Transit Spectroscopy with NIRISS

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FGS/NIRISS PI

Collaborators

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- Loic Abert, UdeM
- Etienne Artigau, UdeM
- Mike Meyer, ETH, Switzerland
- Ray Jayawardhana, York
- Lisa Kaltenegger, Cornell

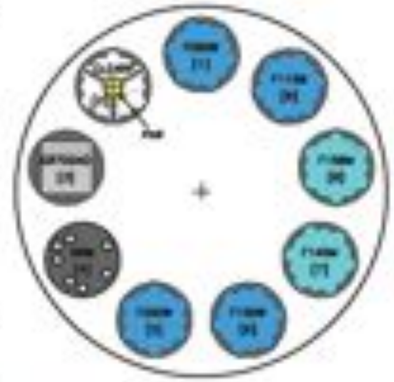
The Near-Infrared Imager and Slitless Spectrograph (NIRISS)

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 "C" Slitless Spectroscopy

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

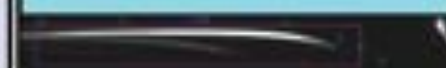
Single-Object Slitless Spectroscopy

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.

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

Mask → Interferogram

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: $\sim 2 \times 10^{-4}$ (S/N~5)
Separations: 70 – 400 mas

Fourier Transform

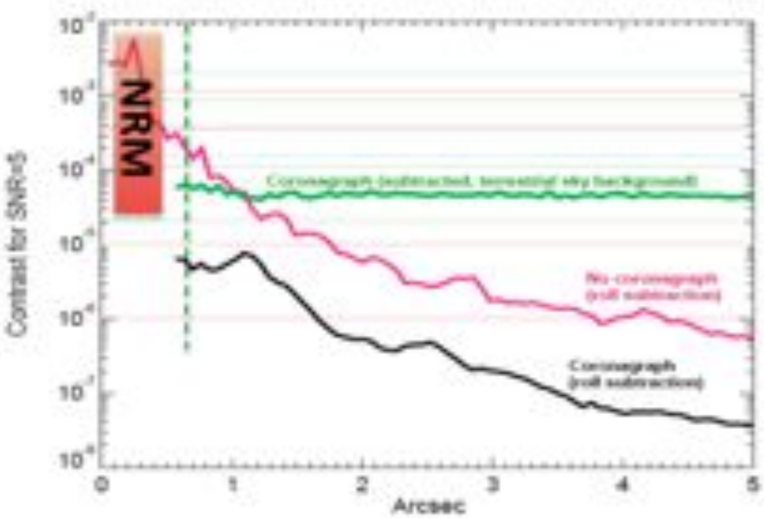
Aperture synthesis imaging (cf. e.g., AGN) is also enabled.

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

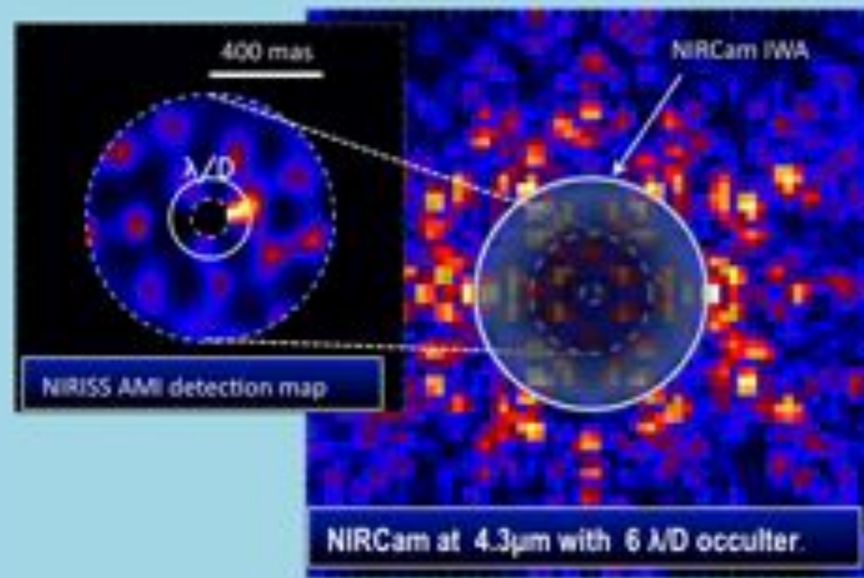
Available in 3 broad-band filters:
3.8, 4.3, 4.8 um over which NIRISS is Nyquist sampled

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

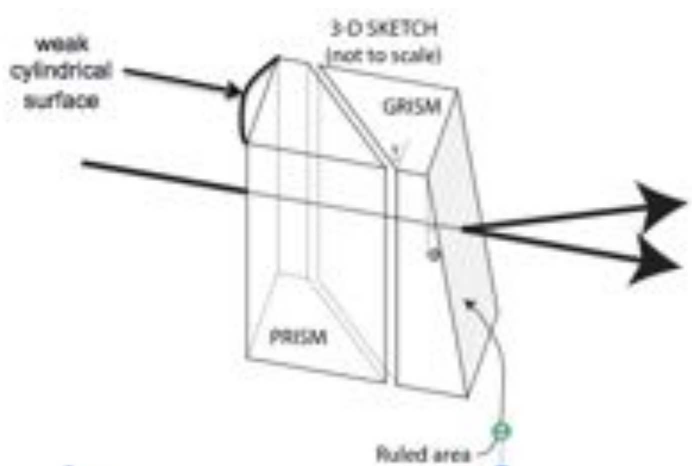


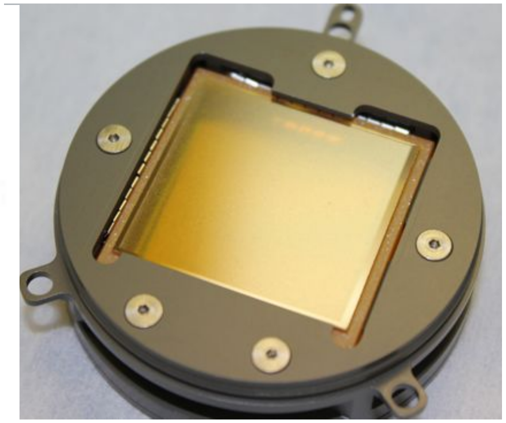
Simulated companion above has contrast of 10 mag at a separation of 130 mas

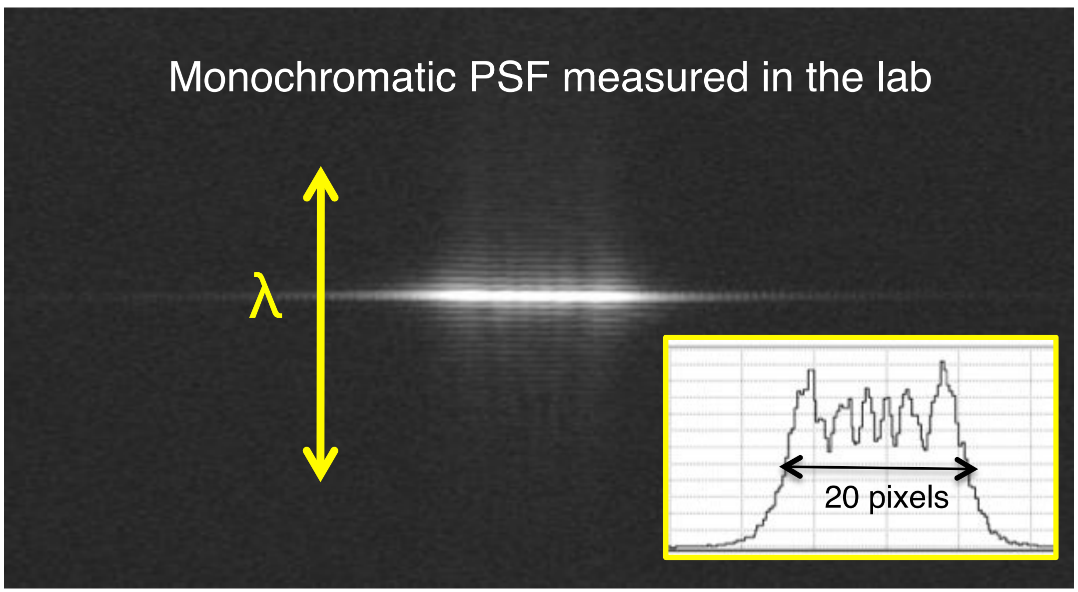
Equivalent to a 1-2 M_{Jup} planet at ~1 AU of a 50 Myr-old M0V dwarf at a distance of 10 pc from the Sun.

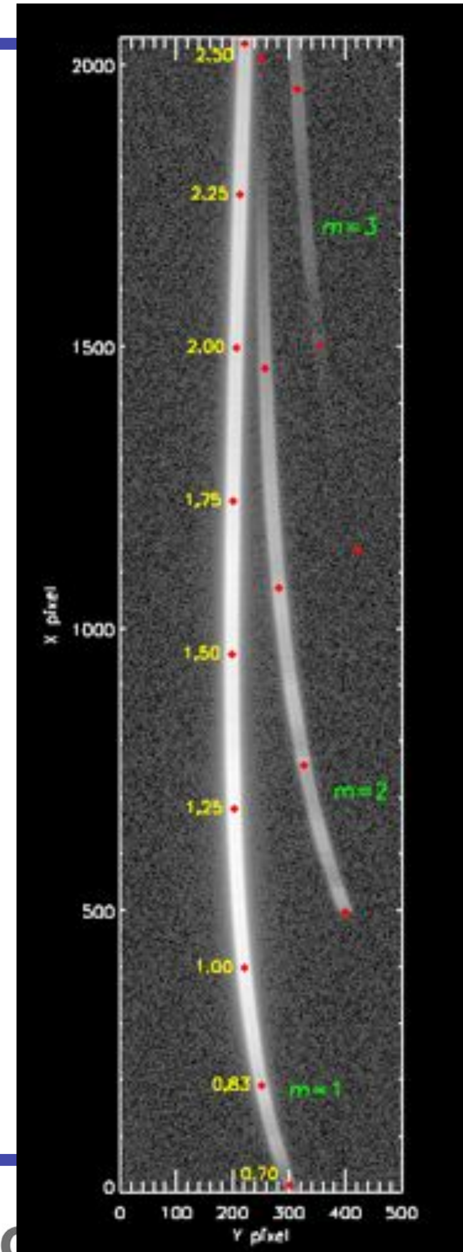
Above simulation corresponds to approximately 3 hours of observing time

