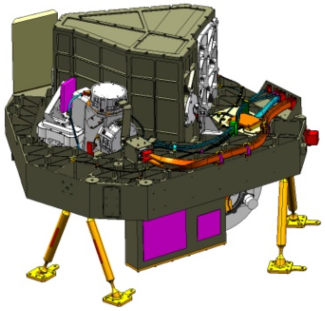
Transit Spectroscopy with NIRISS

René Doyon, Université de Montréal,
FGS/NIRISS PI



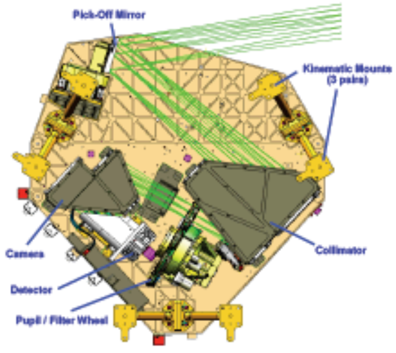
JPL Transit Workshop
12 March 2014

Collaborators

- David Lafrenière, UdeM (NIRISS exoplanet team lead)
- Loic Abert, UdeM
- Etienne Artigau, UdeM
- Mike Meyer, ETH, Switzerland
- Ray Jayawardhana, York
- Lisa Kaltenegger, Cornell

The Near-Infrared Imager and Slitless Spectrograph (NIRISS)

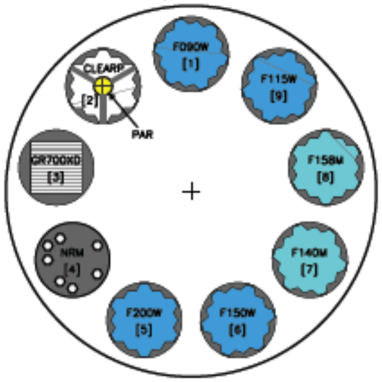
Optical Layout



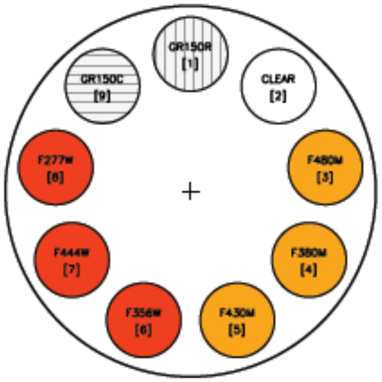
At a glance:

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

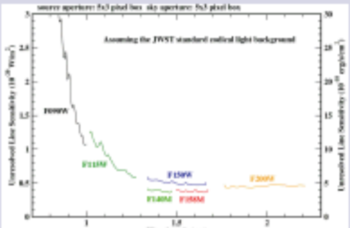
Point-Source Sensitivity:
S/N=10 in 10 ks

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/cm^2 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):

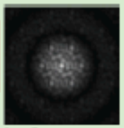
Subarray	**1 pre-amp**	**4 pre-amps**
2048 × 256	8.2	6.7
2048 × 80	6.9	5.5

Aperture Masking Interferometry

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

Mask

Michelson:
δθ = 0.5 λ / D



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: ~2×10^{-5} (S/N~5)
Separations: 70 – 400 mas

Fourier Transform

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

NIRISS Pocket Guide v1.0 (2013 May)

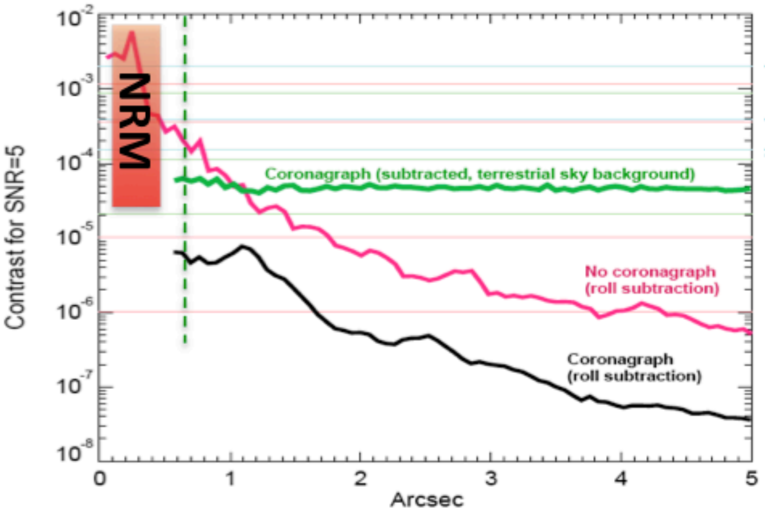
http://www.stsci.edu/jwst/instruments/niriss

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

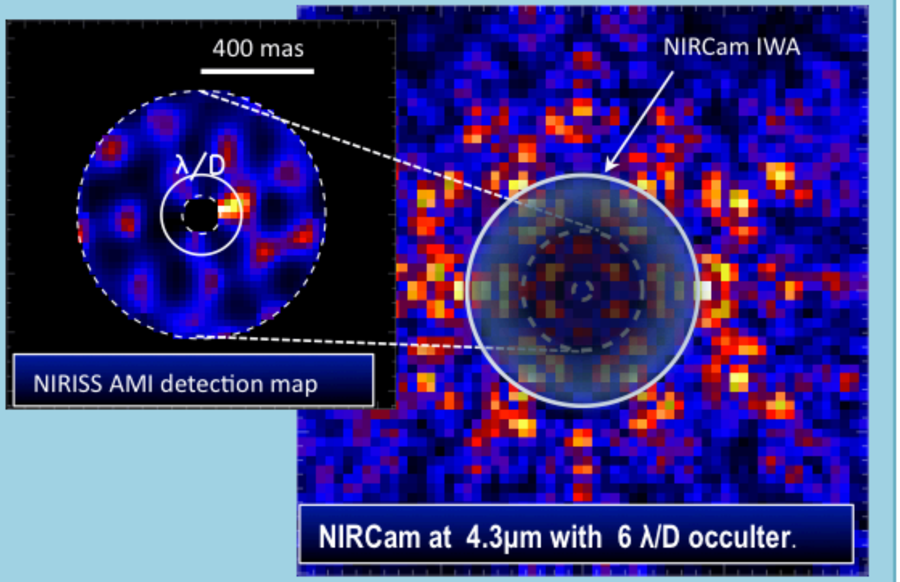
Available in 3 broad-band filters: 3.8, 4.3, 4.8 um over which NIRISS is Nyquist sampled

