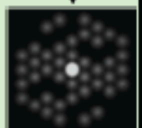
NRM + Medium "Red" Filters
7-hole aperture mask with 21 baselines; all have different ("non-redundant") lengths.

Mask

Michelson:
$\delta\theta = 0.5\ \lambda / D$



Interferogram



Fourier Transform

AMI with NIRISS enables the detection of exoplanets at 3.8, 4.3, and 4.8 µm around stars as bright as **M' ~ 5** with:
Contrast: ~2×10^{-5} (S/N~5)
Separations: 70 – 400 mas

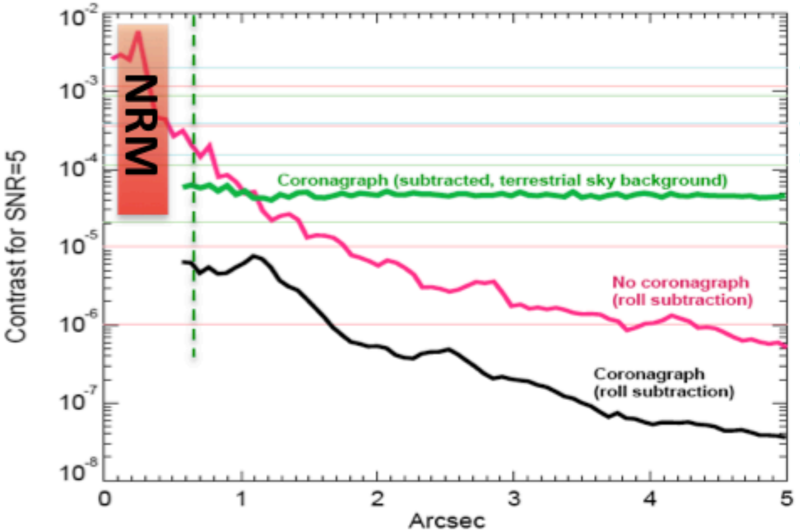
Aperture synthesis imaging (of. e.g., AGN) is also enabled.

The NIRISS includes an Aperture Masking Interferometry (AMI) mode that enables moderate contrast imagery at an inner working angle of λ/2D

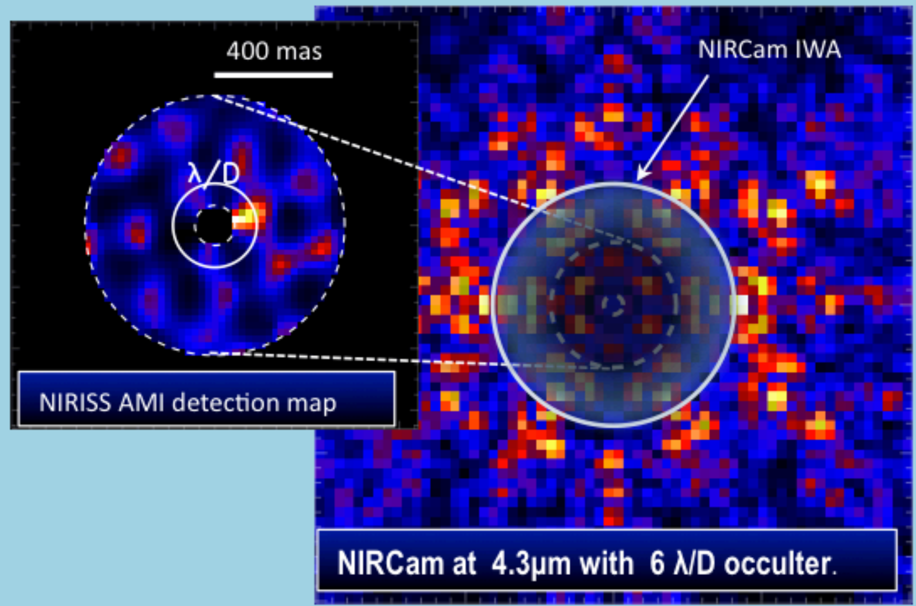
Available in 3 broad-band filters: 3.8, 4.3, 4.8 um over which NIRISS is Nyquist sampled

Yields 10-12 magnitudes of point source contrast over a 70-500 mas annulus

NIRCam coronagraphy limited to an inner working angle of approximately 600 mas



NIRISS & NIRCam IWA and contrast



Simulated companion above has contrast of 10 mag at a separation of 130 mas

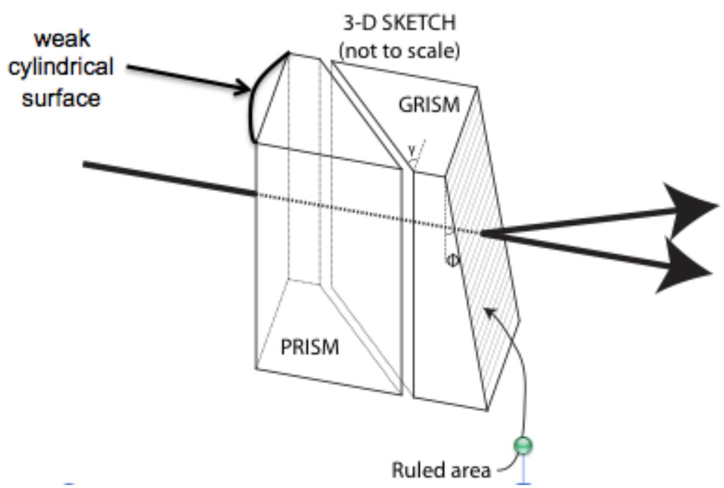
Equivalent to a 1-2 M_{Jup} planet at ~1 AU of a 50 Myr-old M0V dwarf at a distance of 10 pc from the Sun.

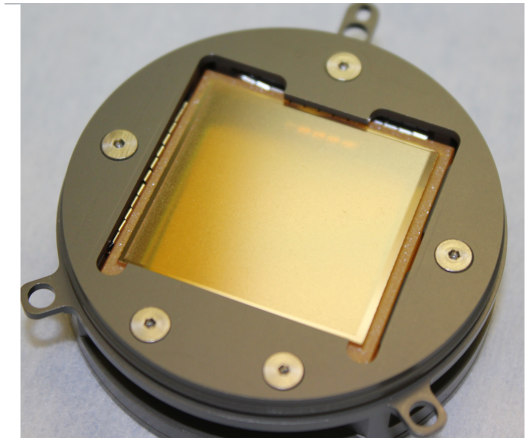
Above simulation corresponds to approximately 3 hours of observing time

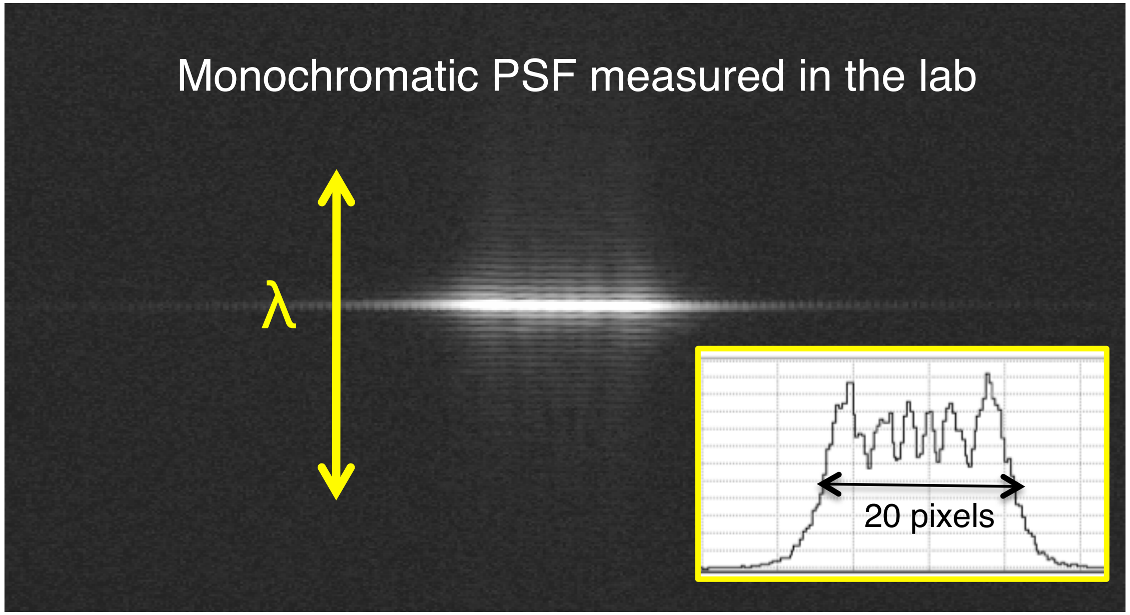
NIRISS SOSS (Single-Object Slitless Spectroscopy) mode