SOSS mode implementation

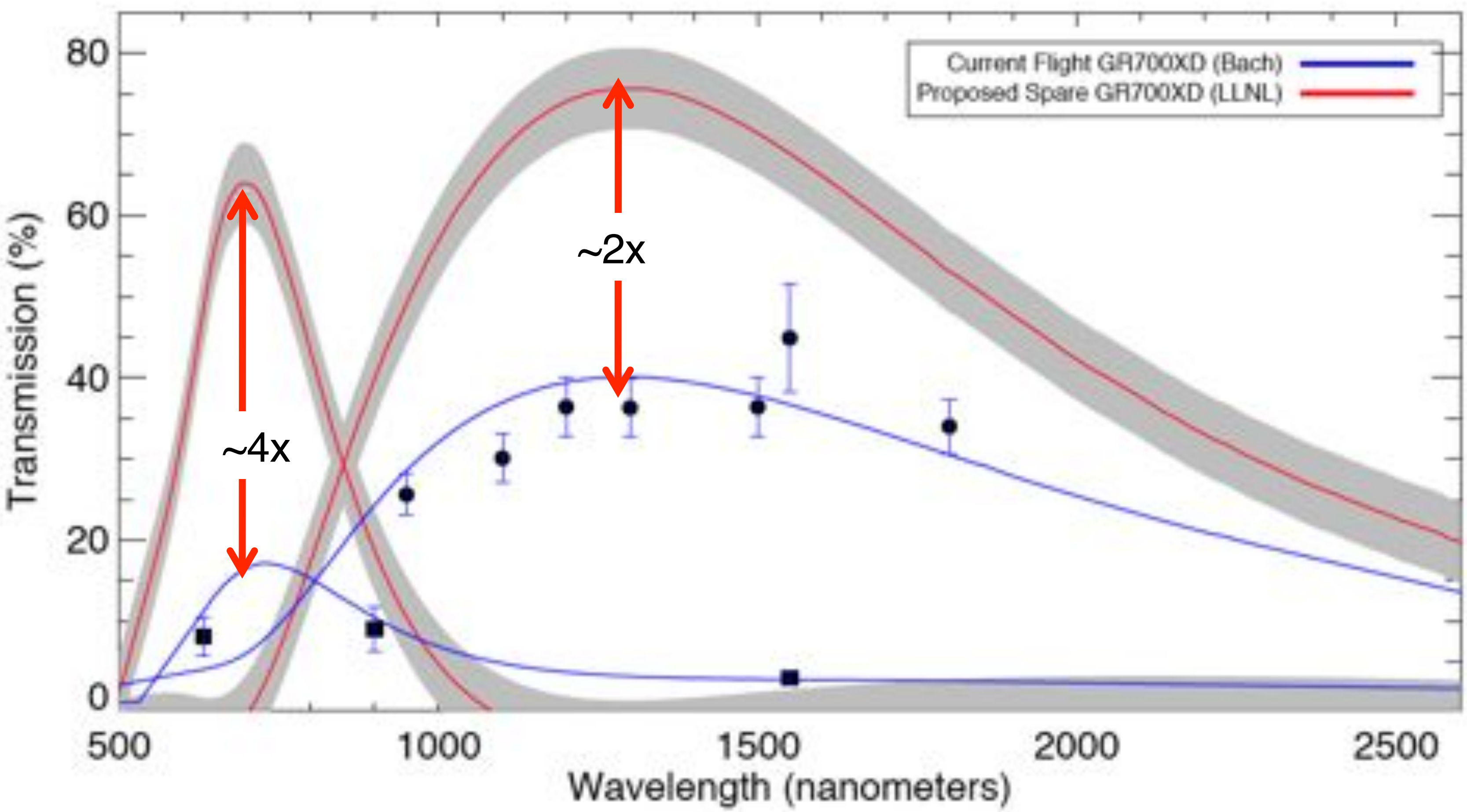




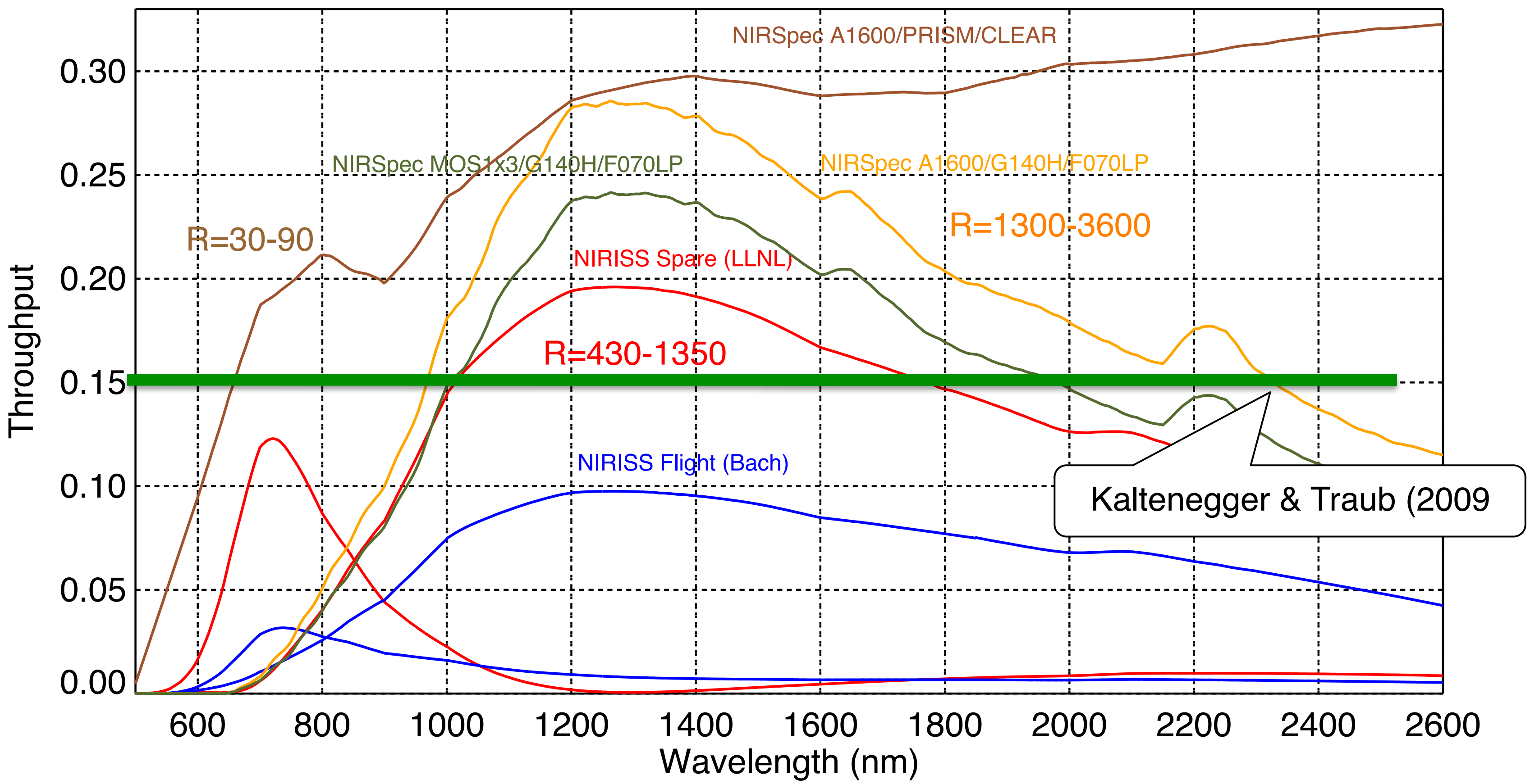




Grism blaze function – Flight vs Spare



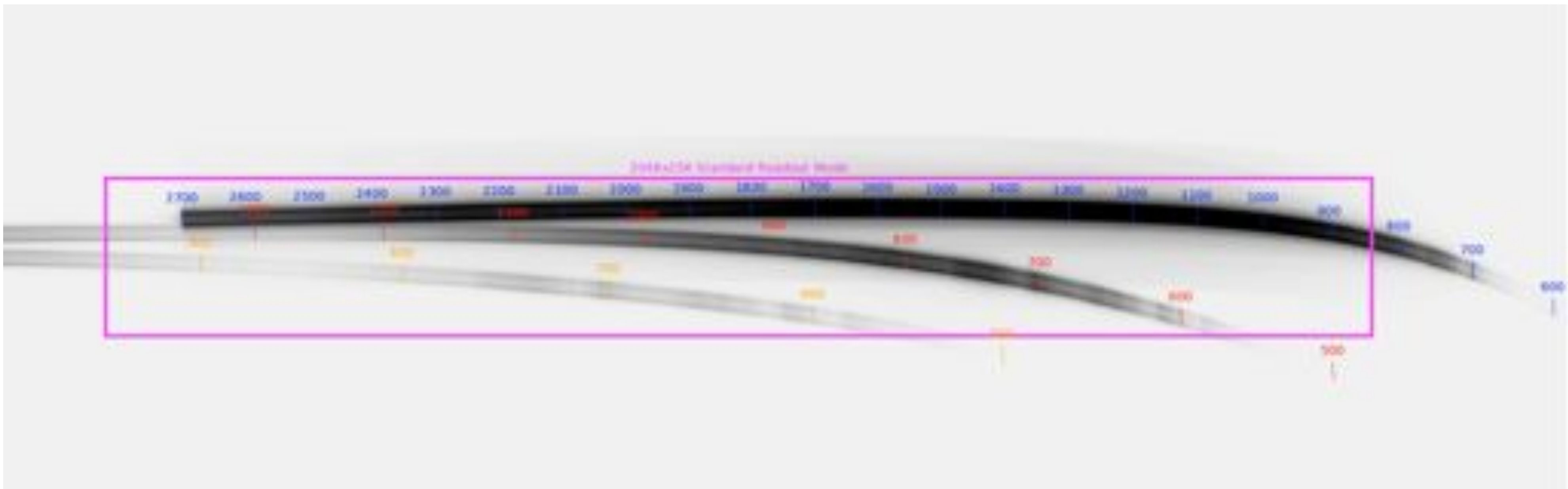
Total throughput – NIRISS vs NIRSpec



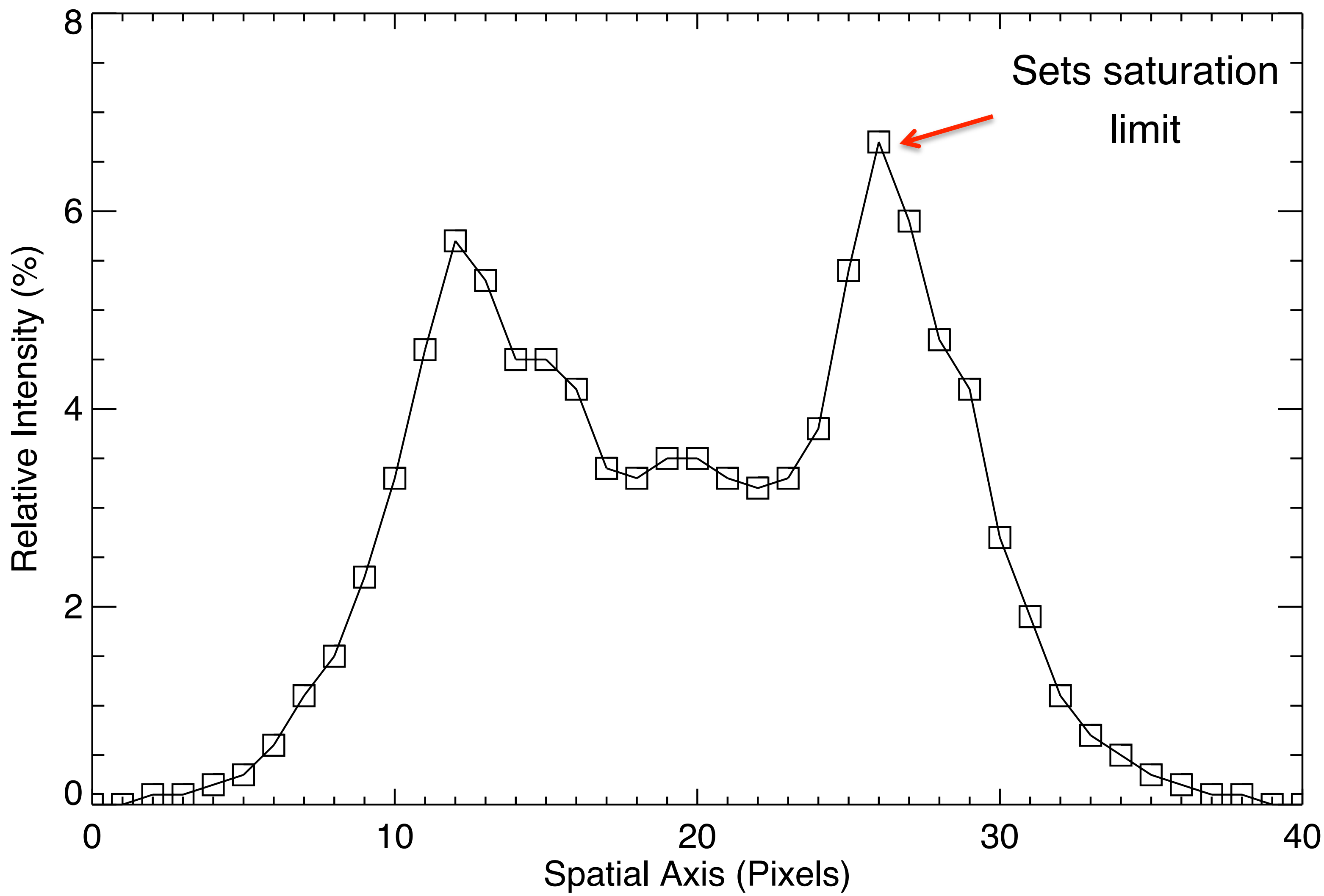
Curves include a conservative margin (~20%)

Observing modes & saturation limits

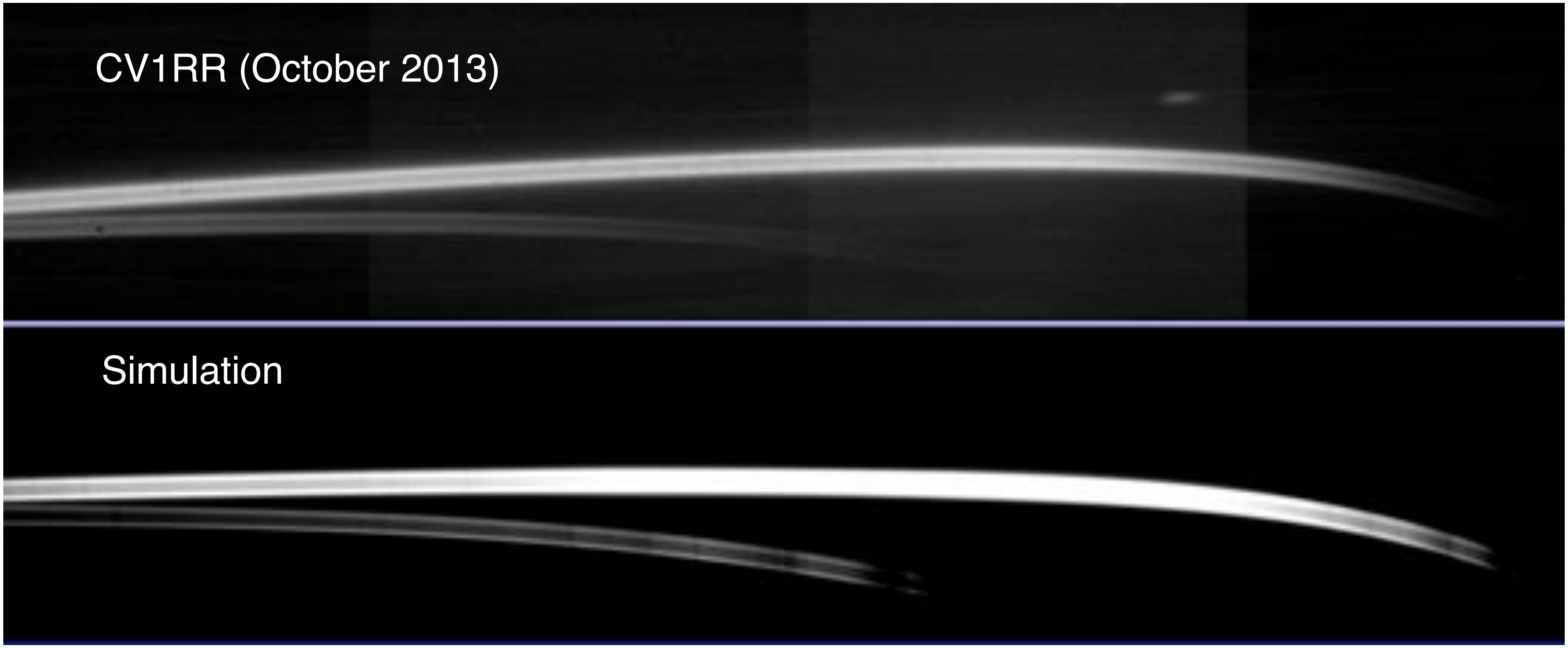
- Standard Mode:
  - Wavelength coverage: 0.6-2.8 µm
  - Subarray: 256x2048 (order m=1 and 2)
  - Saturation limit: J=8.1 (CDS; 70 000 e-)
- Bright mode
  - Wavelength coverage: 1.0-2.8 µm
  - Subarray: 80x2048 (m=1 only)
  - Saturation limit: J=6.9