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

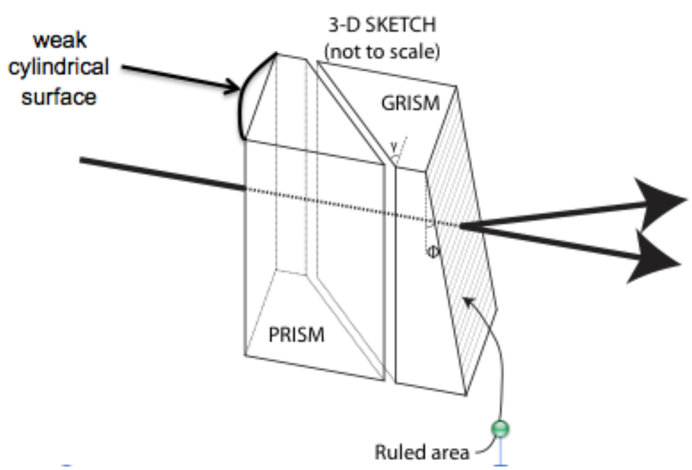


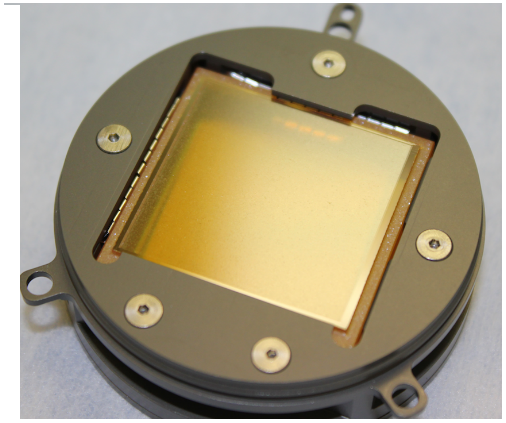
Simulated companion above has contrast of 10 mag at a separation of 130 mas

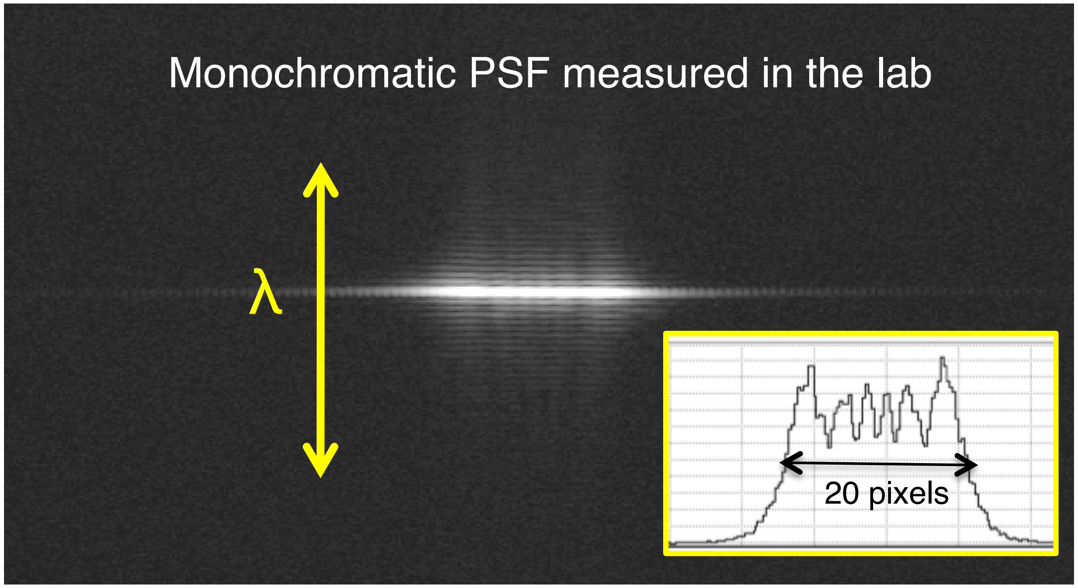
Equivalent to a 1-2 M_{Jup} planet at ~1 AU of a 50 Myr-old M0V dwarf at a distance of 10 pc from the Sun.

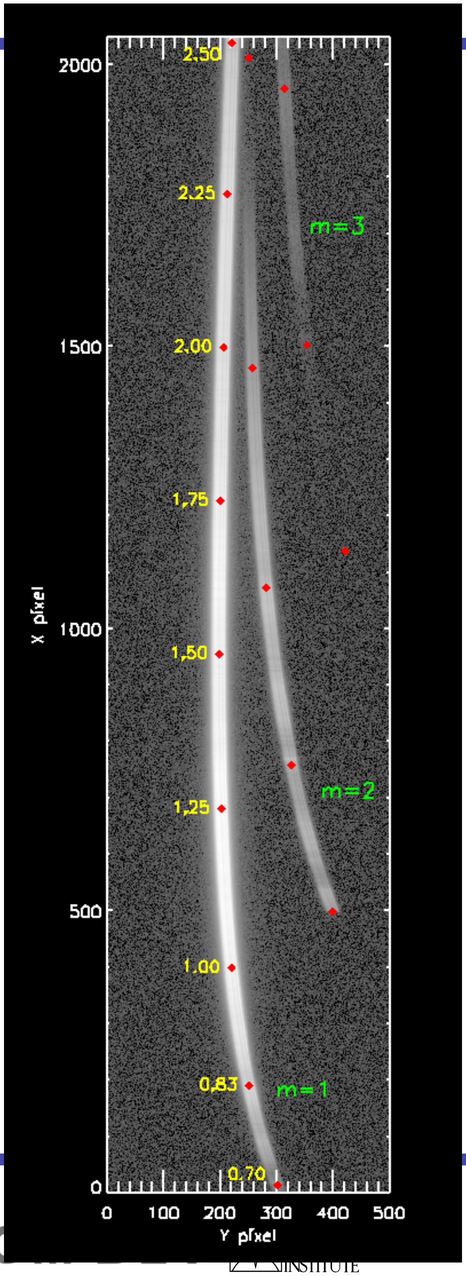
Above simulation corresponds to approximately 3 hours of observing time