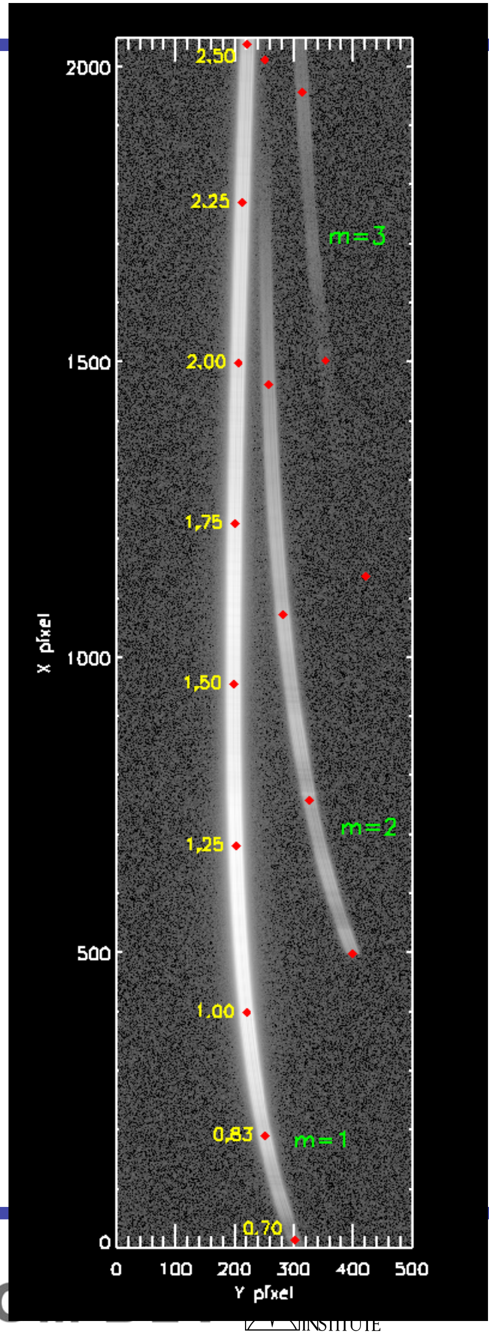
- Specifically optimized for transit spectroscopy
- Unique features
  - Broad simultaneous wavelength range: 0.7-2.5 um
  - Built-in weak lens to increase dynamic range and minimize systematic ''red noise'' due to undersampling and flatfield errors.
- Key component is a directly ruled ZnSe grism (manufactured by Bach) combined with a ZnS prism, all AR coated except the ruled surface on the ZnSe grism.
- Two spares were manufactured by LLNL and received October 2012 (after instrument delivery in July 2012)
  - Groove quality much better/sharper compared to the flight grism. Measurements and model suggested improved efficiency by > 2x.
  - Plan is to swap grism after CV2.