Trace Profile (CV1RR Trace)

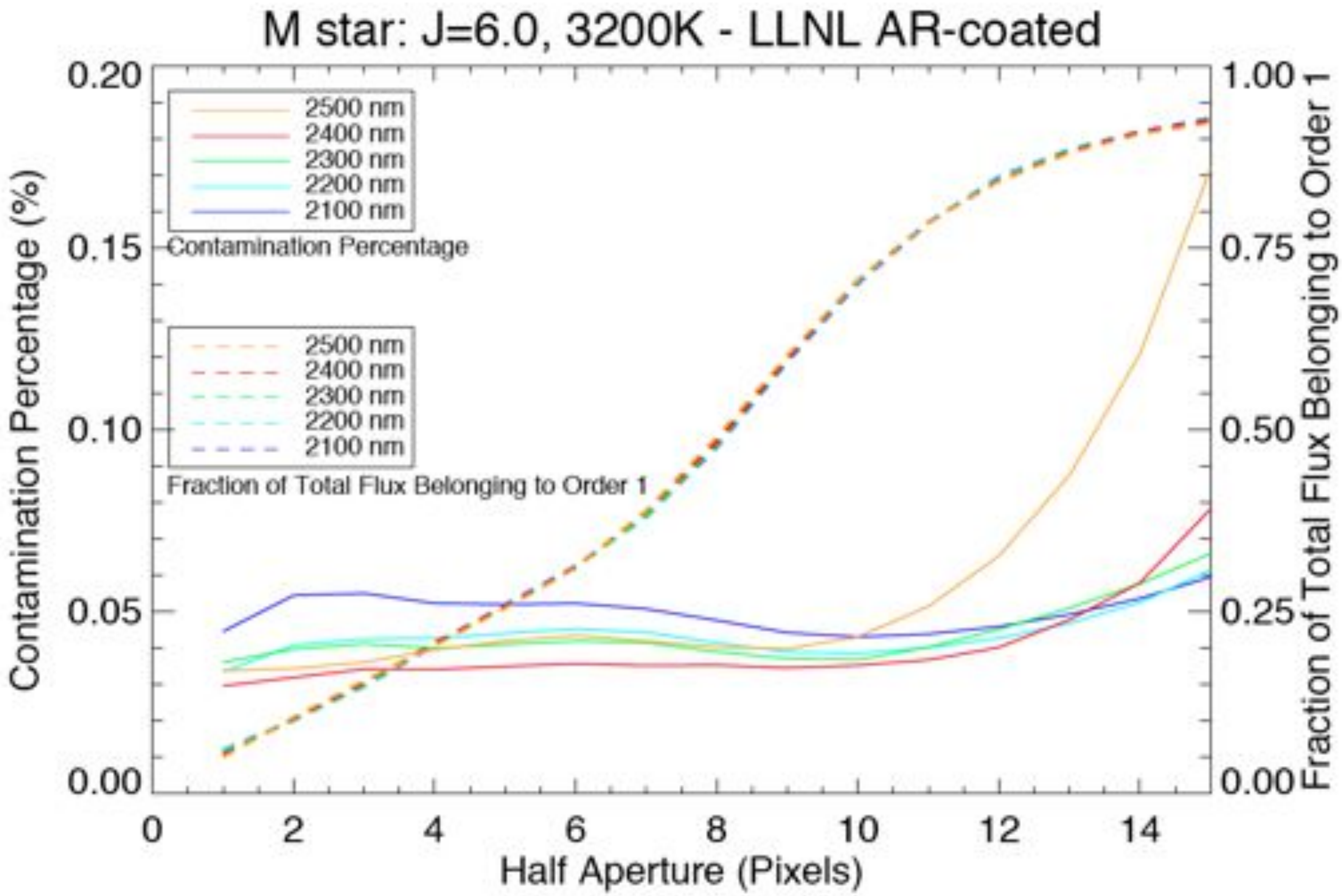


Real data vs simulation

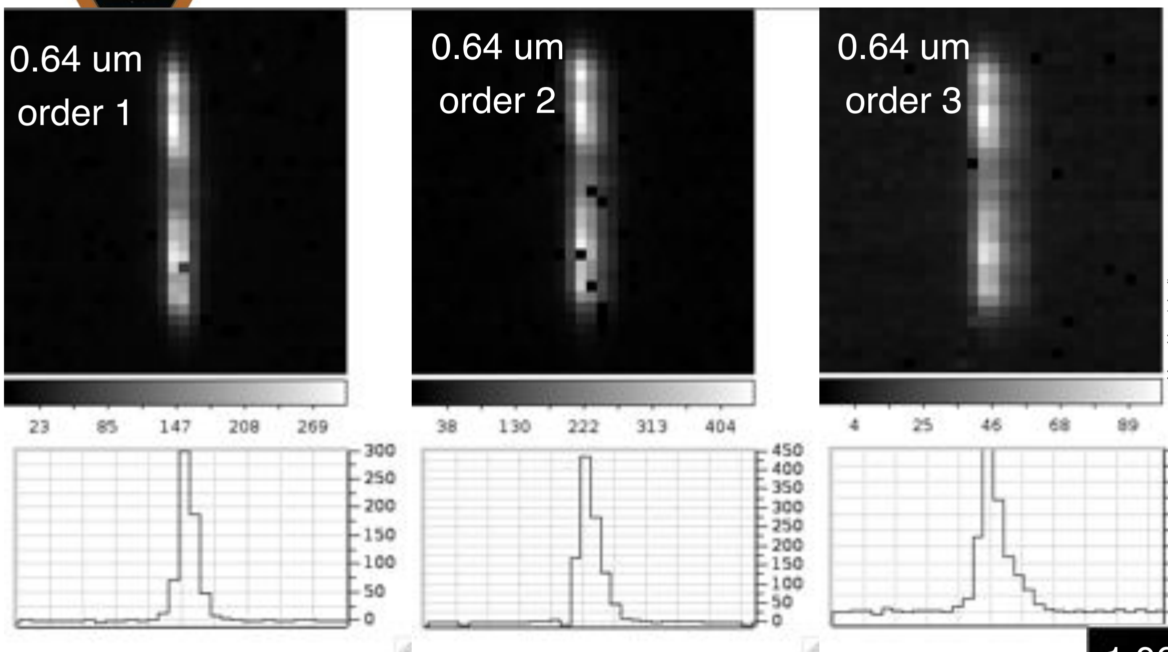


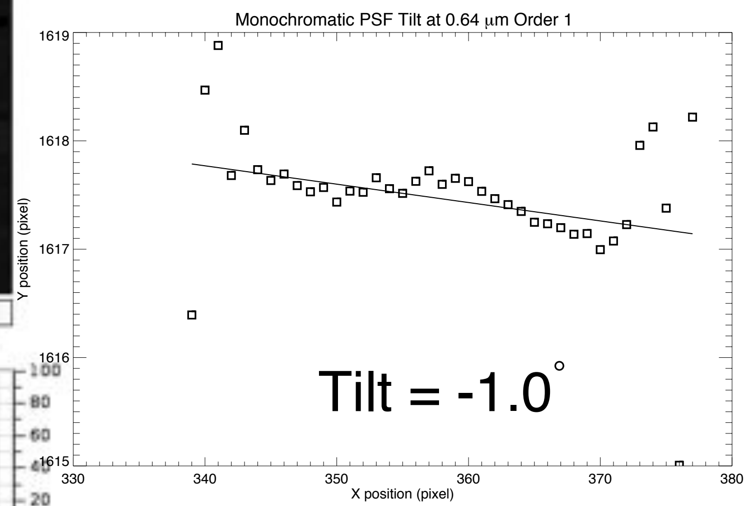
- Good correlation between data and simulations

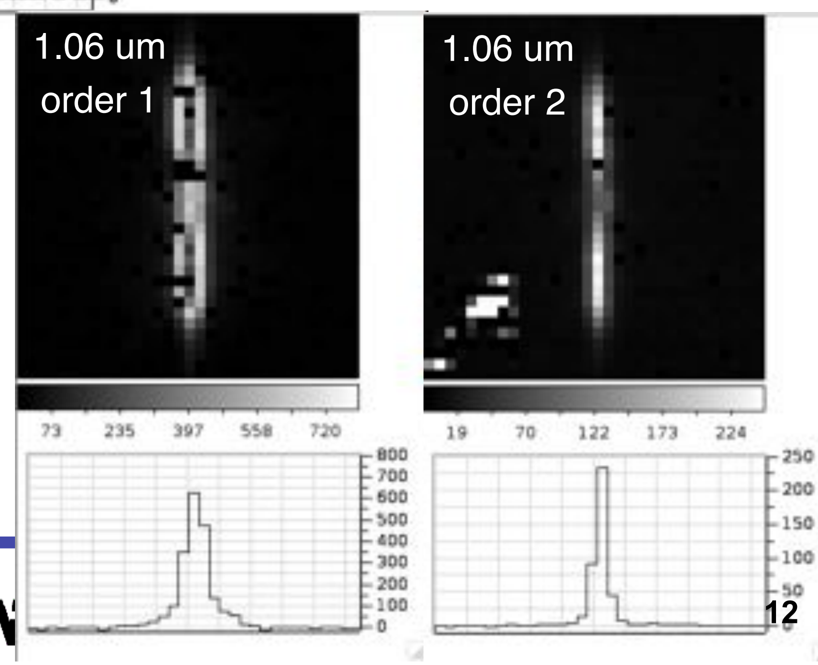
Inter-order contamination



Monochromatic PSFs (CV1RR data)







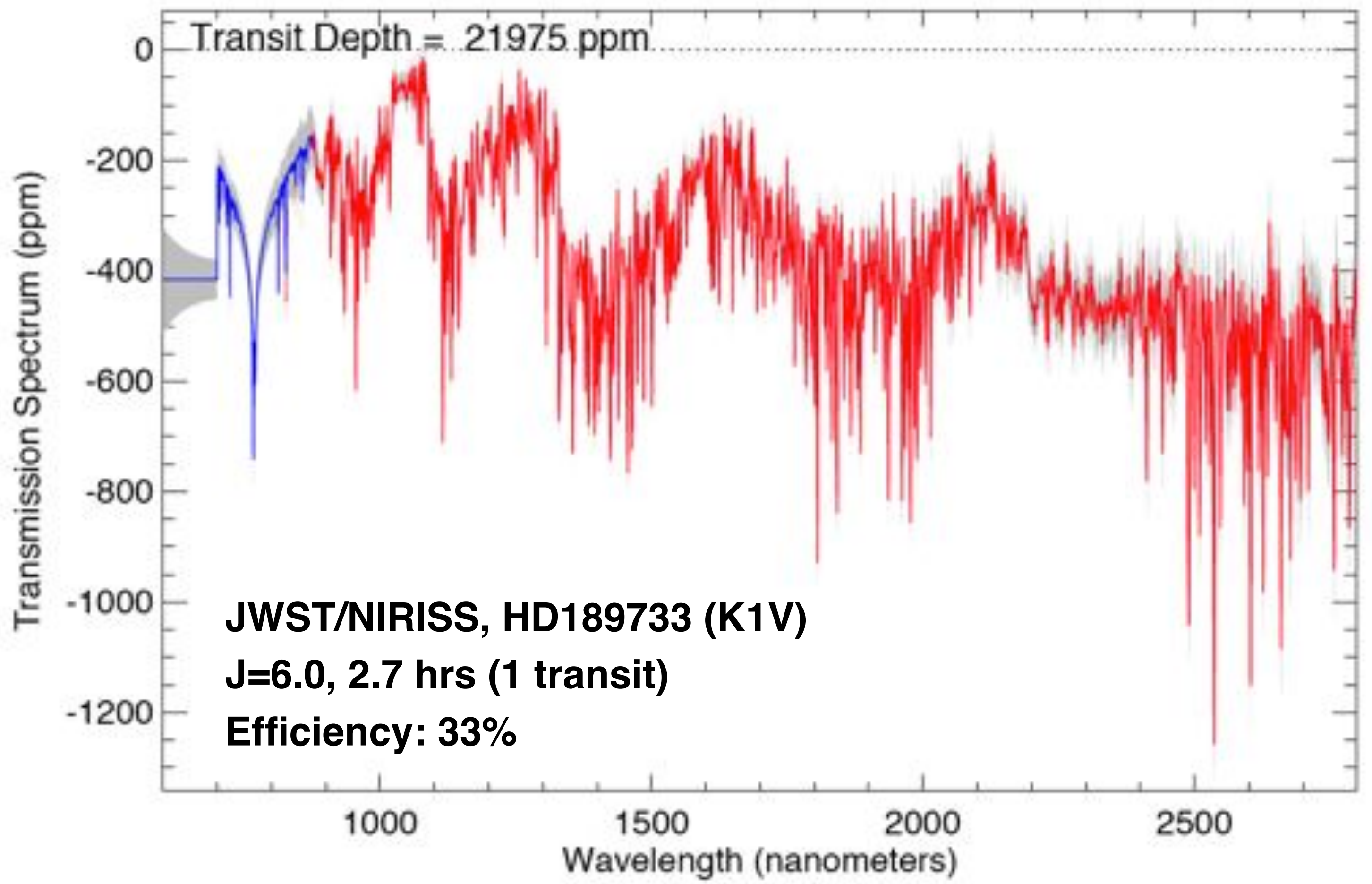
NIRISS grism is designed to have a PSF slanted by ~3° to mitigate undersampling problems.