SOSS mode implementation

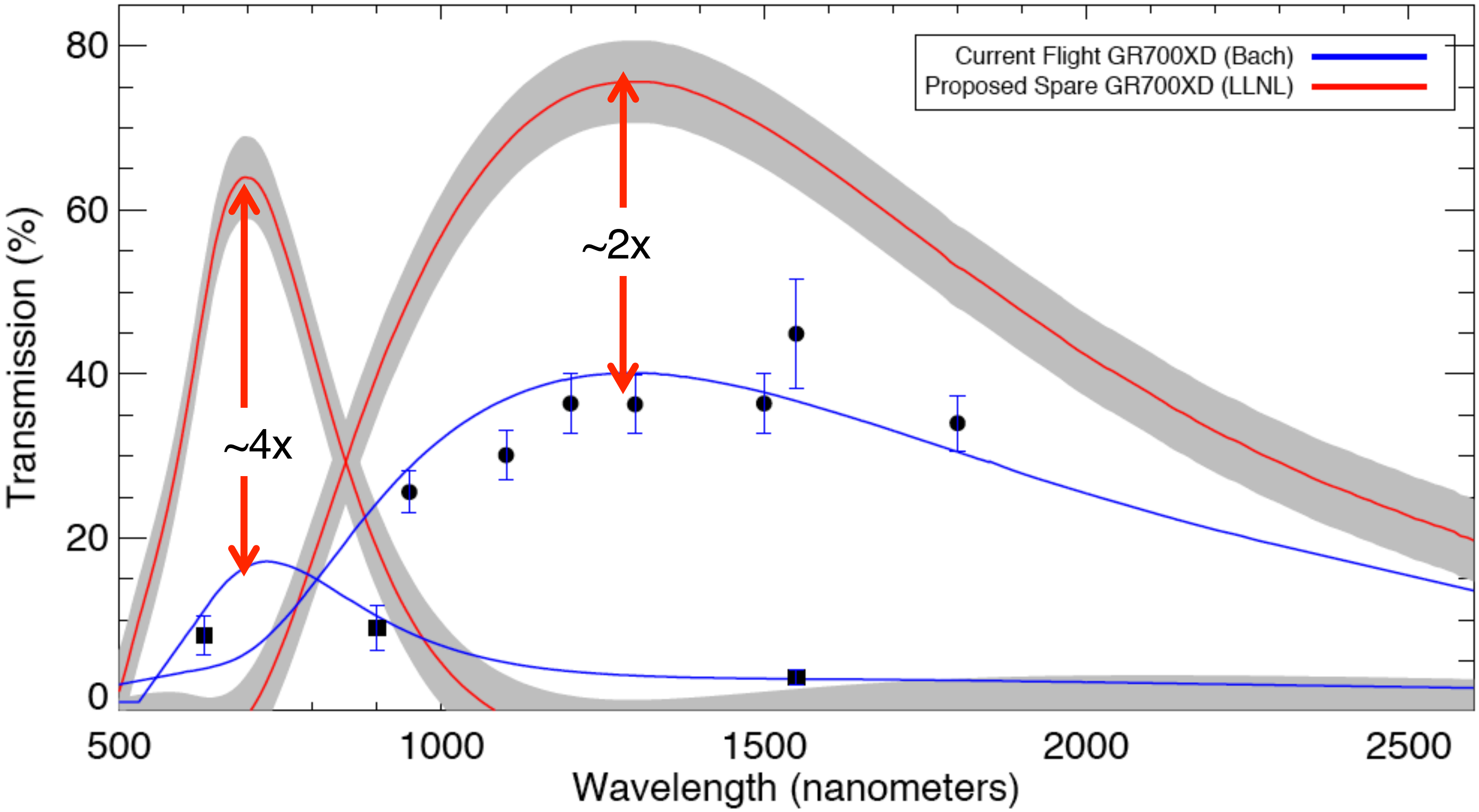




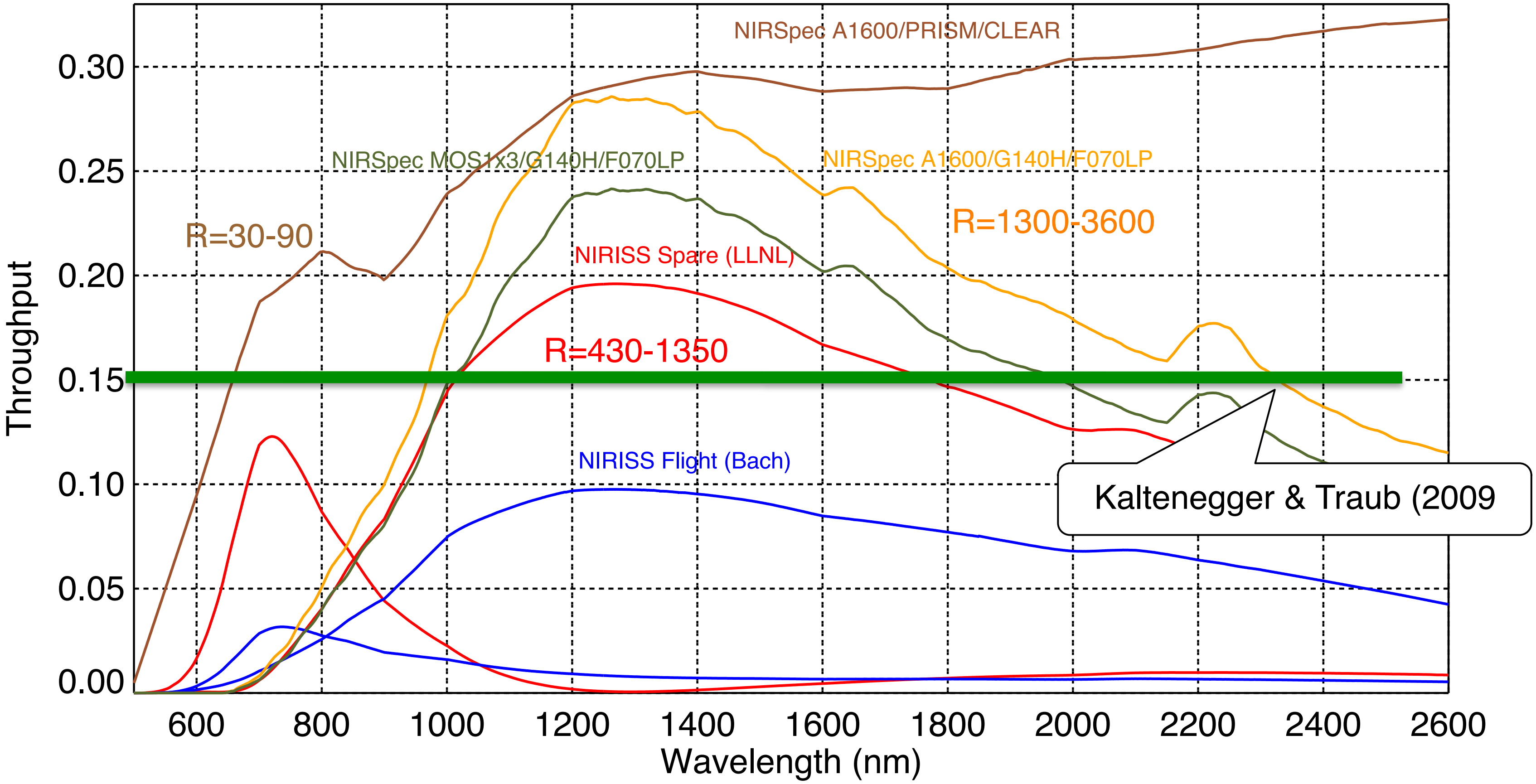

Monochromatic PSF measured in the lab



Grism blaze function – Flight vs Spare



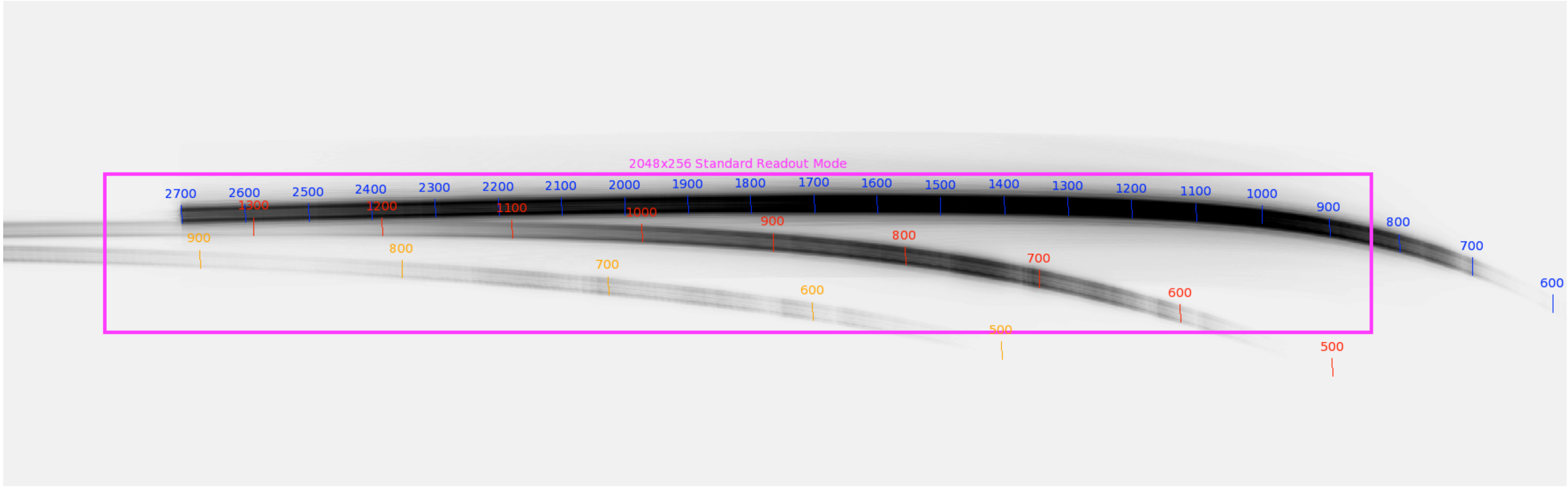