SOSS mode implementation

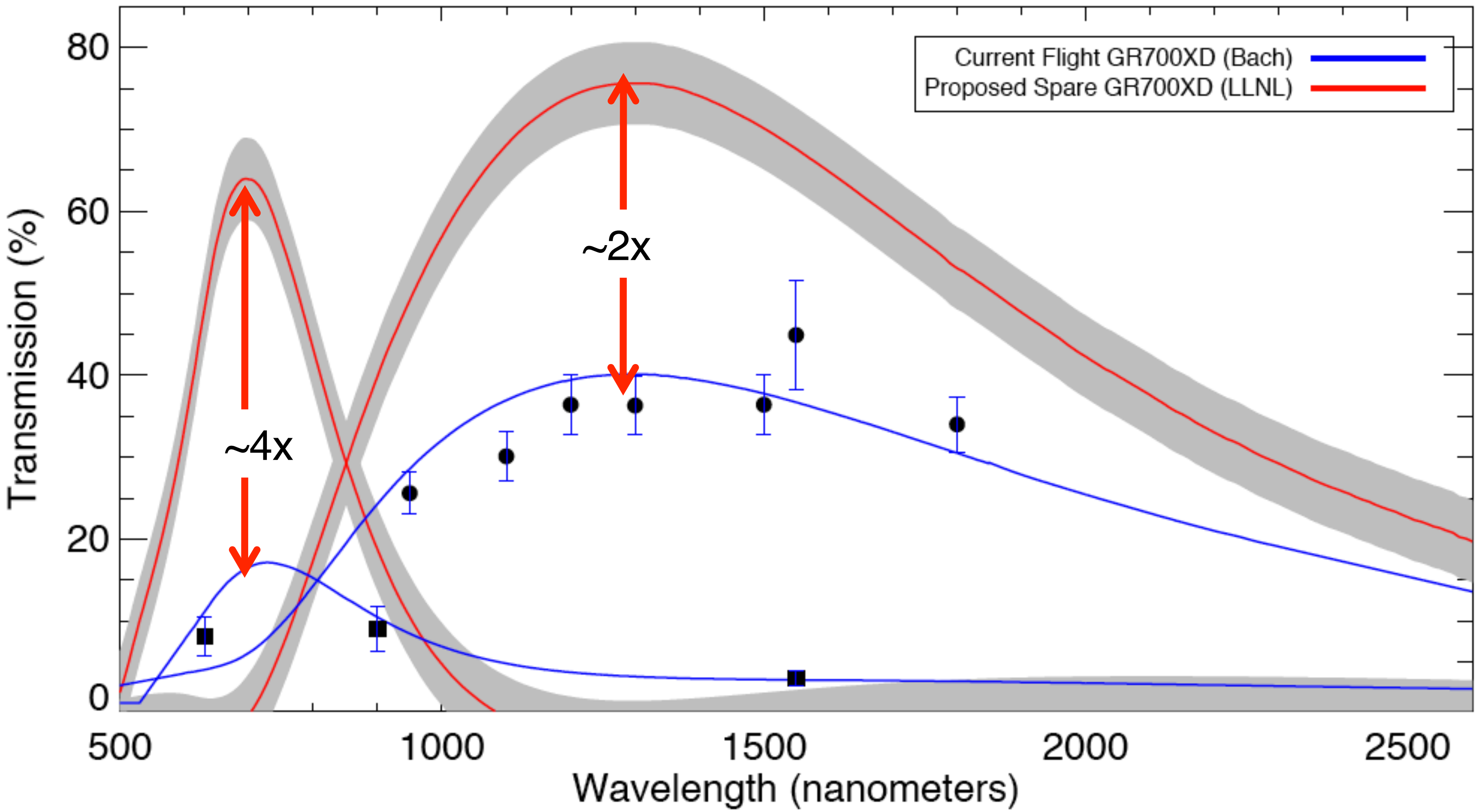




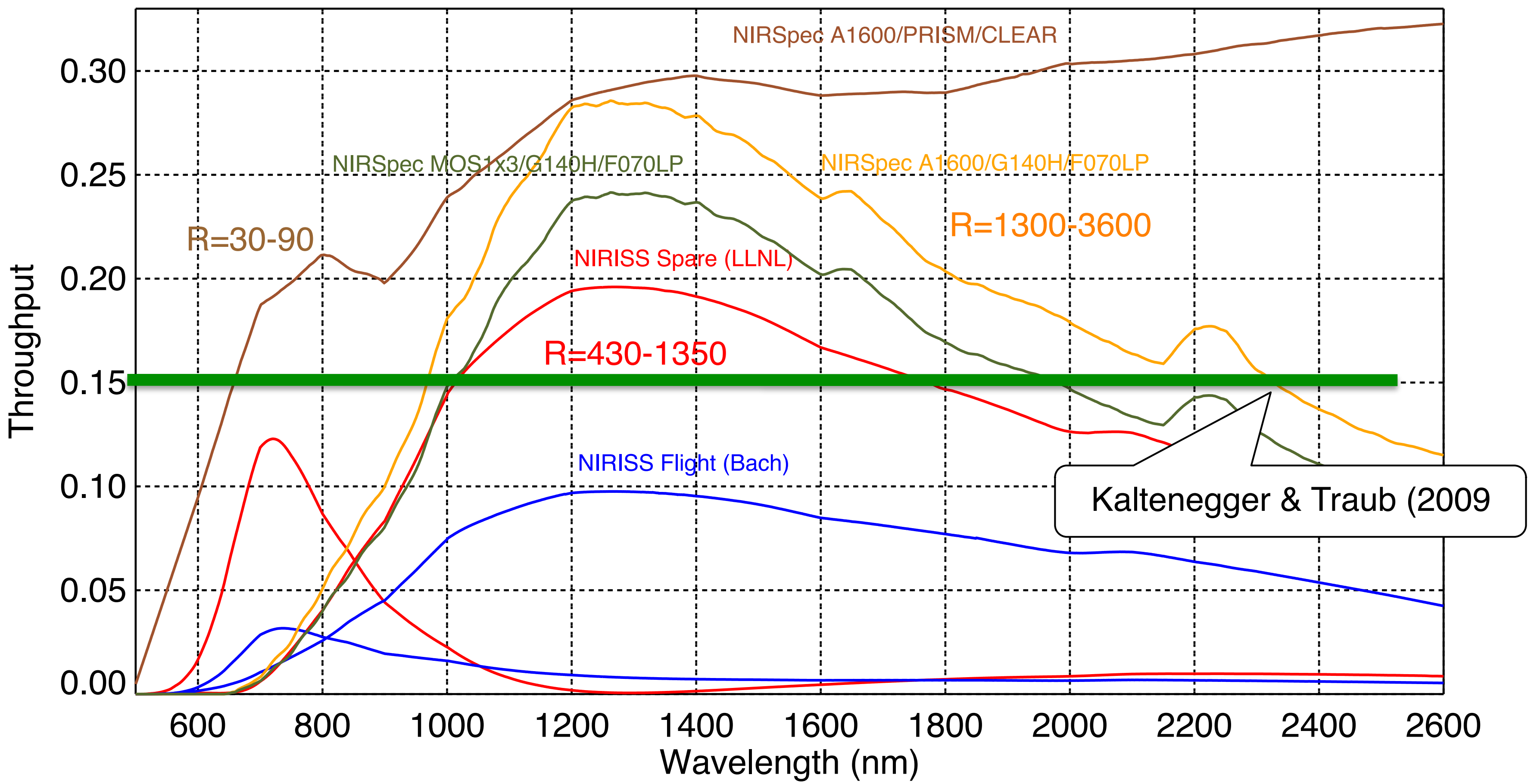




Blaze function – Flight vs Spare

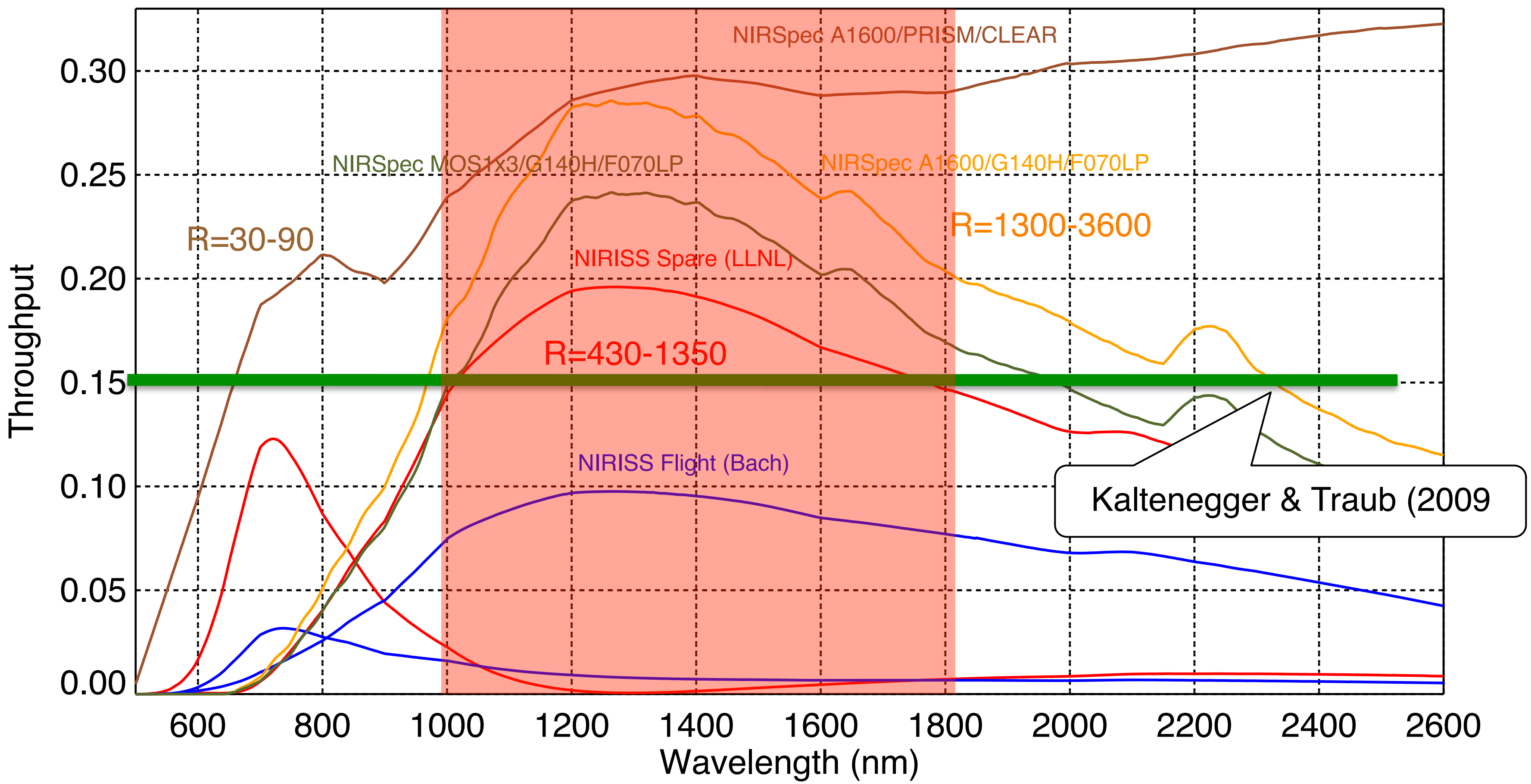


Total throughput – NIRISS vs NIRSpec



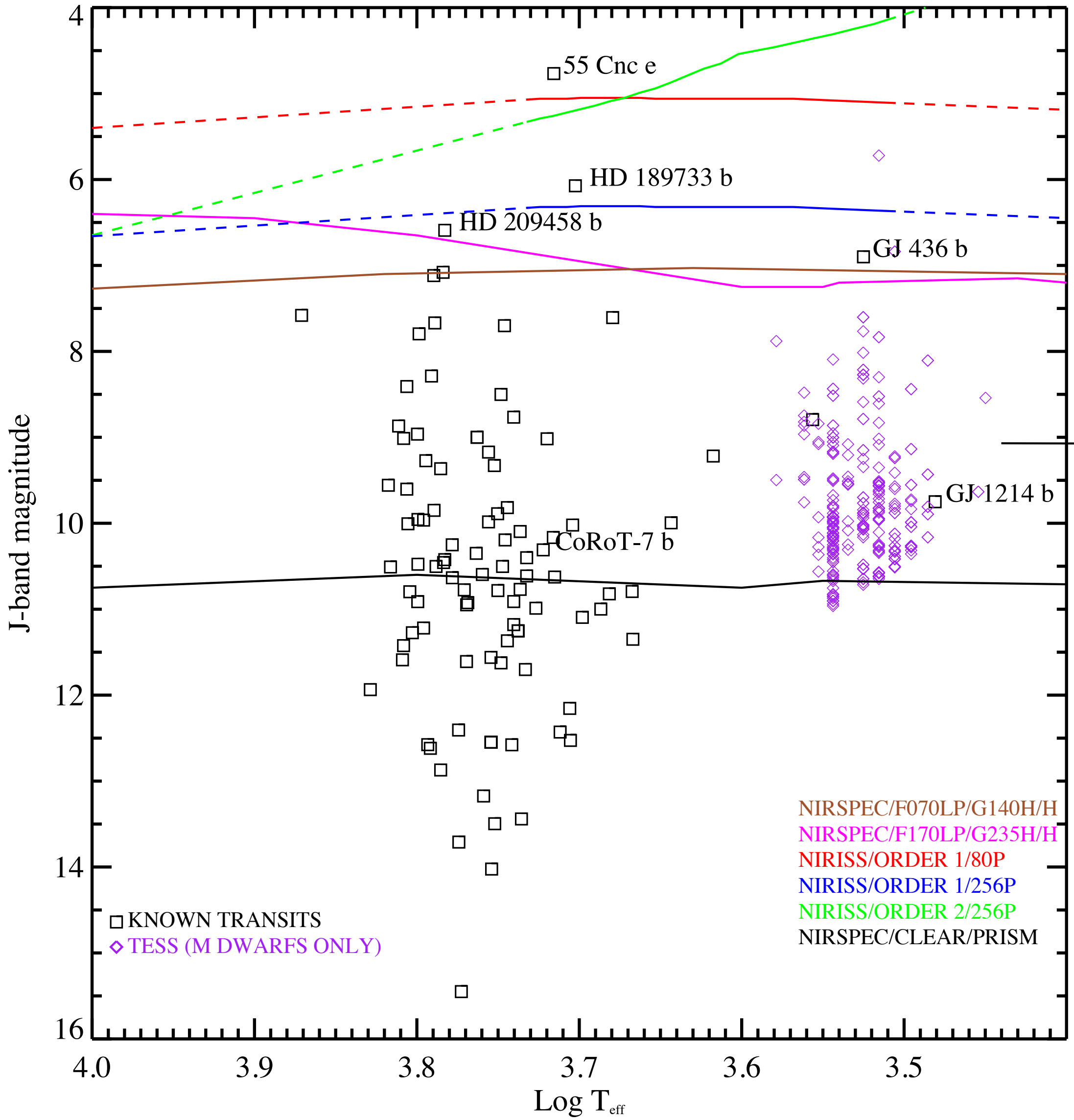
Curves include a conservative margin (~20%)

Total throughput – NIRISS vs NIRSpec



Curves include a conservative margin (~20%)

Saturatiom limits – NIRISS & NIRSPec



Unsaturated m=2, partial saturation in m=1 (256-pixel sub-arrray)

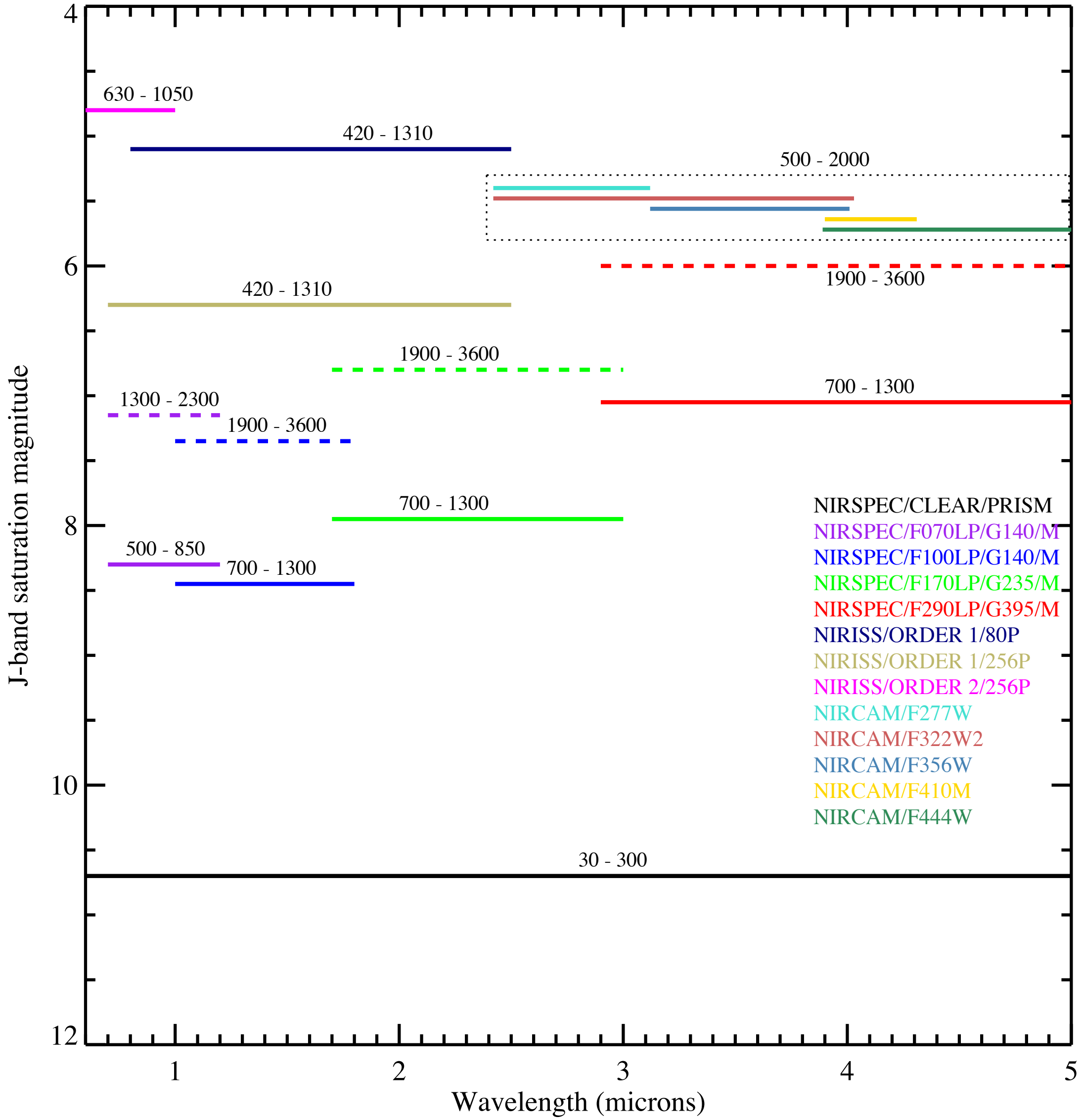
0.9-2.5 µm , m=1 only (80-pixel sub-array)

0.7-2.5 µm , m=1, m=2 (256-pixel sub-array)

→ Educated guess of M dwarfs yield from TESS.