Target acquisition

- Configure for full field mode
- Use NRM mask + F480 + 64x64 subarray
- Peak up on « hot spot »
- Magnitude limits: ~2.7
- Move GR700XD in place
- Repeatability of the pupil wheel: ~0.15 degrees
  - Translate into trace rotation by same amout, ~3-4 pixels from both ends of te spectral trace
  - To be tested at CV3.

Transit Spectroscopy Simulations (photon-noise limited)

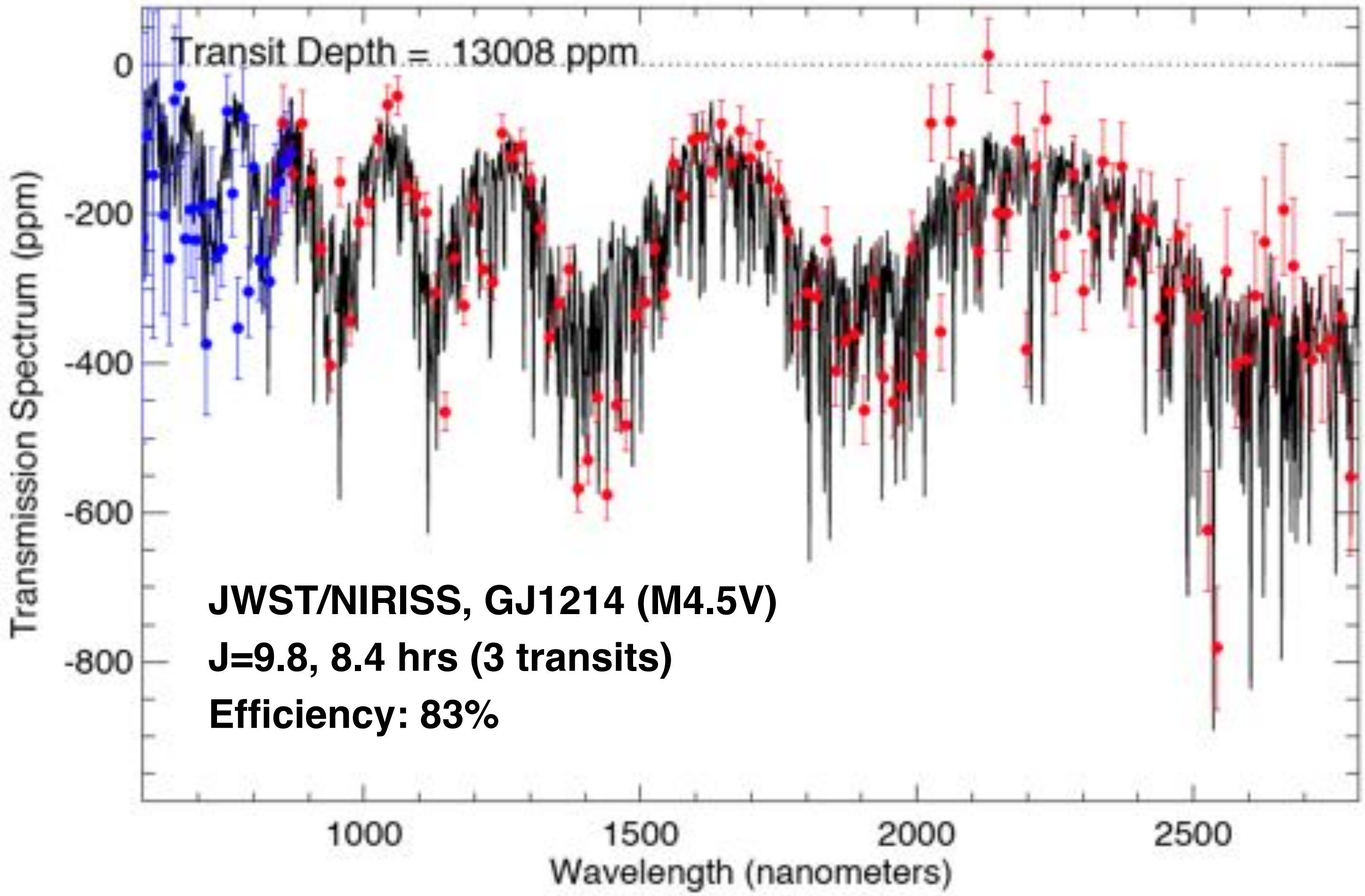
Hot Jupiter



Noise level: 25 – 100 ppm

Model courtesy of J. Fortney

Super-Earth (GJ1214: water-rich)



Noise level: 25 – 100 ppm

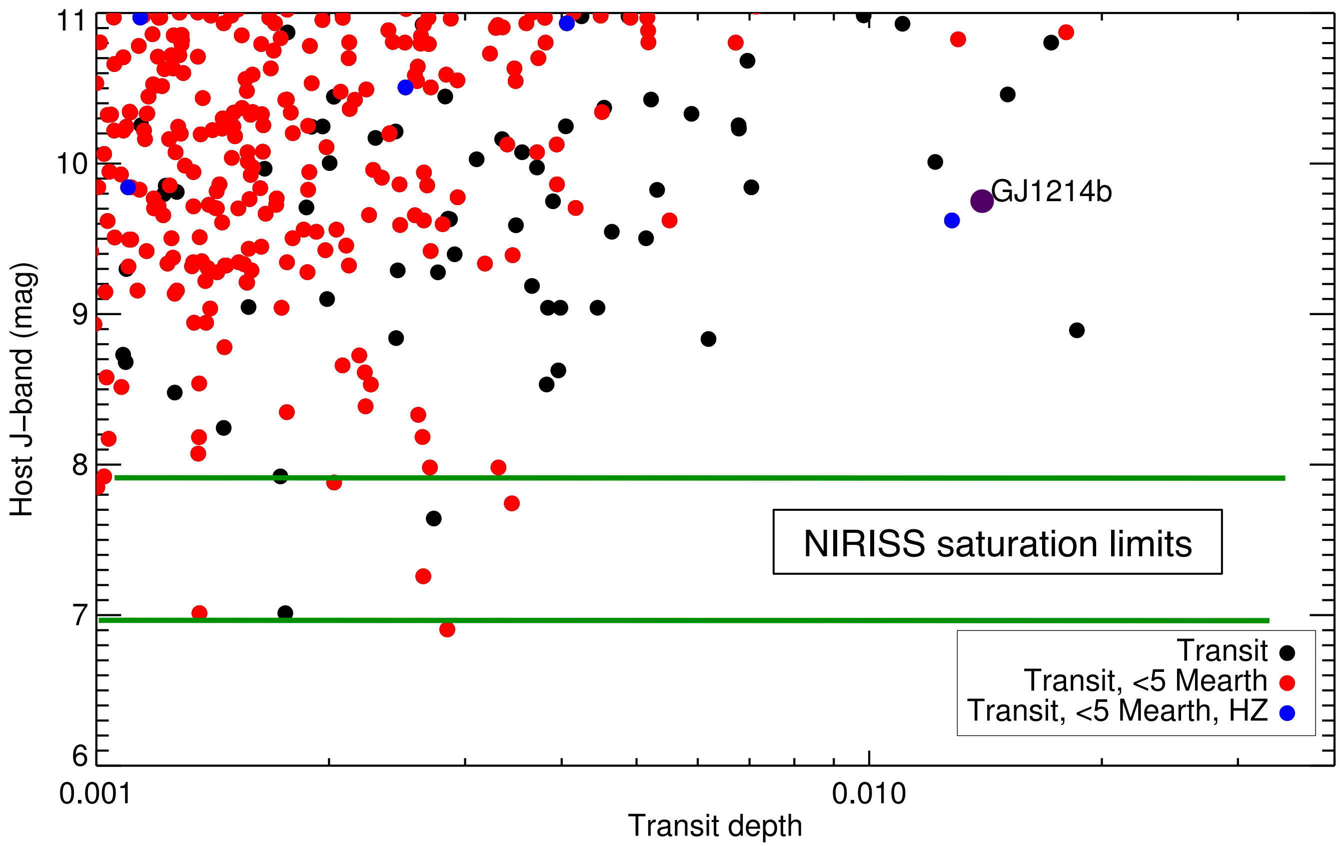
Model courtesy of J. Fortney

TESS yield

Simulation methodology

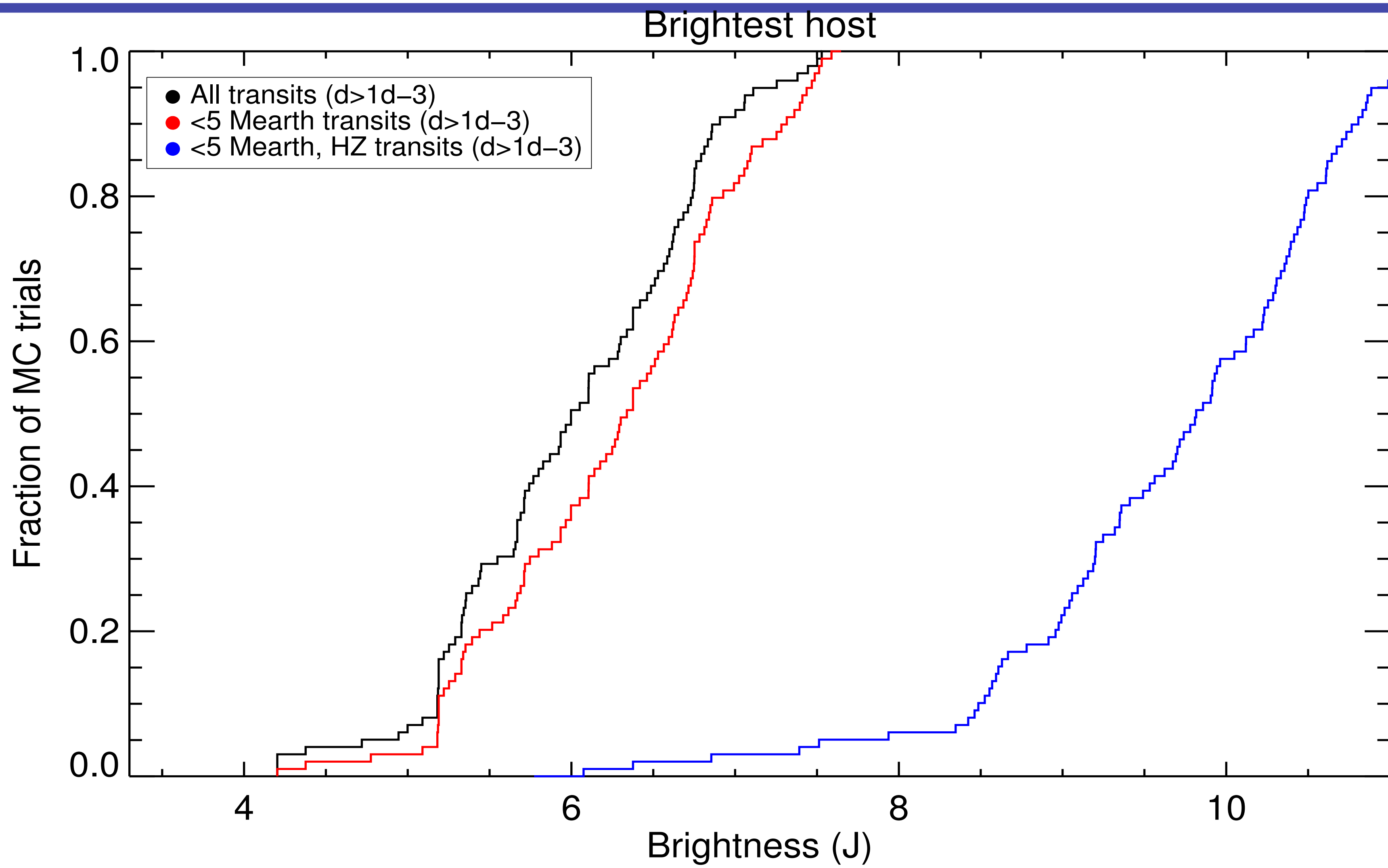
- Take all known M dwarfs within 10 pc
- Expand sample isotropically with same density and properties (sp types, abs mags, etc.) out to 50 pc
- Take 2MASS mags
- Planet statistics follows Bonfils et al. 2012
  - Eta_Earth~0.5
- Extrapolated at low masses
  - log normal distribution centered at 1 M_Earth
- Consider only those with transit depth > 0.1%