Total throughput – NIRISS vs NIRSpec



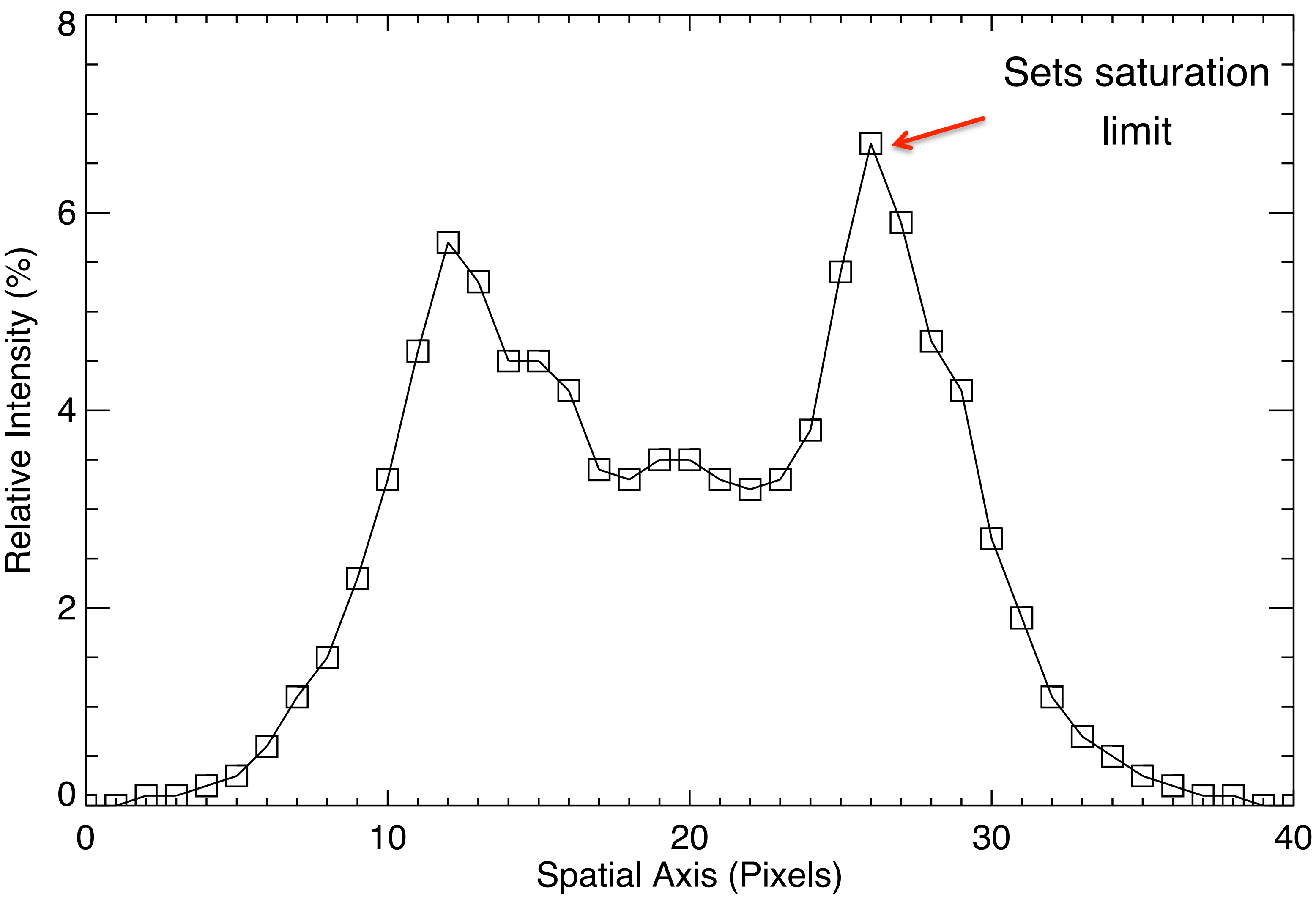
Curves include a conservative margin (~20%)

Observing modes & saturation limits

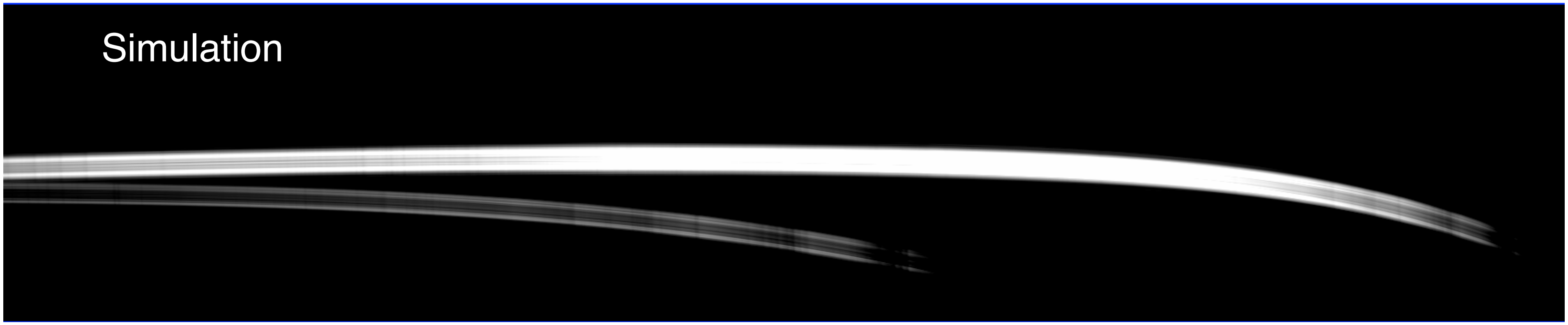
- Standard Mode:
  - Wavelength coverage: 0.6-2.8 µm
  - Subarray: 256x2048 (order m=1 and 2)
  - Saturation limit: J=8.1 (CDS; 70 000 e-)
- Bright mode
  - Wavelength coverage: 1.0-2.8 µm
  - Subarray: 80x2048 (m=1 only)
  - Saturation limit: J=6.9



Trace Profile (CV1RR Trace)