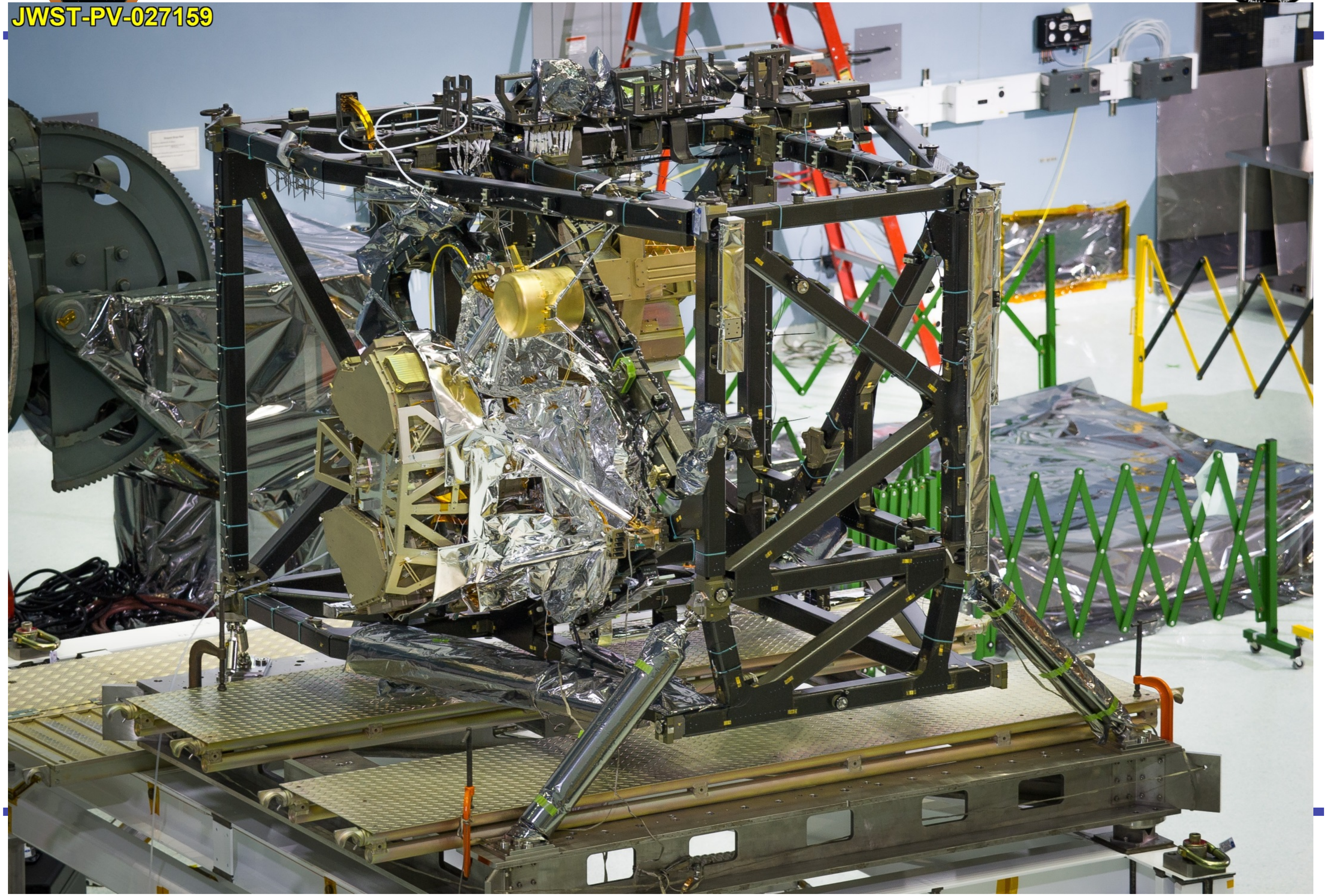
Assumes 4-amp read-out mode or high-gain mode

Saturation limit *vs* wavelength

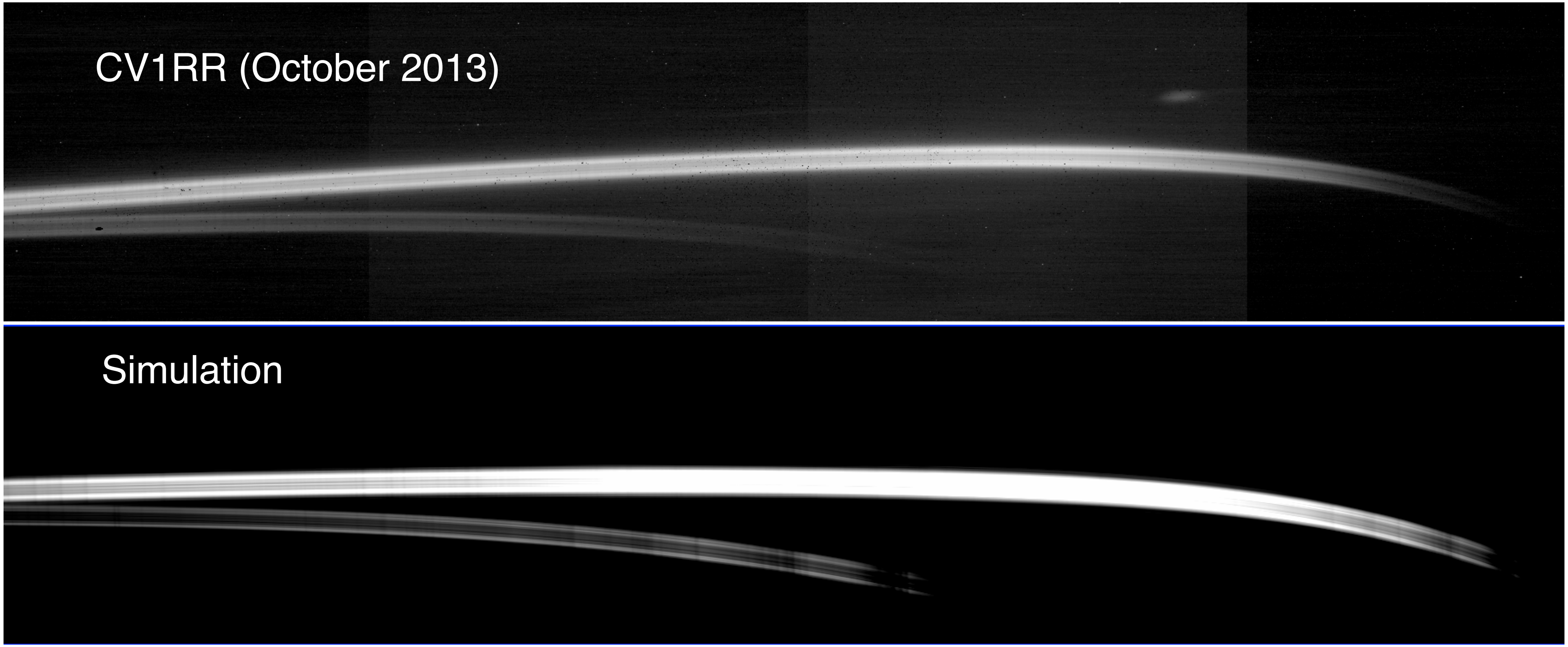


NIRISS First Light with the GR700 grism (GSFC, October 2013)