TESS synthetic population

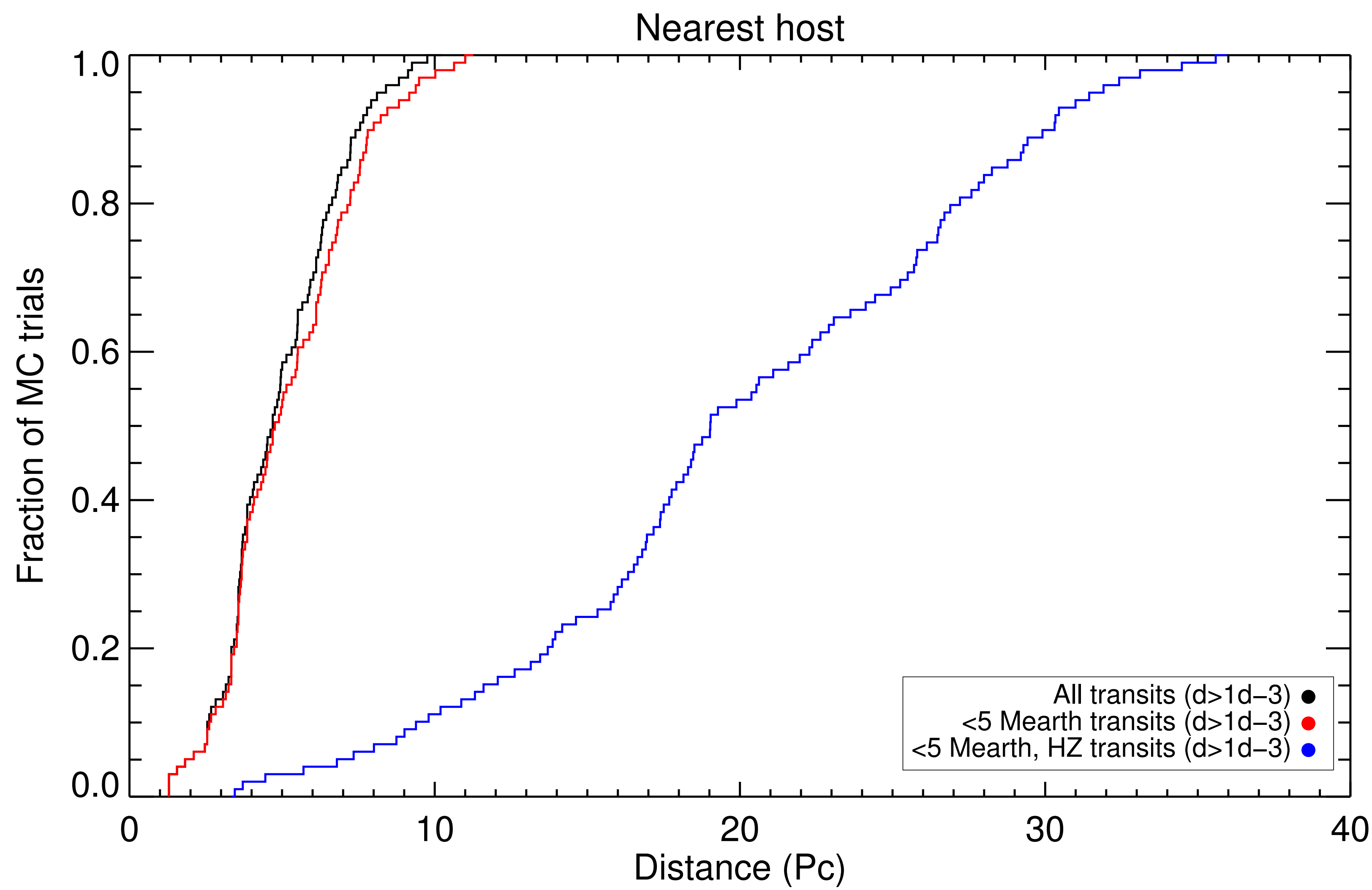


- Only 1-2 objects similar to GJ1214b
- Most transits at a few 0.1% depth, mostly early Ms with larger radii and lower-mass planets

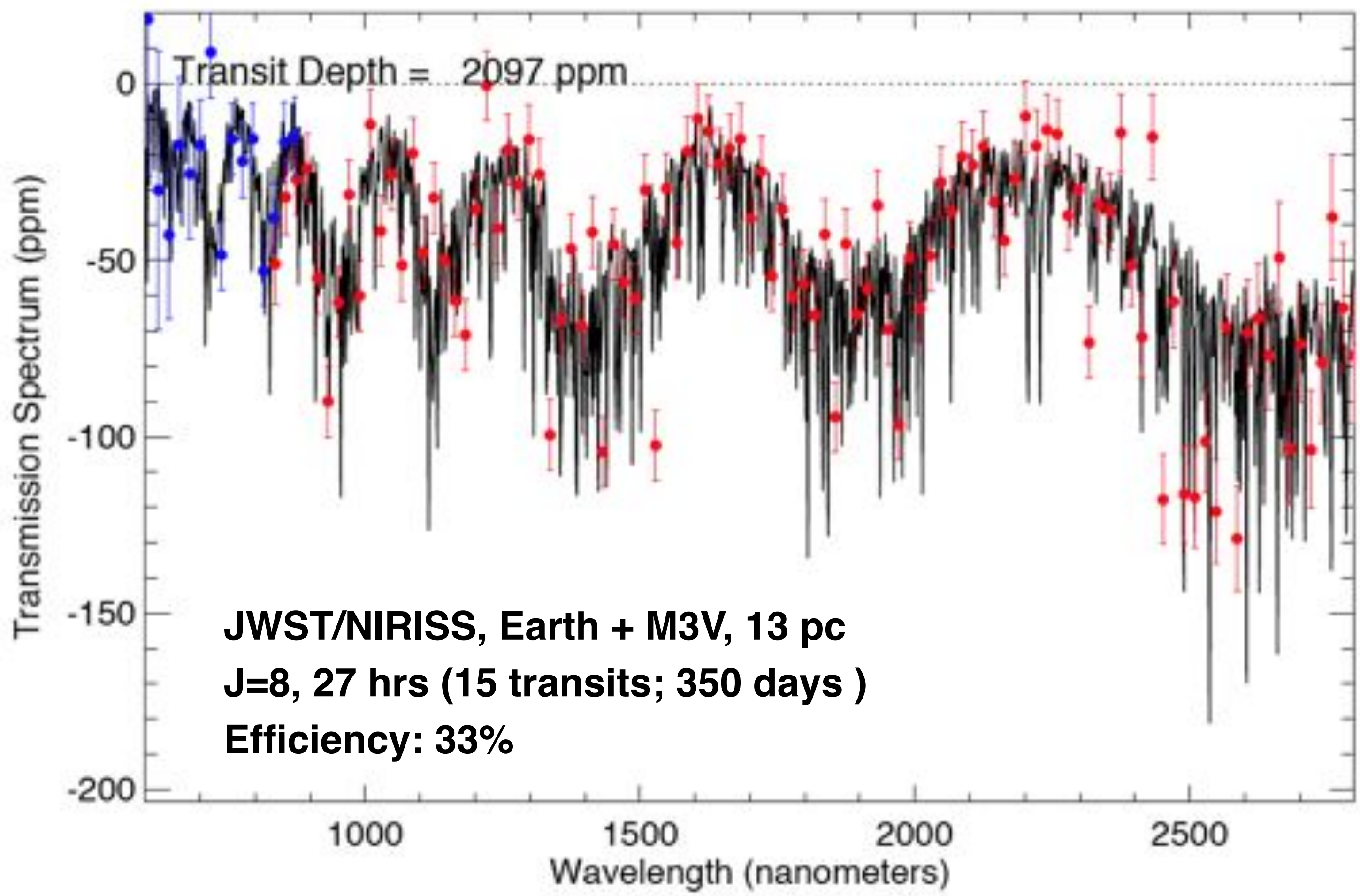
Most likely *brightest* host: J~6



Most likely distance

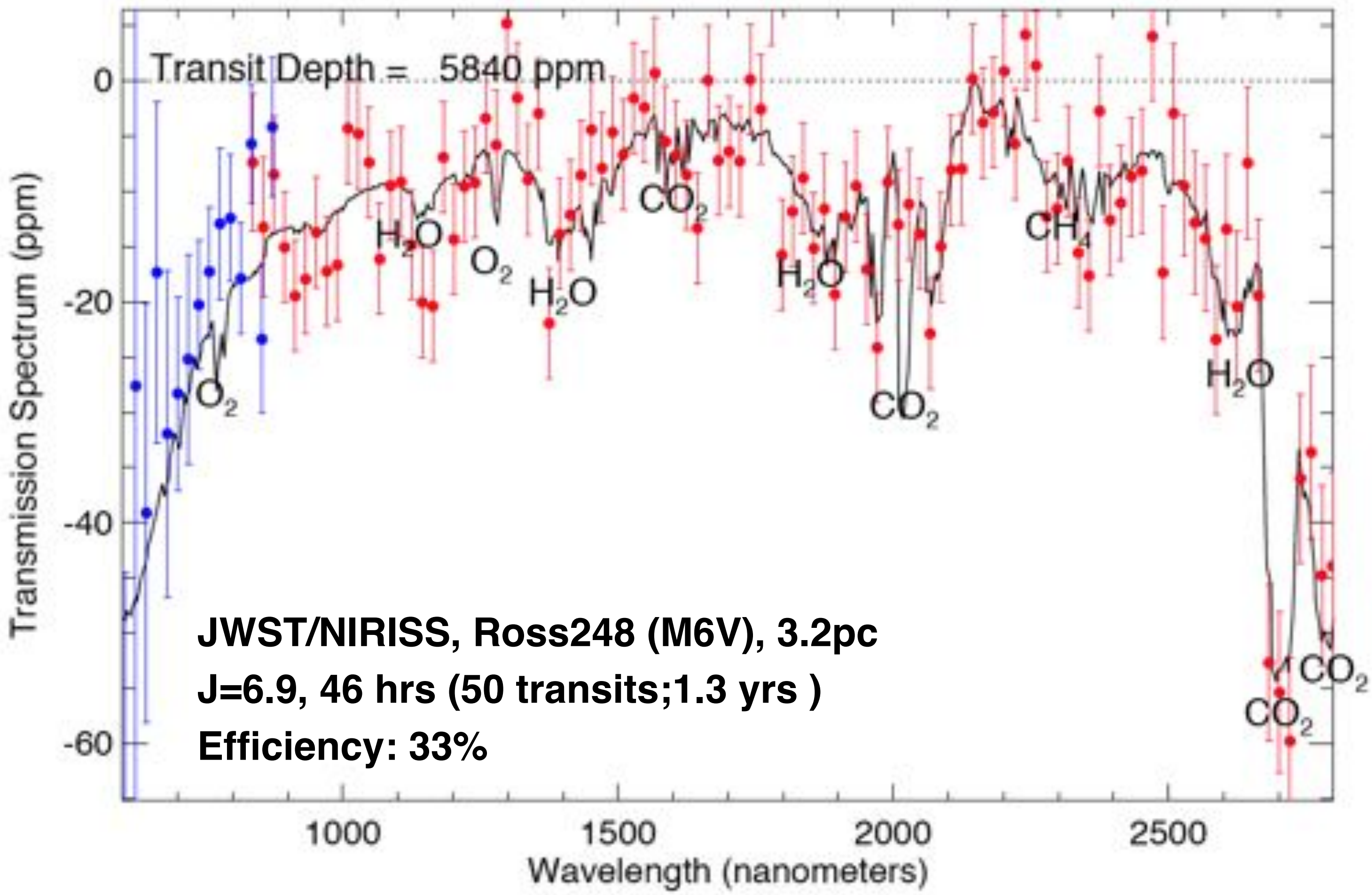


Earth size HZ water-world + M3V



Noise level: 10 – 20 ppm

Earth 2.0 around Ross248 (M6V)