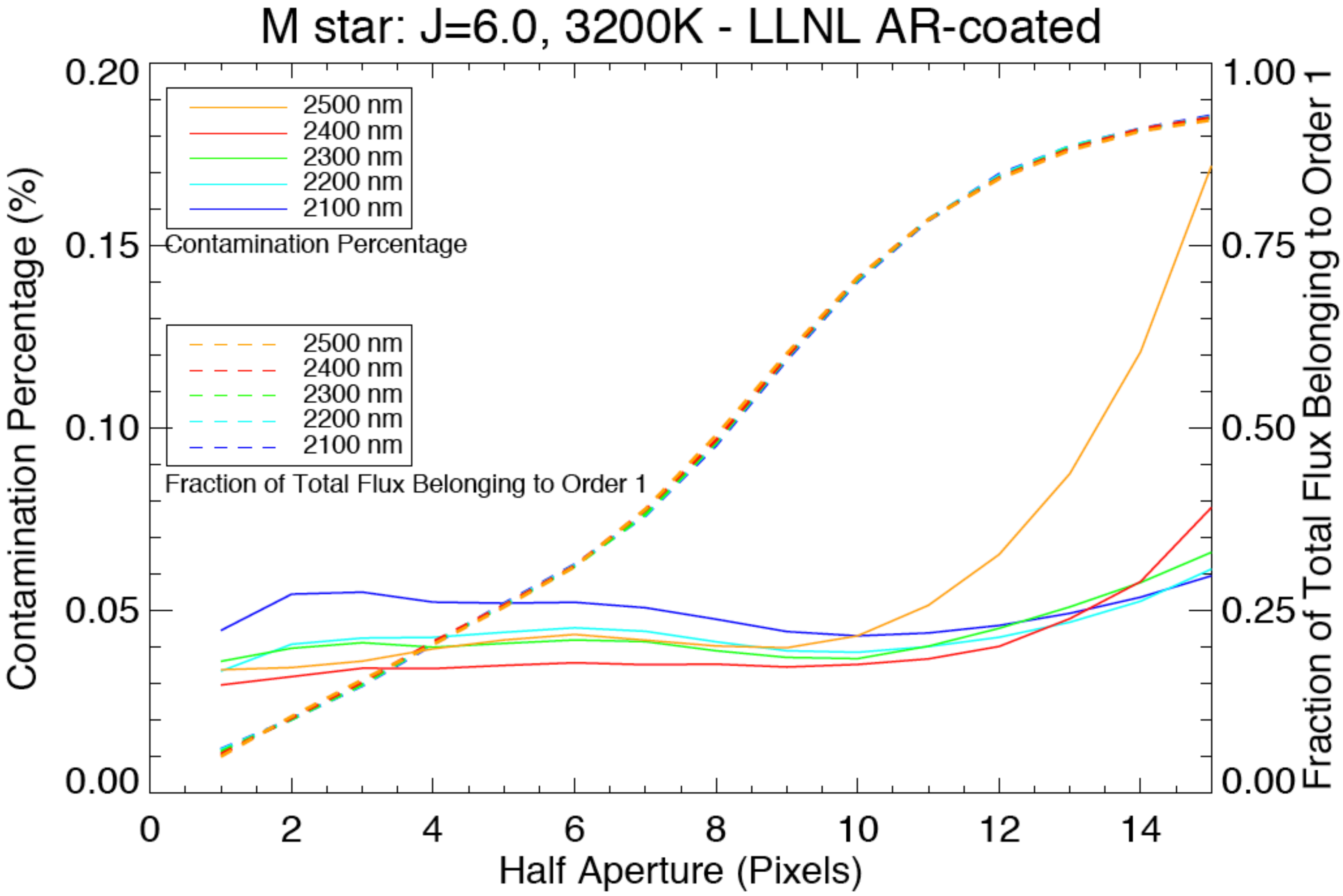


Real data vs simulation

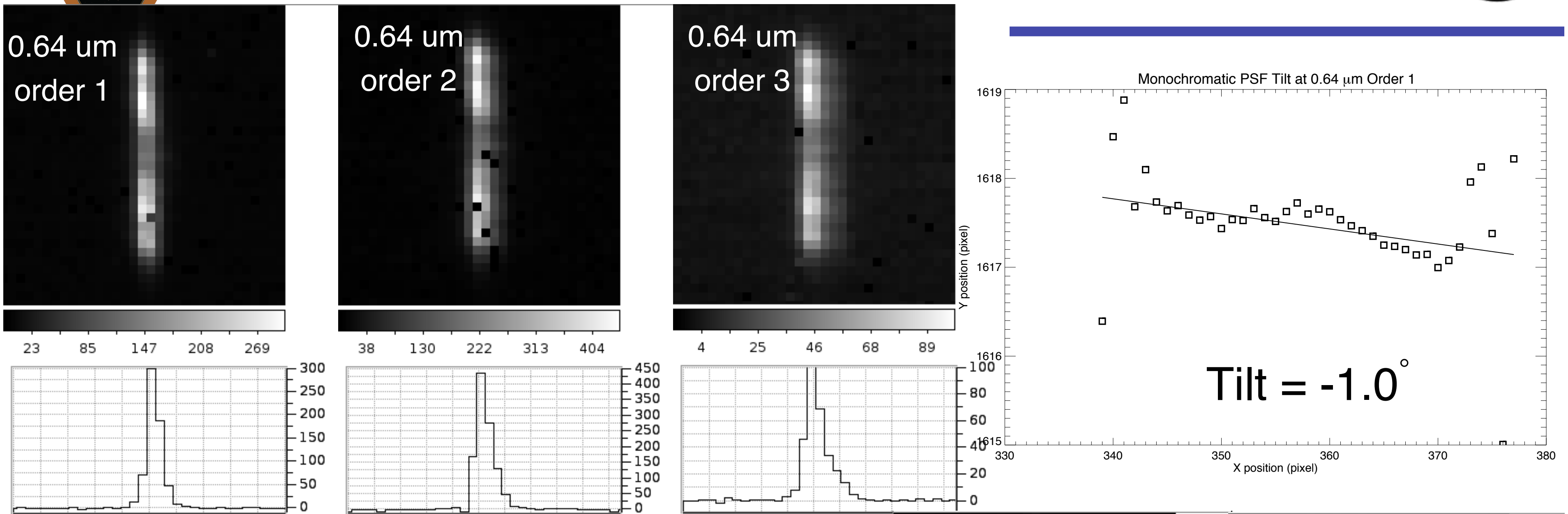


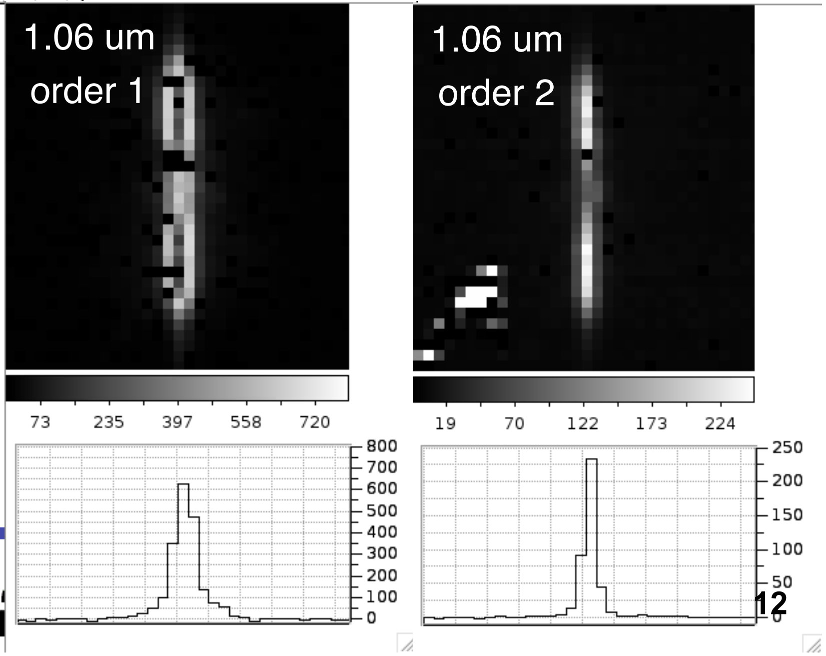
- Good correlation between data and simulations