MIRI & FGS into ISIM

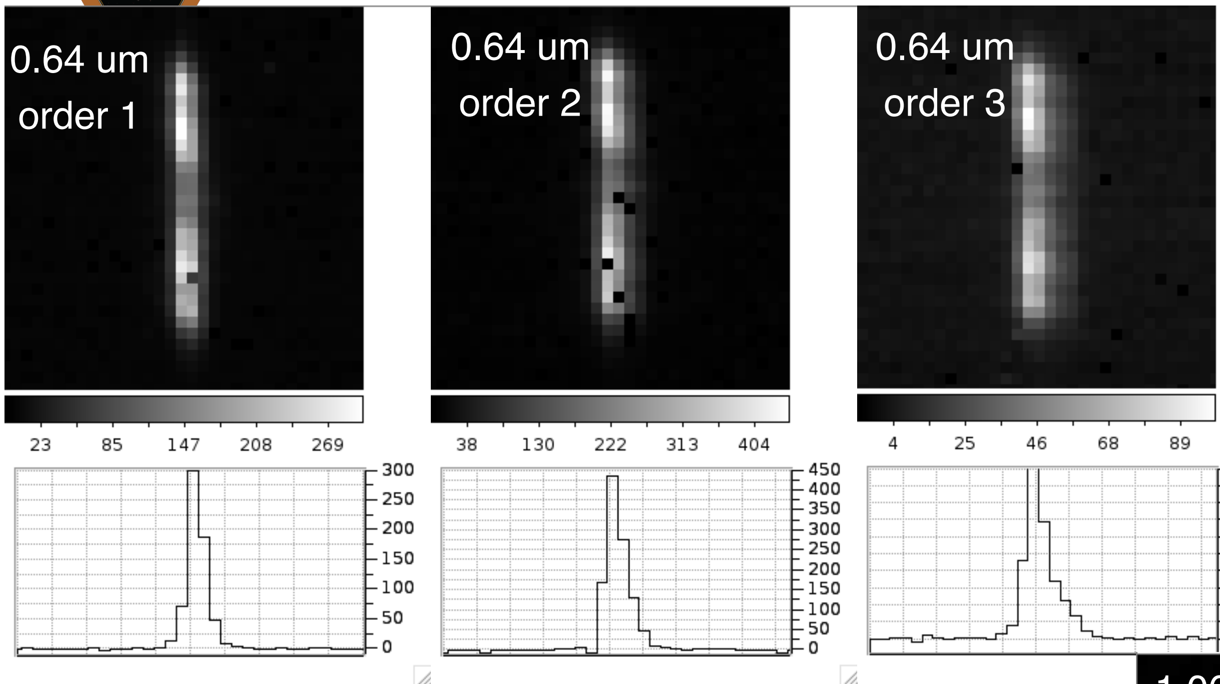


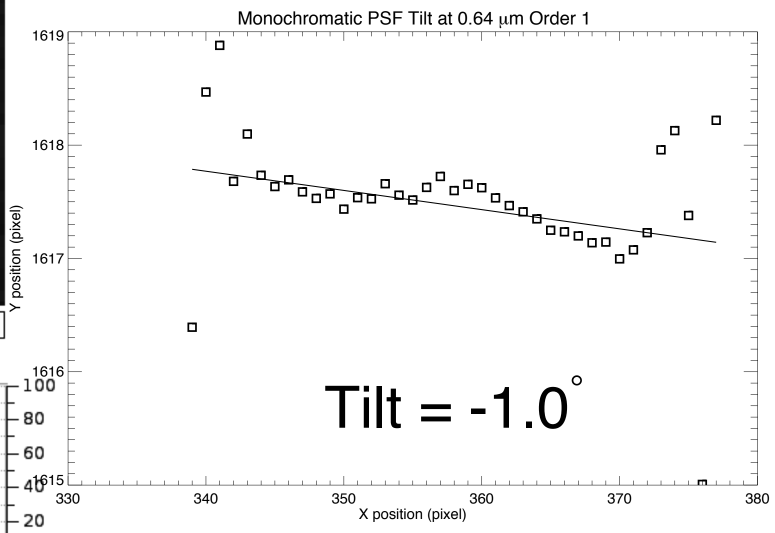
Real data vs simulation



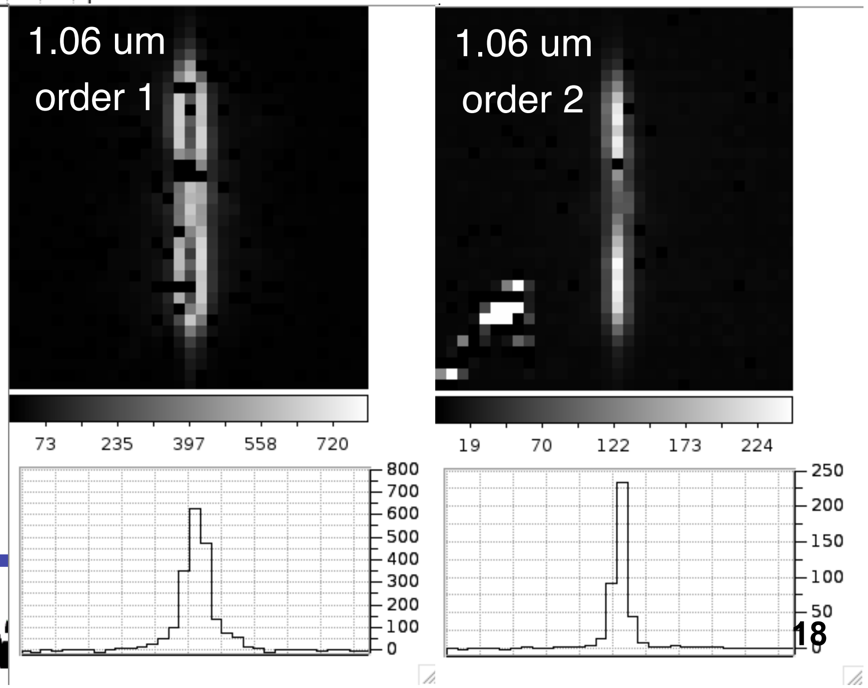
Excellent correlation between data and simulations.

GR700XD Monochromatic PSFs



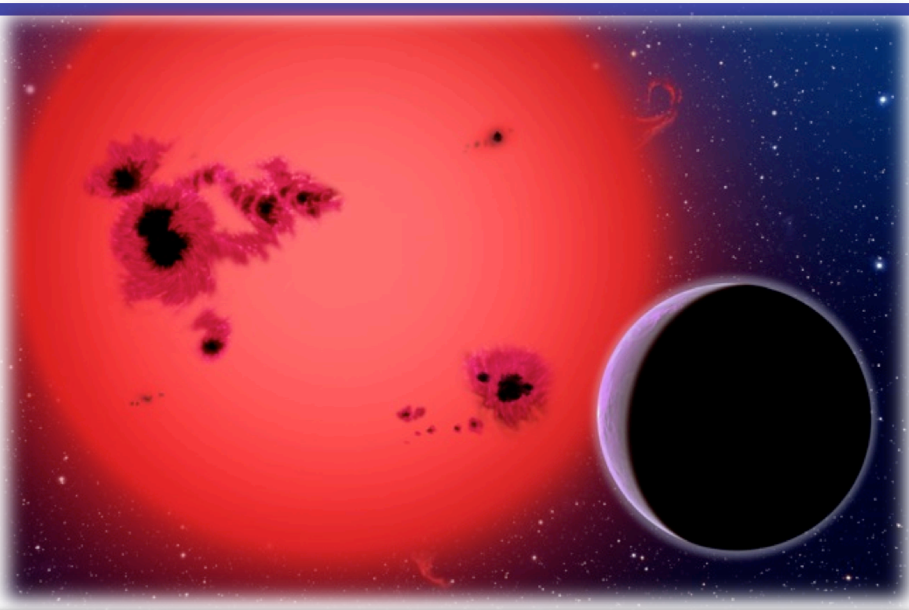


NIRISS grism is designed to have a PSF slanted by ~2° to mitigate undersampling problems.

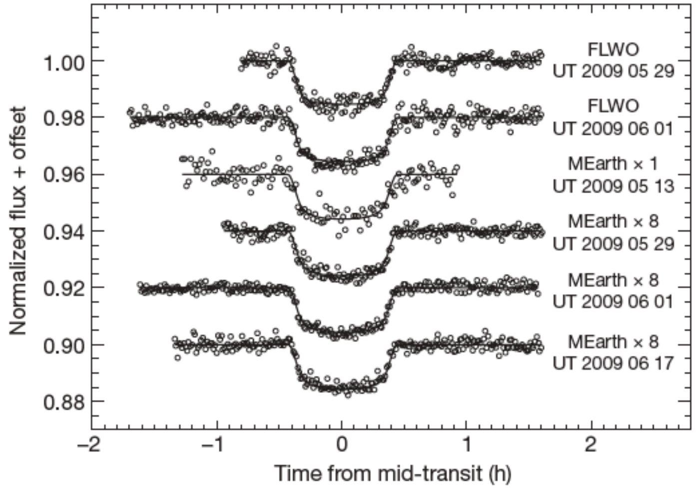


NIRISS Transit Spectroscopy Simulations (photon-noise limited)

GJ1214b

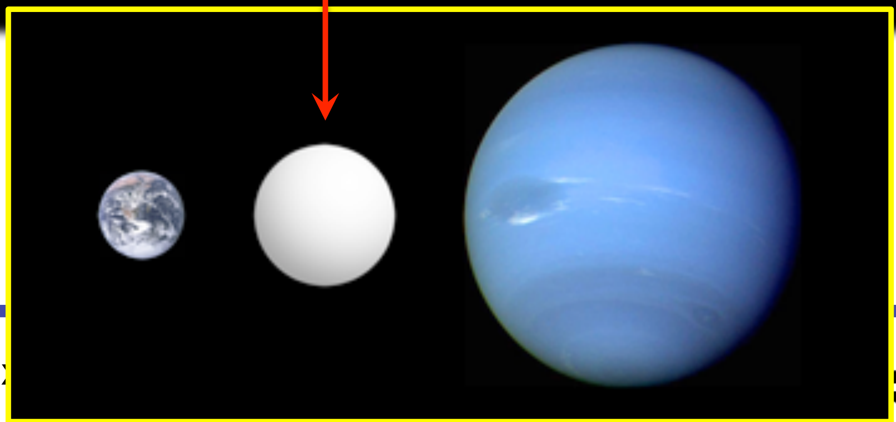


Charbonneau et al 2009, Nature, 462, 17



What's the nature of GJ1214b?

- An ice giant (a mini Neptune) ?
- A water world ?