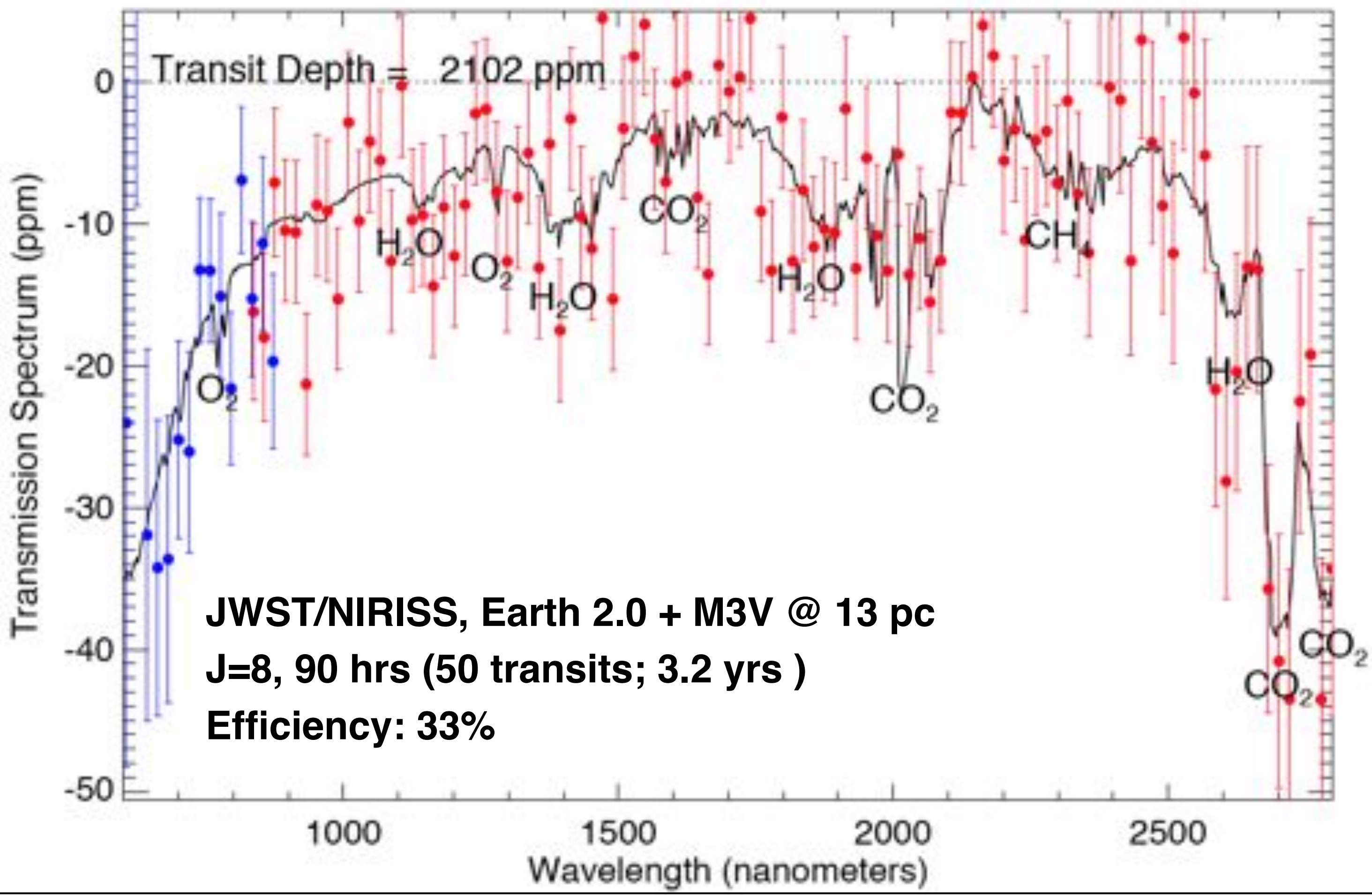


Noise level: 5 – 10 ppm

Model courtesy of L. Kaltenegger

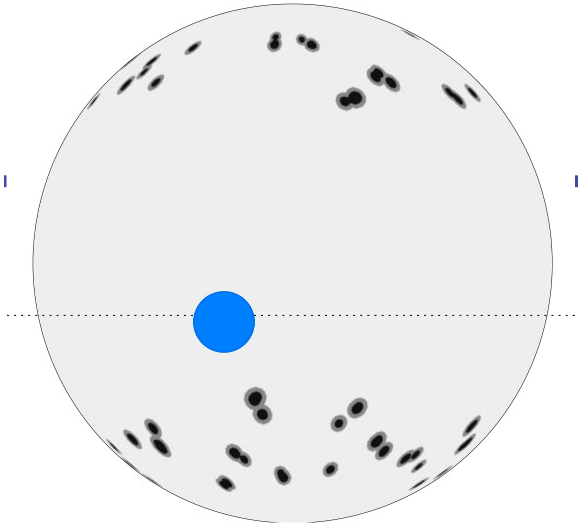
Earth 2.0 + M3V @ 13 pc (likely TESS HZ planet)

$$1\,R_{\oplus}, \rho = \rho_{\oplus}/2$$

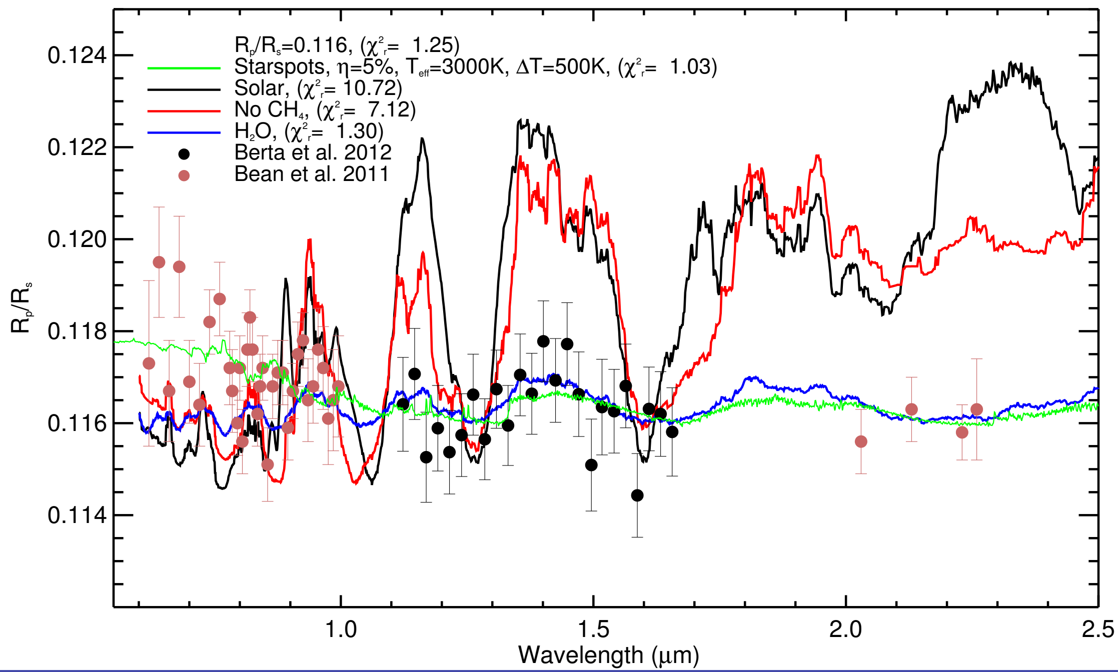


Characterization of habitable Earths possible with a noise floor of 5-10 ppm.

Water vapor from unocculted star spots. GJ1614 as a test case.



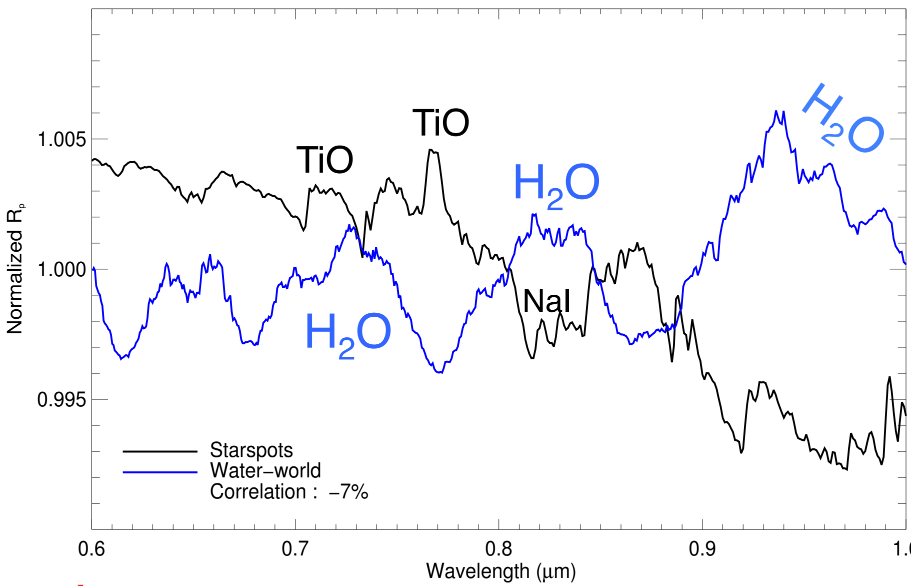
- If GJ1214 is spotted over 5% of its surface and GJ1214b happens to transit a spot-free area …
- Out-of-transit spectrum : 95% star, 5% spots
- In-transit spectrum: 93.6% star, 5% spots
- Spot spectra, 500 K cooler than photosphere, has significantly deeper water bands and a redder overall SED.
- In-transit/out-of-transit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

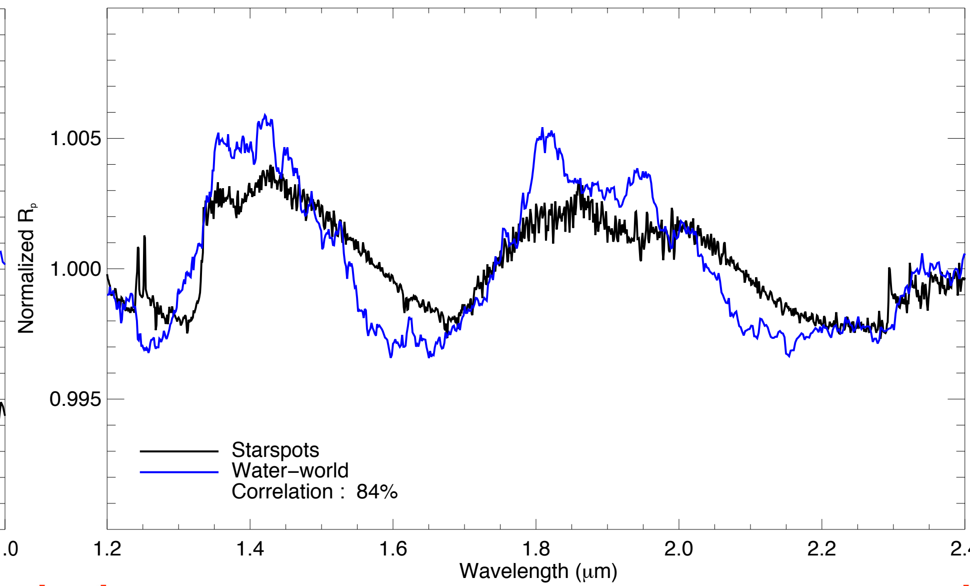


Star spot-induced transit spectrum fits data better than any planet atmosphere model!

Artigau et al, in prep.

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





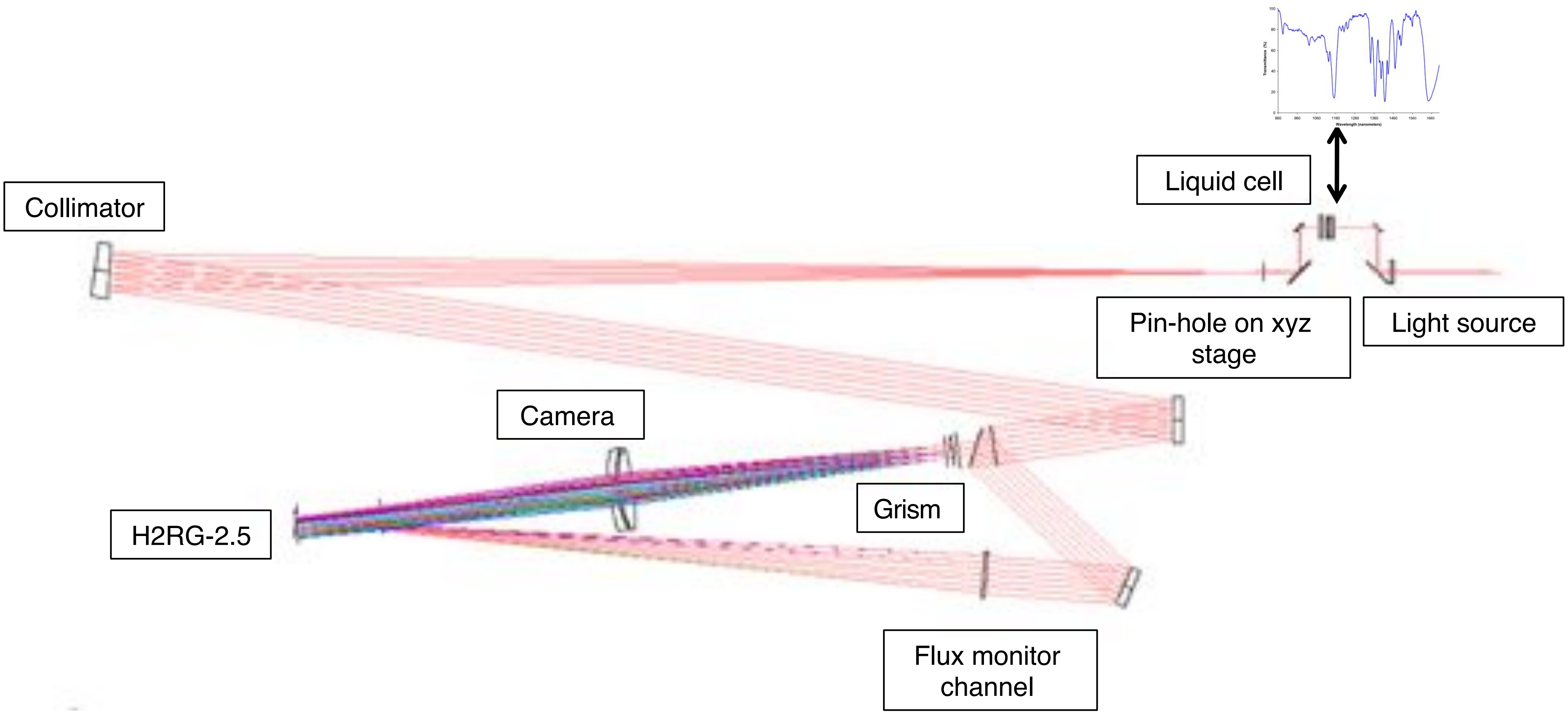
- TiO, NaI, FeH dominate the star spot-induced spectrum.
- Water absorption dominates the planetary features.
- Good spectral resolution needed to detect some features (e.g. NaI, KI)

- 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).

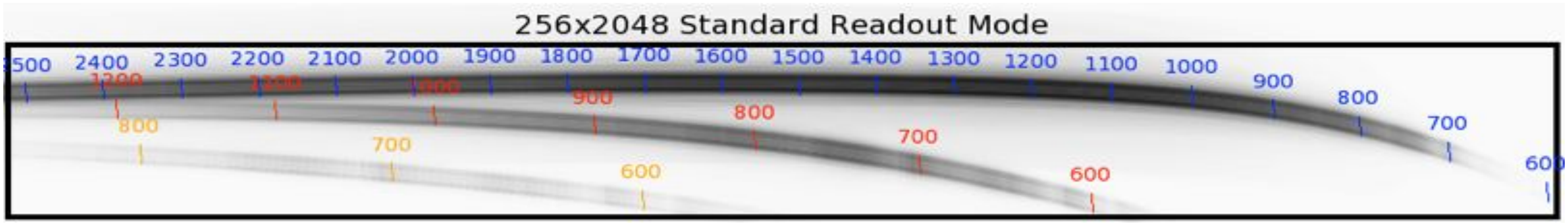
On-going work

- 2d simulations for data pipeline development
- NIRISS Optical Simulator
  - Optical test bed to simulate NIRISS optical system
  - ASIC-driven H2RG-2.5 um detector + flight software emulator
  - Wavelength range: 0.9-1.9 μm
  - Include GR700XD grism w/o weak lens
  - NOS will have the capability to simulate multi-visit transit observations (liquid cell).
  - Optical design completed.
  - Procurement completed
  - Operational in 2015.