Inter-order contamination



Monochromatic PSFs (CV1RR data)





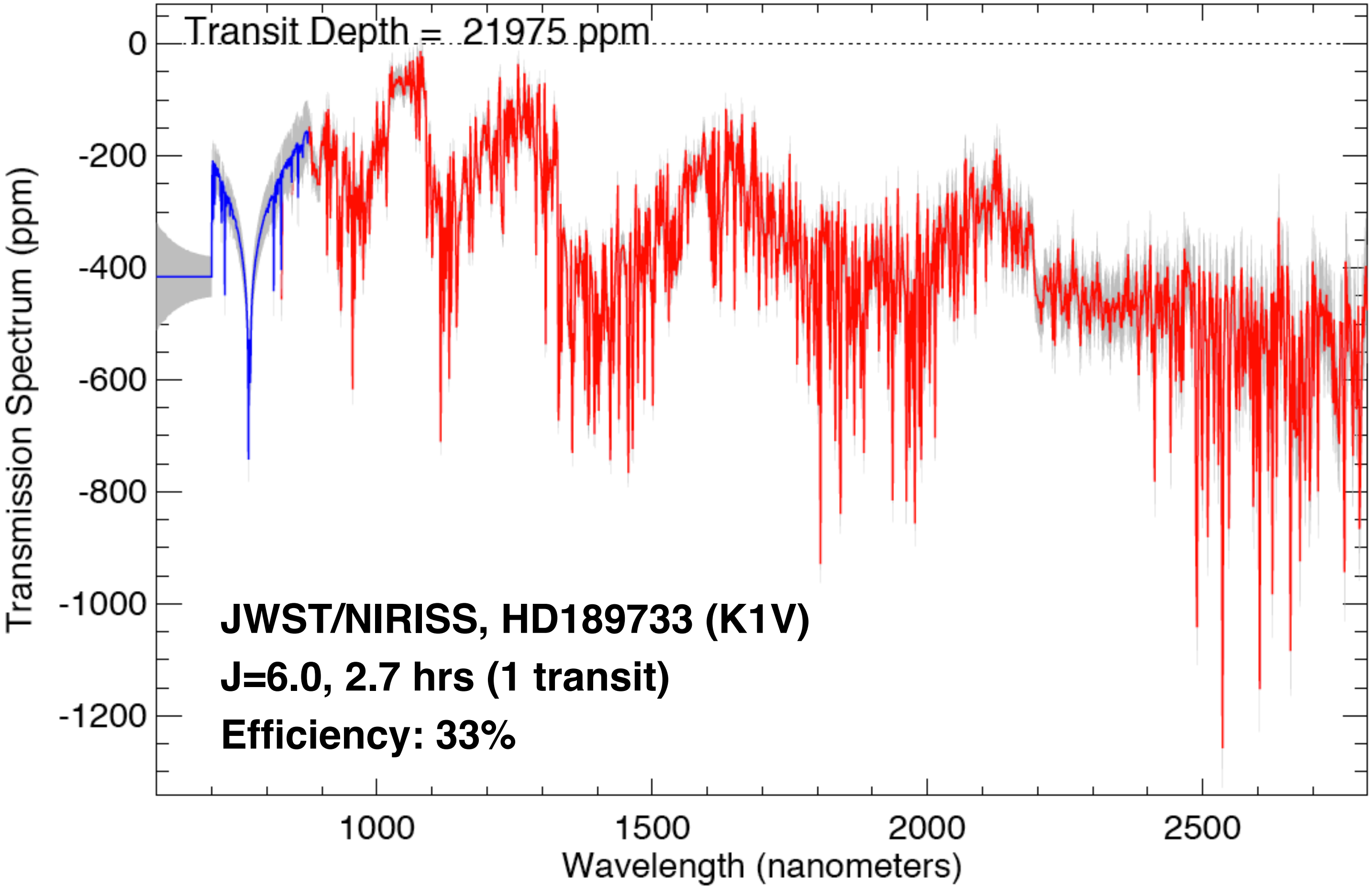
NIRISS grism is designed to have a PSF slanted by ~3° to mitigate undersampling problems.

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)