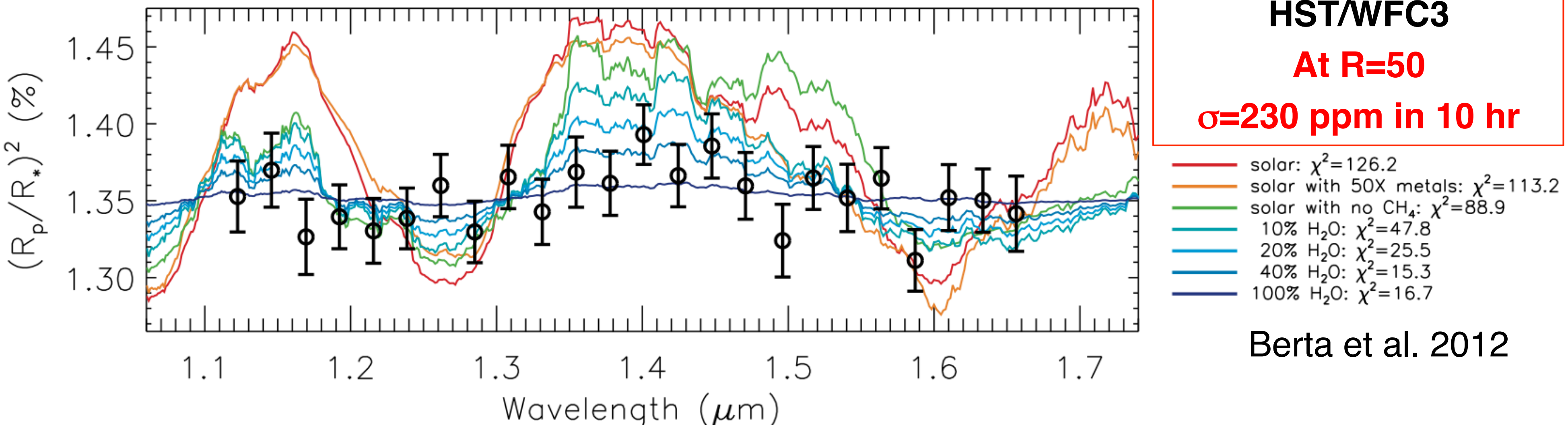
	GJ1214b	Earth	Neptune
Mass	6.5	1.0	17
Radius	2.7	1.0	4.0
Temperature (Kelvin)	400-600	300	55
Density (g/cm^3)	1.9	5.5	1.7

Current observations of GJ1214b

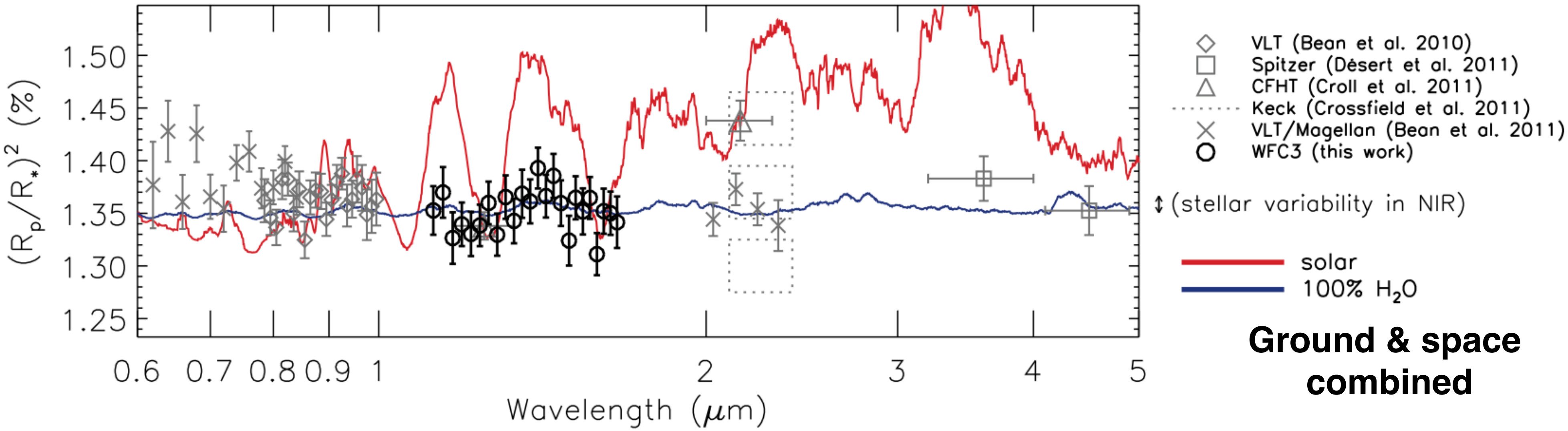
HST/WFC3

At R=50

σ=230 ppm in 10 hr



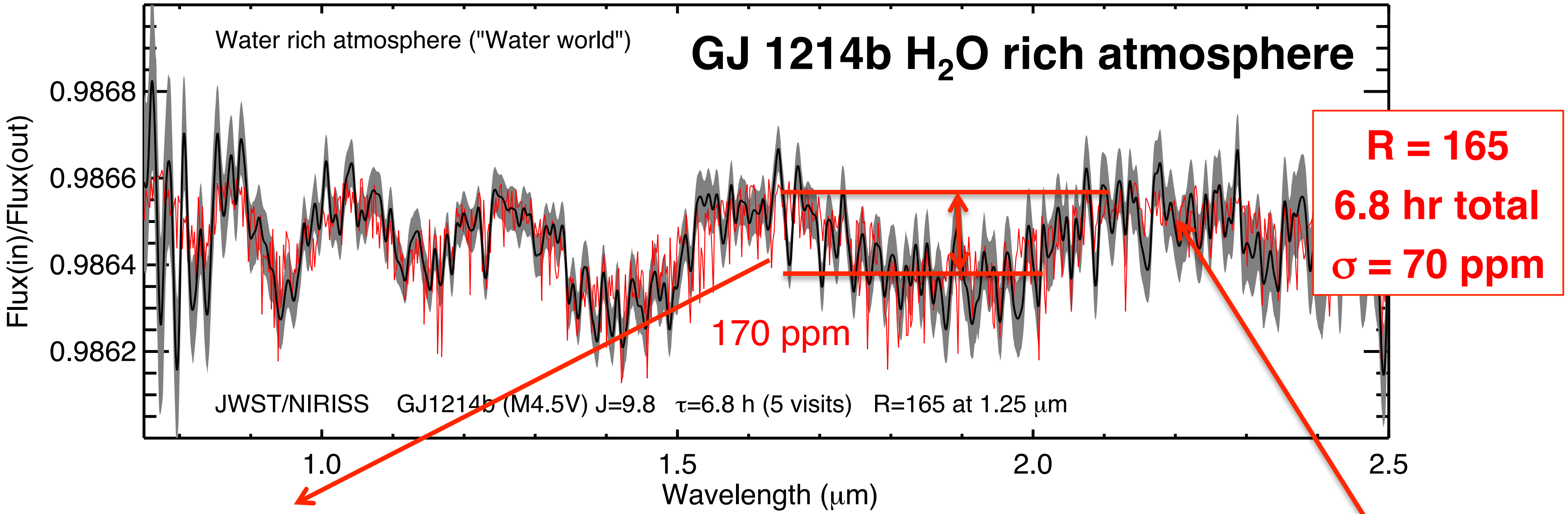
Berta et al. 2012



Ground & space combined

Limited by aperture, platform stability, detector and instrument systematics and atmosphere

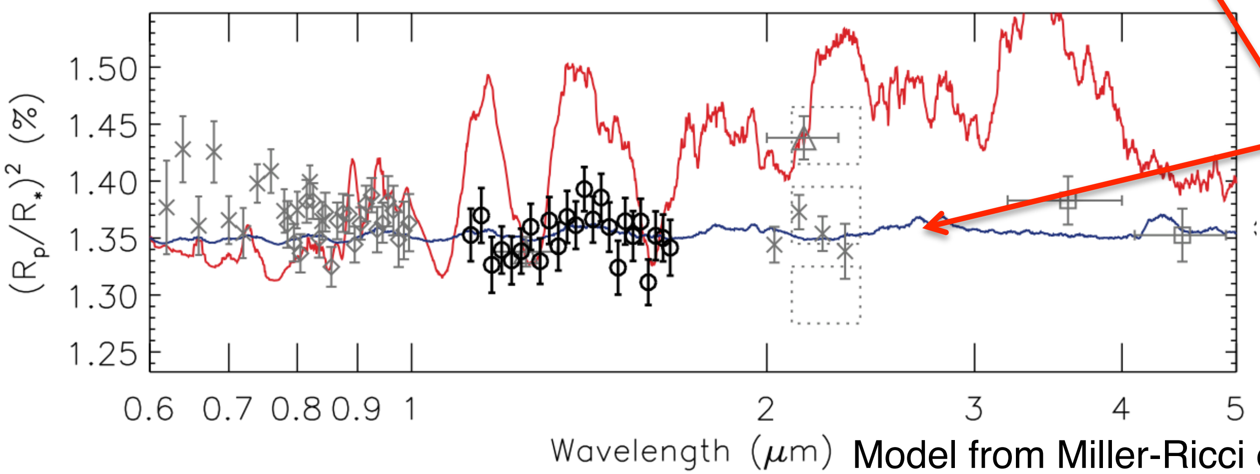
The same observations with JWST/NIRISS



$$\left(\frac{\Delta f}{f}\right)_{atmo} \approx 10\frac{R_p H(\lambda)}{R_\star^2}$$