NOS concept/optical design



Supplementary material



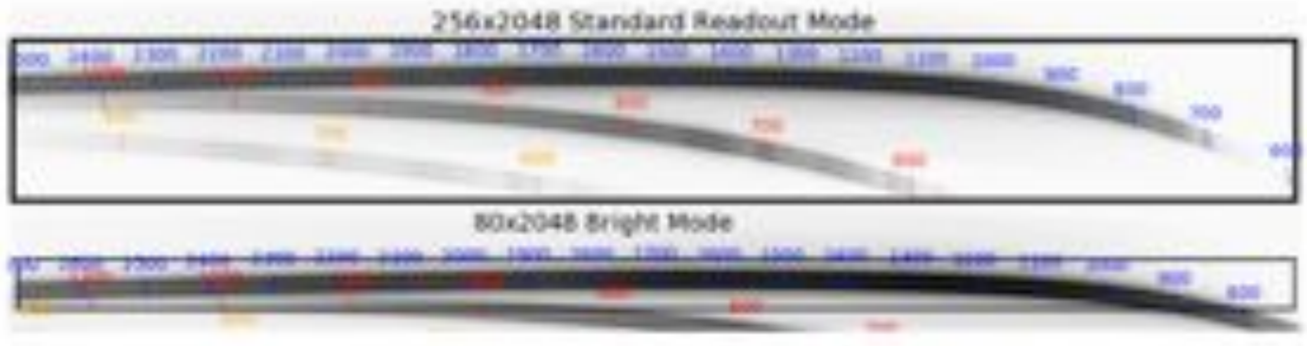
VII. B.
Instrument Modes for Transits - NIRISS

Loïc Albert – NIRISS Instrument Scientist
Université de Montréal

NIRISS Fun Facts

The NIRISS Single Object Slitless Spectroscopy (SOSS) Mode

"A slitless cross-dispersed grism used simultaneously in orders 1 and 2 with a weak cylindrical lens producing traces defocussed along the spatial direction."



Spectral Range: 0.6-2.5 micron (1st order) + 0.6-1.25 micron (2nd order)
Resolving Power: R=700-1000 (1 nm/pixel in order 1, 0.5 nm/pixel in order 2)
Trace Width: 20 pixels
Pixel Scale: 0.065 arcsec/pixel
Blaze Wavelength: 1.25 microns (m=1) and 0.68 microns (m=2)
Throughput (BOL): ~20% (OTE+NIRISS+Detector)
Trace Position Repeatability Between Sequences: ~3-4 pixels
Second Order Contamination On First Order Red End: 5×10^{-4}

High gain mode not Supported yet

Readout Mode	Standard Mode	Full Array Mode	Bright Mode	Very Bright Mode
Sub-Array	256x2048	2048x2048	80x2048	80x2048
Amplifiers Used	1	4	1	1
Saturation Limiting Magnitude	J=8.1	J=9.2	J~6.9	J~5.9
Full Well Depth	70 000 e-	70 000 e-	70 000 e-	180 000 e-
Frame Time	5.491 sec	10.737 sec	1.885 sec	1.885 sec
Observing Duty Cycle	(Reset-Read-Read) 16.47 sec	(Reset-Reset-Read-Read) 42.95 sec (yes 2 resets!)	(Reset-Read-Read) 5.66 sec	(Reset-Read-Read) 5.66 sec

Chas's Assignement

Tried...

- Phase Curve of Teegarden's Star
- TESS-01
- HD189733

Star Name	Observation Goal	Spectral Type	Vmag	Kmag	[4.5]	Rplanet (RJup)	Rstar (Rsun)	Depth (ppm)	Period (d)	Approx Transit Duration (hr)	Approx Observation duration (hr)	Planet Teff (K)
HD209458	Tomographic imaging ingress/egress	F8	7.6	6.3	6.2	1.38	1.16	11,900	3.5	3	9	1450
HD189733	Emission Spectrum	G0	7.7	5.5	5.3	1.14	1.60	4,300	2.2	2	6	1200
KOI-02311.01	Confirmation, precision light curve	G2	12.6	11.0	10.8	0.10	1.00	106	192	5	15	310
HD80606	Periastron light curve	G5	9.0	7.3	7.3	0.98	0.98	8,400	111	12	60	400-1500
TESS-001	Super Earth Spectrum	M2	10.0	5.5	5.3	0.13	0.44	700	30	3	10	300
Teegarden's Star	Super Earth Phase Curve	M6.5	15.1	7.6		0.13	0.14	7,200	12.0	1	300	250-270
Gliese 1214	Super Earth Albedo Spectrum	M4.5	14.7	8.8	8.4	0.20	0.18	13	1.6	1	3	550
GJ 436	Hot Neptune 2D Dayside Map	M1	10.7	6.1	5.8	0.38	0.44	400	2.6	1	3	700
Kepler-7	Hot Jupiter Silicate Cloud Phase curve	G1	13.4	11.5	11.3	1.50	1.80	2,000	4.9	5	120	1400

TESS-01

Star Name	Observation Goal	Spectral Type	Vmag	Kmag	[4.5]	Rplanet (RJup)	Rstar (Rsun)	Depth (ppm)	Period (d)	Approx Transit Duration (hr)	Approx Observation duration (hr)	Planet Teff (K)
HD209458	Tomographic imaging ingress/egress	F8	7.6	6.3	6.2	1.38	1.16	11,900	3.5	3	9	1450
HD189733	Emission Spectrum	G0	7.7	5.5	5.3	1.14	1.60	4,300	2.2	2	6	1200
KOI-02311.01	Confirmation, precision light curve	G2	12.6	11.0	10.8	0.10	1.00	106	192	5	15	310
HD80606	Periastron light curve	G5	9.0	7.3	7.3	0.98	0.98	8,400	111	12	60	400-1500
TESS-001	Super Earth Spectrum	M2	10.0	5.5	5.3	0.13	0.44	700	30	3	10	300
Teegarden's Star	Super Earth Phase Curve	M6.5	15.1	7.6		0.13	0.14	7,200	12.0	1	300	250-270
Gliese 1214	Super Earth Albedo Spectrum	M4.5	14.7	8.8	8.4	0.20	0.18	13	1.6	1	3	550
GJ 436	Hot Neptune 2D Dayside Map	M1	10.7	6.1	5.8	0.38	0.44	400	2.6	1	3	700
Kepler-7	Hot Jupiter Silicate Cloud Phase curve	G1	13.4	11.5	11.3	1.50	1.80	2,000	4.9	5	120	1400

- 1.37 R_{Earth}
- Scale height ratio $H=R^2/M=0.73$ (assumes ρ_{Earth}) – weaker features than Earth
- Transit depth: 800 ppm (not 700 ppm)

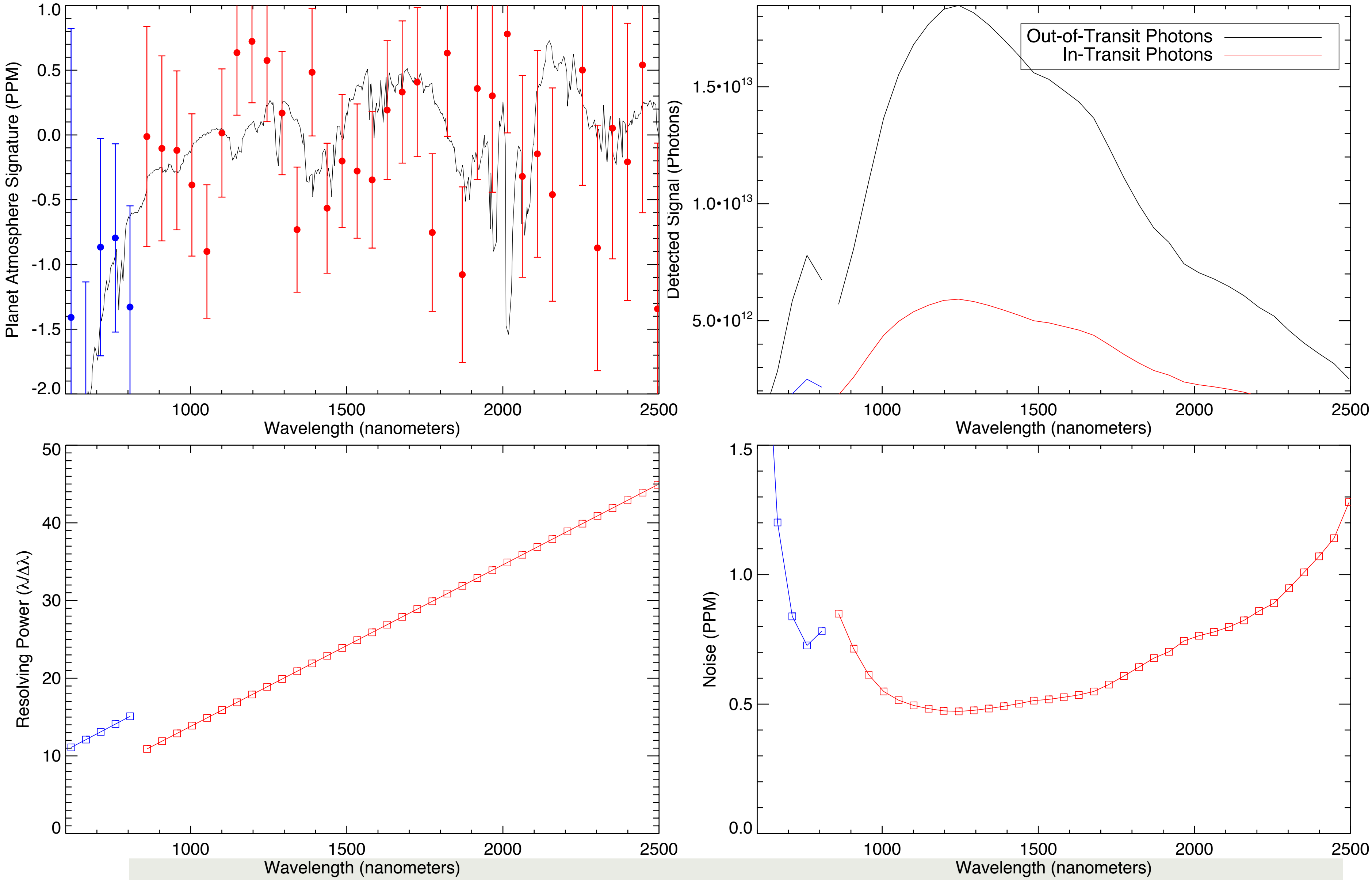
Simulation methodology

- **Photon-Noise Limited**
- **1-D** Simulation (2-D in the works)
- Star Model Atmospheres**: BT-Settl**
- Use **Measured Throughputs** for the Observatory and Instrument (OTE+2 TMAs + Grism Blaze) – no conservative fudge factor.
- Assume a Full-Well Depth of **70 000 e-** and Use the Measured Spectral Trace Profile for Saturation Calculations
- Assume a CDS **(reset-read-read) Minimum Duty Cycle** which Yields a Photon Statistics of 1/3 Efficiency in this Limiting Case
- Use Realistic Read-Out Schemes (Nbr. of Reads in a Ramp Set by Saturation Limit)
- For Transits/Secondary Eclipses, Use **Out-of-Transit/In-Transit Integration Time Ratio of 2X**
- Use **Habitable Zone Definition** of Jones 2010 eq. 1 and 2 – Use the Mean
- **Teff-Radius-Mass Empirical Relation** from Boyajian 2012

TESS-01 Input Parameters

System: TESS-01
Planet Model: ./PlanetModels/Earth_kaltenegger2009.txt
Star Model: ./InputSpectra/lte036-4.5-0.0.BT-Settl.fits
Star J magnitude: 6.33 (K=5.5) (per assignment)
Grism: LLNL_Coated
Average Transit Depth: 0.08%
Efficiency (Integration Time/Elapsed Time): 50.0%
Readout Scheme: 80 x 2048 *** WIth gain boosted to full well depth of 180000 e- otherwise saturated with regular 70000 e- full well ***
N reads per ramp: 3
N Ramps During Transit: 76554.9
N Ramps Out of Transit: 238726.8
Integration Time During Transit (hours) = 80.2
Integration Time Out of Transit (hours) = 250.0
Nbr of Transits = 50
Transit Duration (hours) = 3.21
Orbital Period (days) = 30.00 (per assignment)
Pixel Binning Order 1 = 50
Pixel Binning Order 2 = 100
Planet Radius = 1.37 Earth
Planet Mass = 2.58 Earth
Earth Planet Atmosphere of Kalteneger 2009 with H scaled as R^2/M

TESS-01



Planet Atmosphere Signature (PPM)
Wavelength (nanometers)
Detected Signal (Photons)
Out-of-Transit Photons
In-Transit Photons
Resolving Power (λ/Δλ)
Noise (PPM)

TESS-01

- Sub PPM signal !!! Not realistic to do with NIRISS for an M2 primary
- However, an Earth-twin around an ~M6 primary (T_{eff}=3200K, R=0.18) of J=7 offers slightly better hope

Teegarden's Star Phase Function

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HD209458	Tomographic imaging ingress/egress	F8	7.6	6.3	6.2	1.38	1.16	11,900	3.5	3	9	1450
HD189733	Emission Spectrum	G0	7.7	5.5	5.3	1.14	1.60	4,300	2.2	2	6	1200
KOI-02311.01	Confirmation, precision light curve	G2	12.6	11.0	10.8	0.10	1.00	106	192	5	15	310
HD80606	Periastron light curve	G5	9.0	7.3	7.3	0.98	0.98	8,400	111	12	60	400-1500
TESS-001	Super Earth Spectrum	M2	10.0	5.5	5.3	0.13	0.44	700	30	3	10	300
Teegarden's Star	Super Earth Phase Curve	M6.5	15.1	7.6		0.13	0.14	7,200	12.0	1	300	250-270
Gliese 1214	Super Earth Albedo Spectrum	M4.5	14.7	8.8	8.4	0.20	0.18	13	1.6	1	3	550
GJ 436	Hot Neptune 2D Dayside Map	M1	10.7	6.1	5.8	0.38	0.44	400	2.6	1	3	700
Kepler-7	Hot Jupiter Silicate Cloud Phase curve	G1	13.4	11.5	11.3	1.50	1.80	2,000	4.9	5	120	1400

- 1.43 R_{Earth} (0.13 $R_{Jupiter}$)
- Depth = 1 ppm
- Following Results are for 100 full orbits!