$$H = kT/\mu g$$

$$\mu \sim 18$$

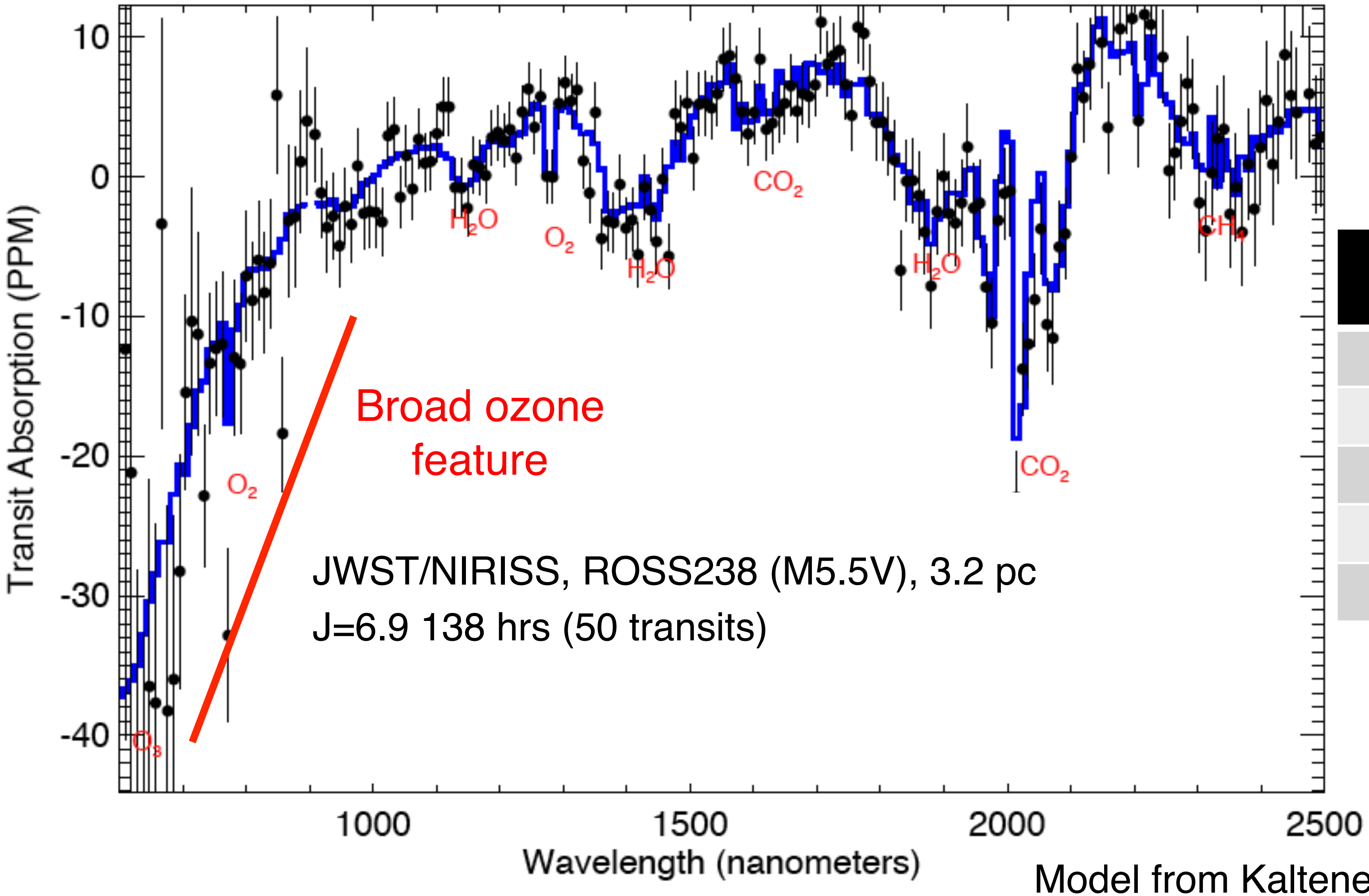


Credit: D. Lafrenière

Model from Miller-Ricci et al. 2010

A more challenging observation…

An Earth analog around an M dwarf (R~100)



Feature	Strength (ppm)
H_20	5-15
CH_4	~10
CO_2	5-30
O_2	<5
O_3	~30

Model from Kaltenegger et al. 2009

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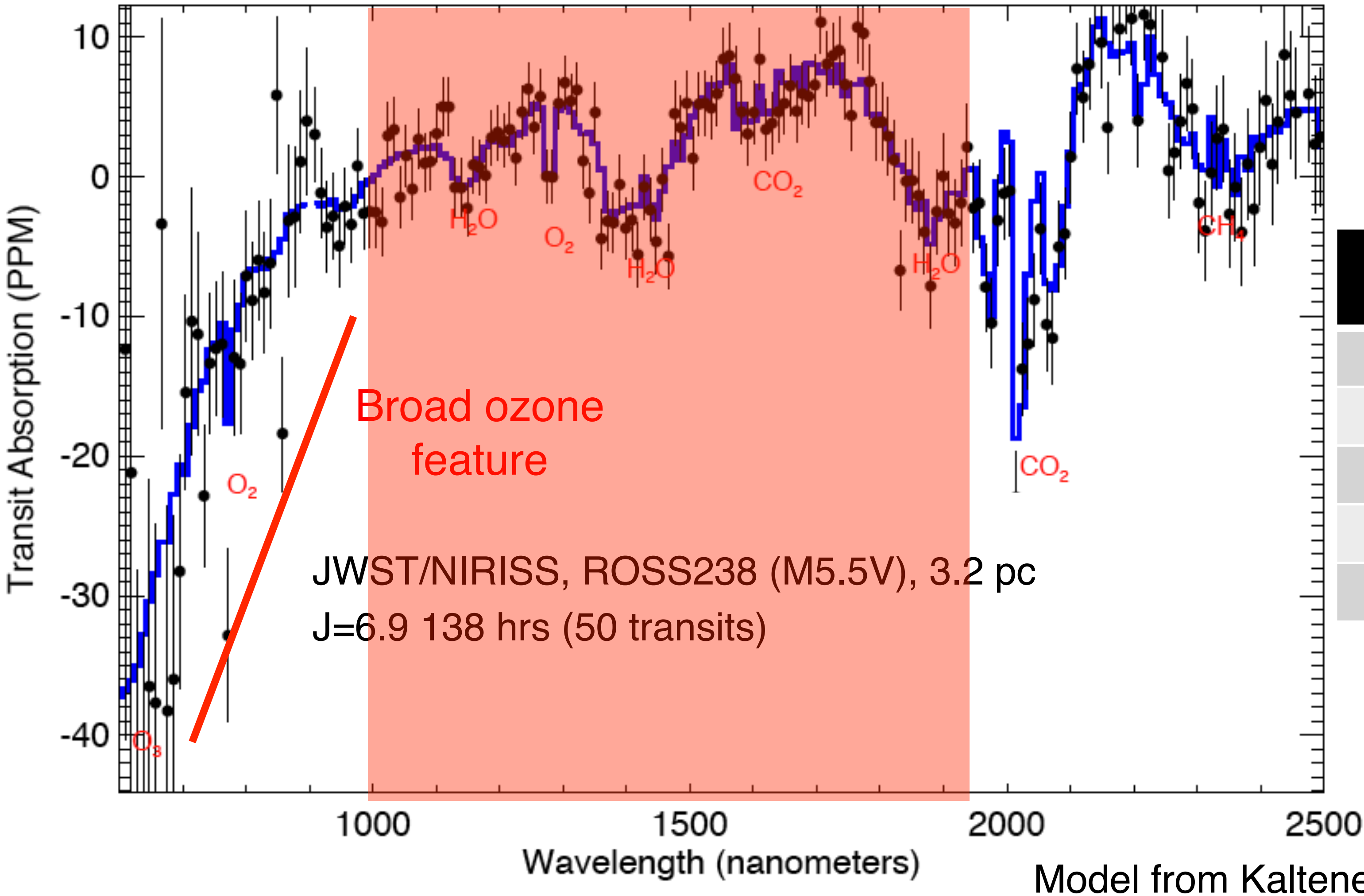

Feature	Strength (ppm)
H_20	5-15
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O_3	~30