Teegarden's Star Input Parameters

System: TeegardenPhaseCurve
Planet Model: ./PlanetModels/Earthshine_Turnbull/F7_alldata.txt
Star Model: ./InputSpectra/lte028-4.5-0.0.BT-Settl.fits
Star J magnitude: 8.39
Star Radius: 0.14 Sun Radii
Star Mass: 0.10 Sun Mass
Grism: LLNL_Coated
Planet Radius: 1.43 Earth Radii
Semi-Major Axis: 0.049 AU
Efficiency (Integration Time/Elapsed Time): 33.3%
Readout Scheme: 256 x 2048
N Phase Bins: 3
N reads per ramp: 2
N Ramps per Phase Bin: 2226766.2
Integration Time Per Phase Bin (hours) = 3396.4
Orbital Period (days) = 12.74
N Periods Observed: 100 !!!
Pixel Binning Order 1 = 200
Pixel Binning Order 2 = 300

Other Parameters

- 2800 K
- Phase contrast: 1 ppm
- No Slewing Overheads
- No Observability Constraints

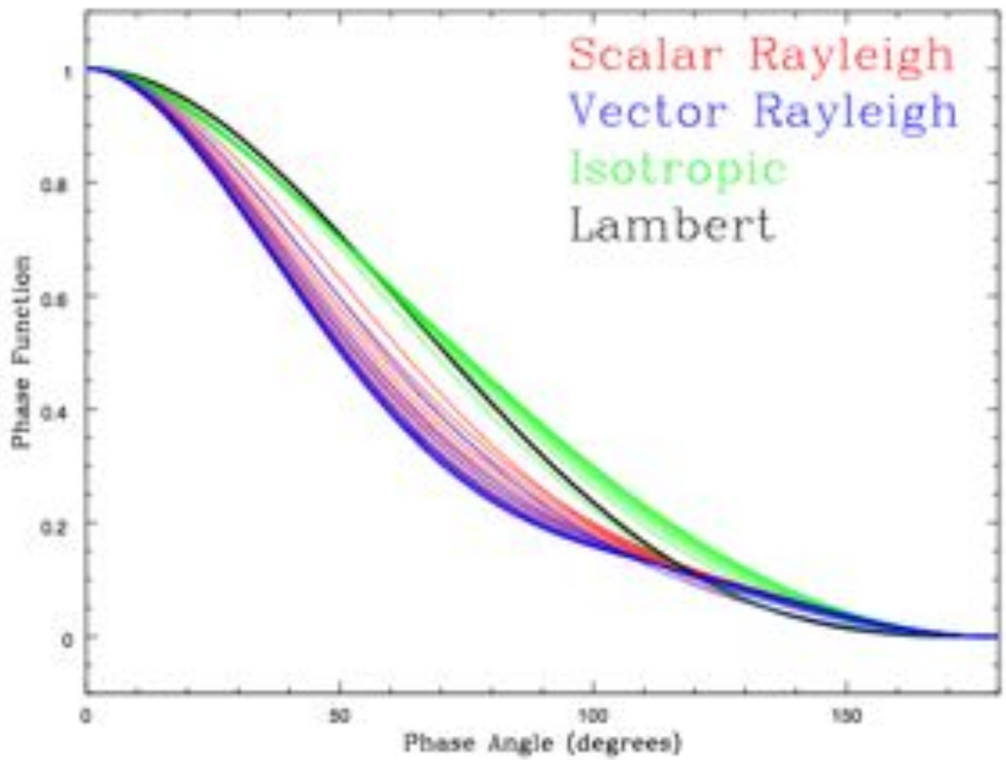
Teegarden's Star Phase Function

- Flux ratio given by Eqn 3 of Madhusudhan & Burrows 2011
- Use Turnbull 2006 (fig 7) Earth Shine Reflection Spectrum for the Geometric Albedo (A_g)
- Assume Lambertian Scattering
- Photon-Noise Limited Simulation

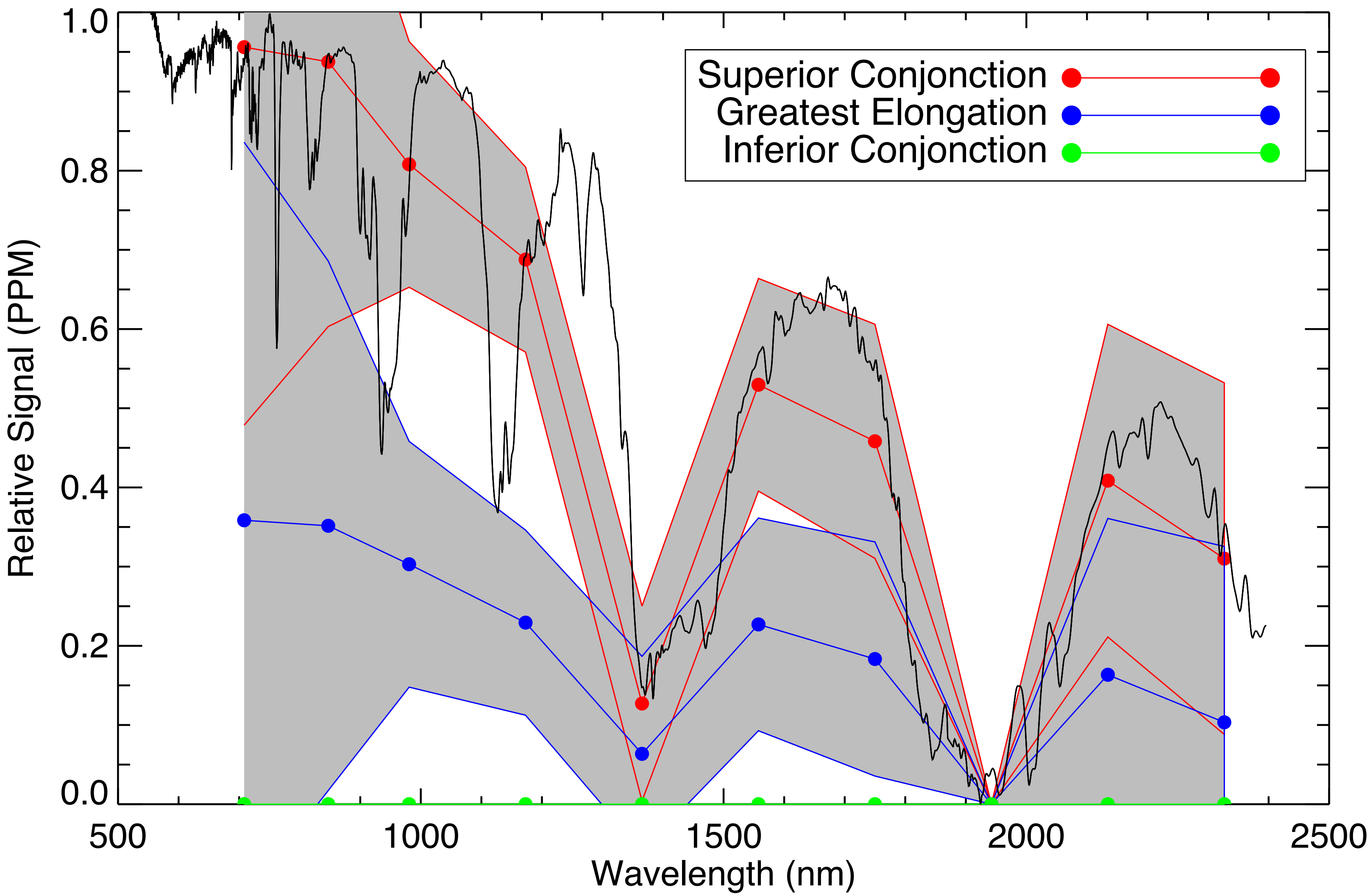
The quantity $\Phi(\alpha) = j(\alpha)/j(0)$ is the classical phase function[5]. The planet-star flux ratio observed at Earth as a function of the phase angle is given by

$$\frac{F_p}{F_\star} = A_g \left(\frac{R_p}{a}\right)^2 \Phi(\alpha), \tag{3}$$

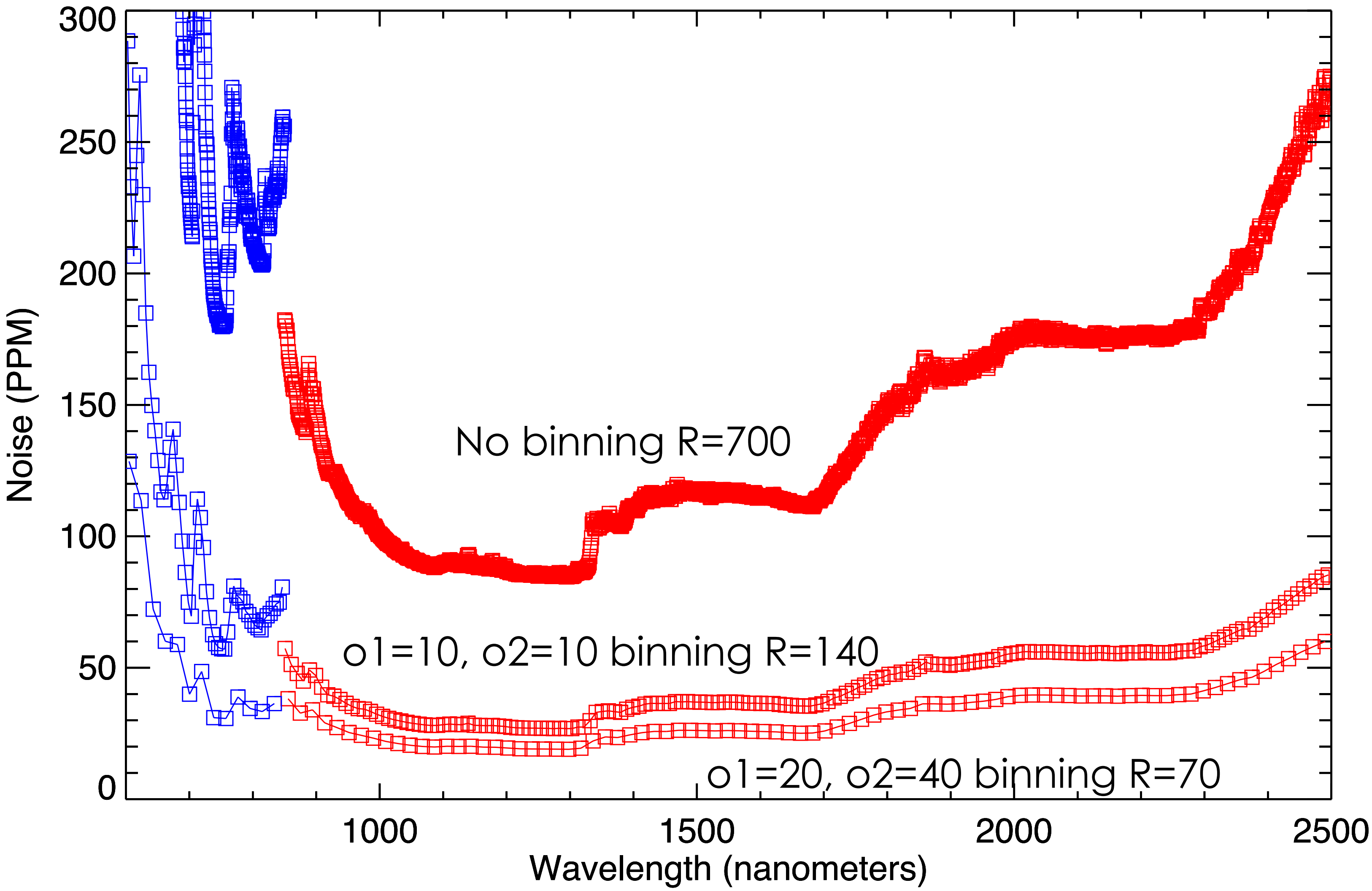
where R_p is the planetary radius and a is the orbital separation.



Teegarden's Star Phase Curve
(grey regions represent 1-sigma noise)



SNR Curves with 6-hr Clock Time



SNR with 6-hr Clock Time (excluding slew overheads)

Mag	Read out Mode	Efficiency (NReads)	PPM Floor @ 1.3 microns & Pixel binning in orders 1 and 2		
			no binning	o1=10, o2=10	o1=20, o2=40
			R=700	R=140	R=70
J=7	Mode: 80x2048 (1000-2600 nm)	33% (2)	54	17	12
J=8	Mode: 256x2048 (600-2500 nm)	33% (2)	85	27	19
J=9	Mode: 256x2048 (600-2500 nm)	67% (5)	95	30	21
J=10	Mode: 256x2048 (600-2500 nm)	87% (13)	132	42	30