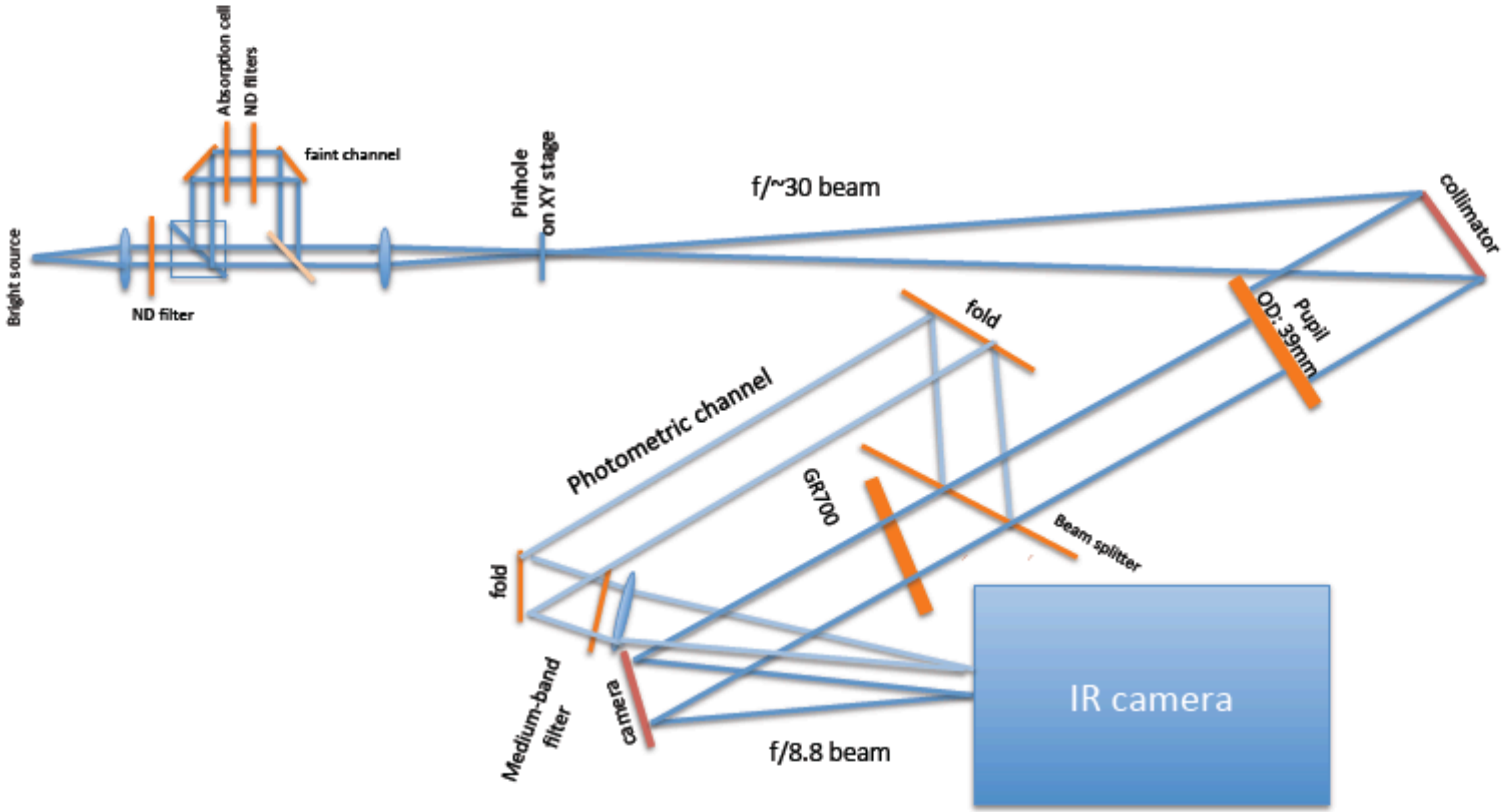
Model from Kaltenegger et al. 2009

Performance limitations

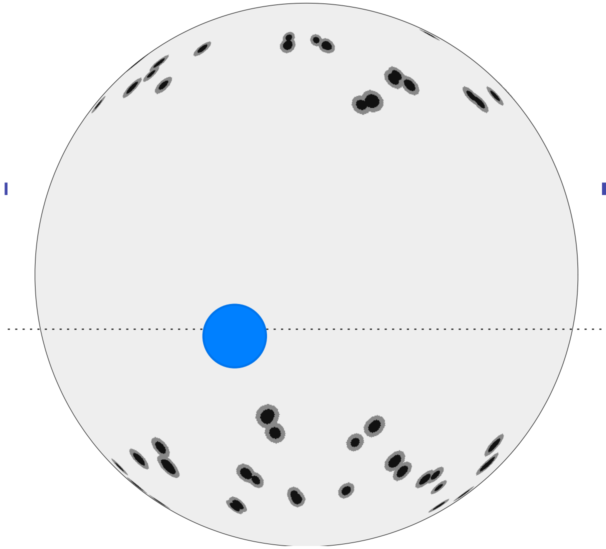
5 ppm is about the noise level needed for minimal characterization of super-Earths. What will prevent reaching the photon-noise limit at this level?

- Instrumental « red noise »
  - Already well-known from SPITZER and HST experience
  - Detector-related issues
    - Undersampling + jitter (may be okay with NIRISS)
    - Persistence
    - Long term stability (thermal instability)
  - Could probably be mitigated if noise is well characterized
    - Detailed simulations needed along with flight-like simulator testbed investigations.
- Astrophysical « red noise »
  - Intrinsic variability (e.g. spots on M dwarfs)

The NIRISS Optical Simulator concept

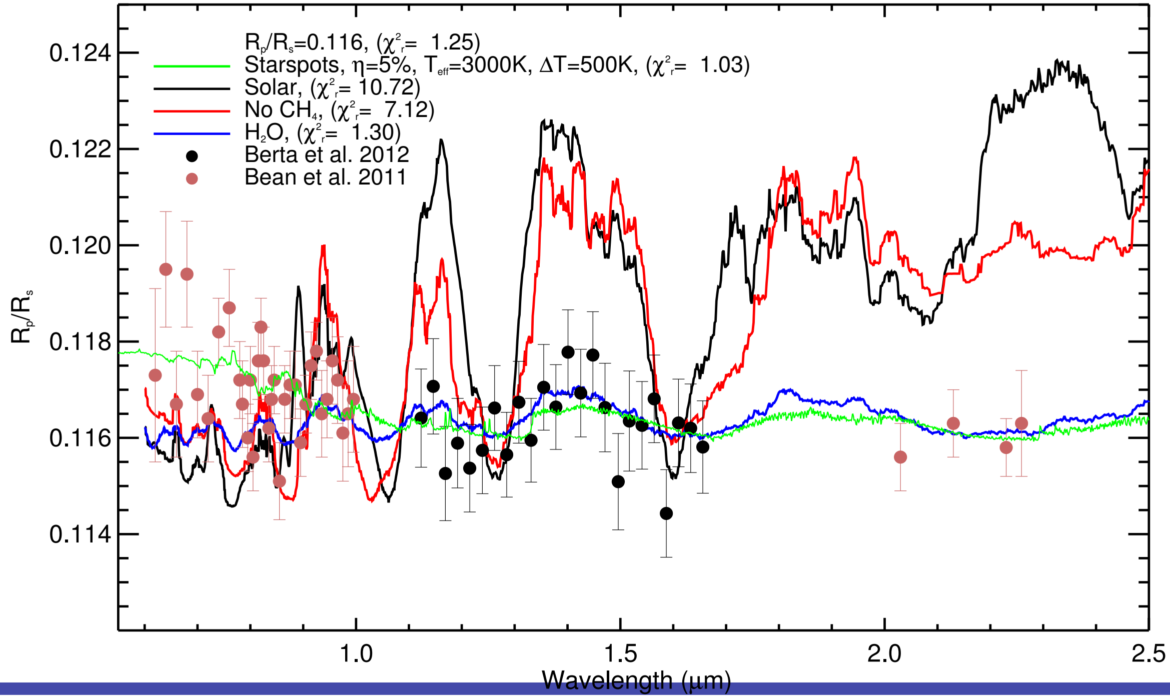


Astrophysical noise associated with star spots



GJ1214b: are we seeing star spots?

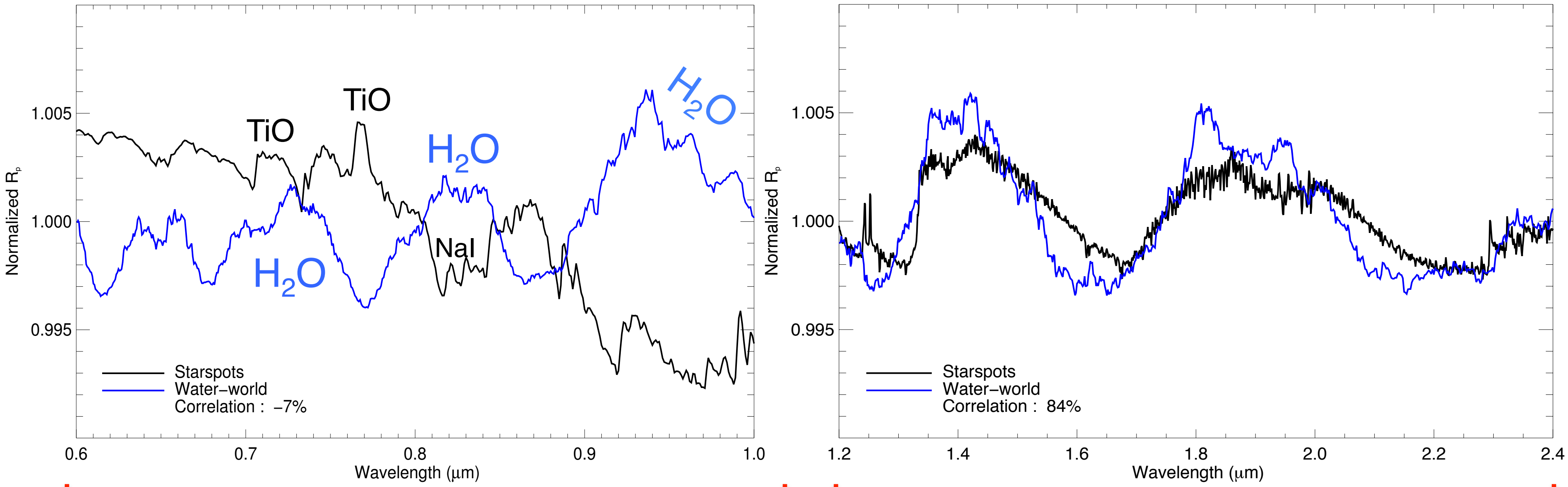
- If GJ1214 is spotted over 5% of its surface and GJ1214b happens to transit a spot-free area …
- Out-of-transit spectrum : 95% star, 5% spots
- In-transit spectrum: 93.6% star, 5% spots
- Spot spectra, 500 K cooler than photosphere, has significantly deeper water bands and a redder overall SED.
- In-transit/out-of-transit spectrum will contain significant spectral structures at a level comparable to that induced by an exoplanet's atmosphere



Star spot-induced transit spectrum fits data better than any planet atmosphere model!

Artigau et al, in prep.

Spectrum blueward of 1 μm may be key for discriminating between star spots and water vapor from the exoplanet.



- TiO, NaI, FeH dominate the star spot-induced spectrum.
- Water absorption dominates the planetary features.
- Good spectral resolution needed to detect some features (e.g. NaI, KI)

- In near-IR domain, both star spots and exoplanets induce very similar signals, both dominated by deep water features. Slight difference in the shape spectra arise from the important difference in temperature (2500 K versus 500 K).

Summary

- NIRISS will be a powerful capability for high-precision transit spectroscopy work
- Pros
  - Broad simultaneous wavelength coverage (0.7-2.5 μm)
  - Medium resolving power (~700). Unique capability < 1 μm.
  - Bright saturation limit (J<5)
  - Most of HZ transiting super-Earths from TESS should be observable.
  - Grism designed to mitigate undersampling problems.
- Cons
  - Lower throughput compared to NIRSpec. May favor NIRSpec for deep observations provided NIRSPec's noise floor is lower than NIRISS.
- Detailed simulations and flight-like detector testbed activities needed to investigate and characterize systematic noise.
- Astrophysical noise (spots in particular) may be an issue for H_2O detection on super-Earths. Broad wavelength coverage will key for discriminating between genuine atmospheric H_2O from residual stellar spot.
- Let's not give up too quickly on achieving photon-limited performance with JWST, especially with NIRISS !