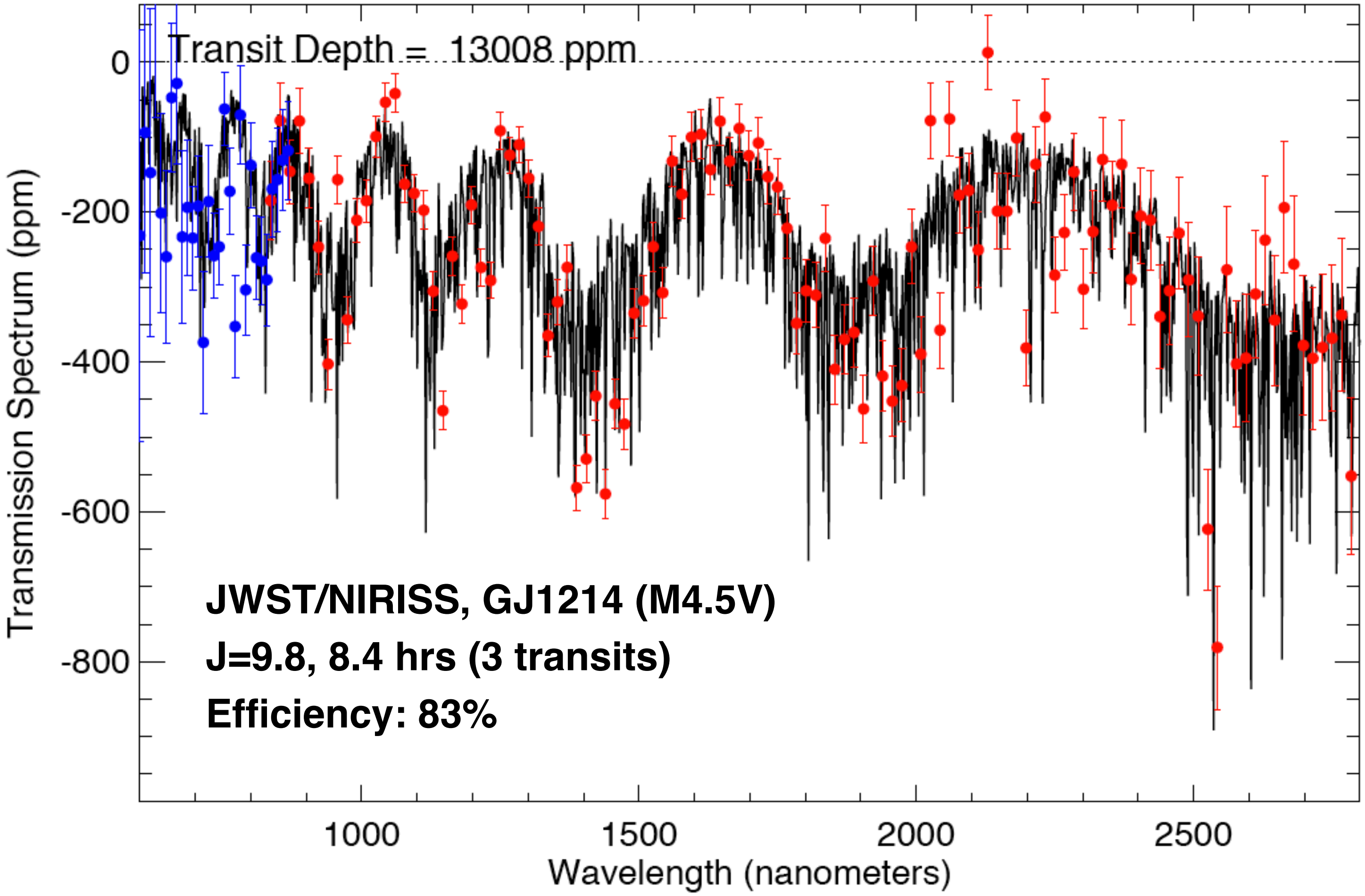
Hot Jupiter



Noise level: 25 – 100 ppm

Model courtesy of J. Fortney

Super-Earth (GJ1214: water-rich)



Noise level: 25 – 100 ppm

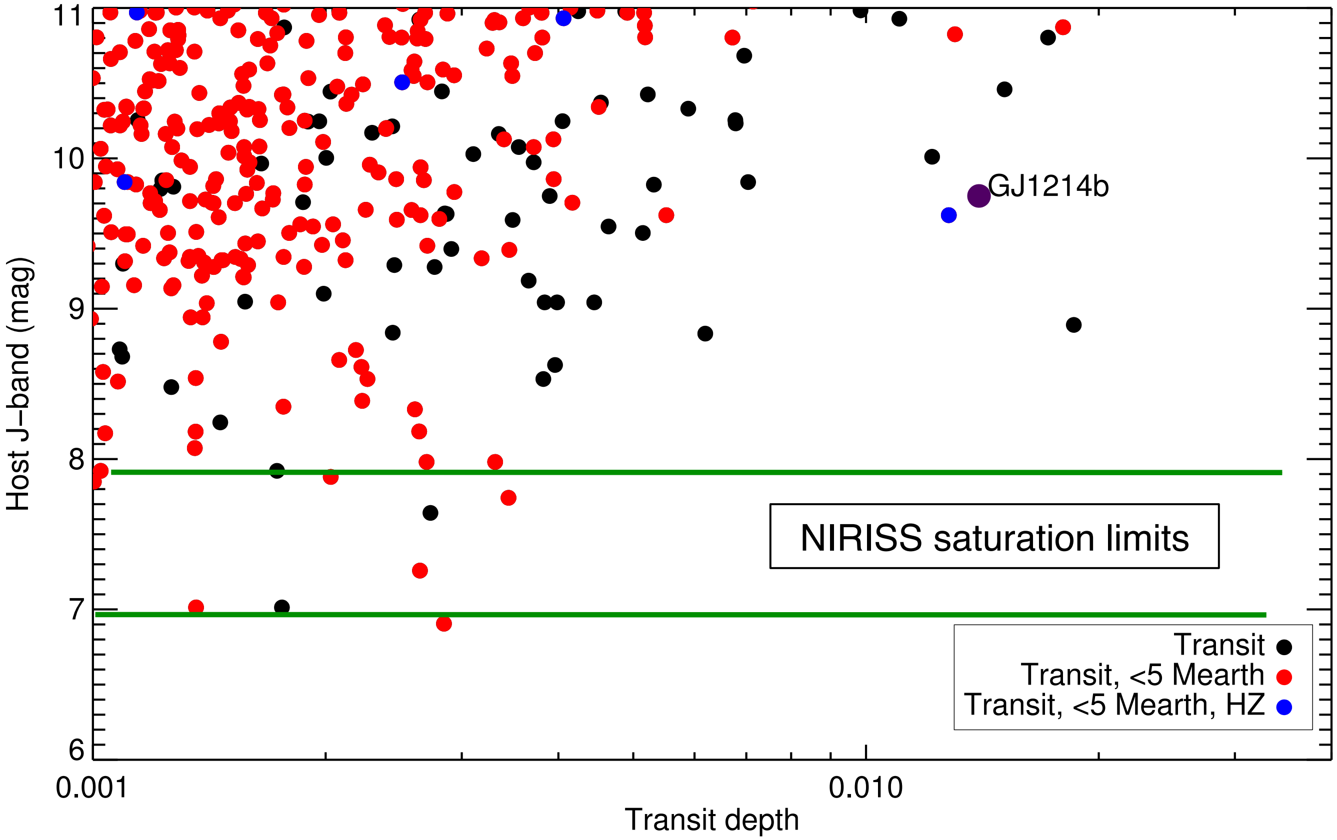
Model courtesy of J. Fortney

TESS yield

Simulation methodology

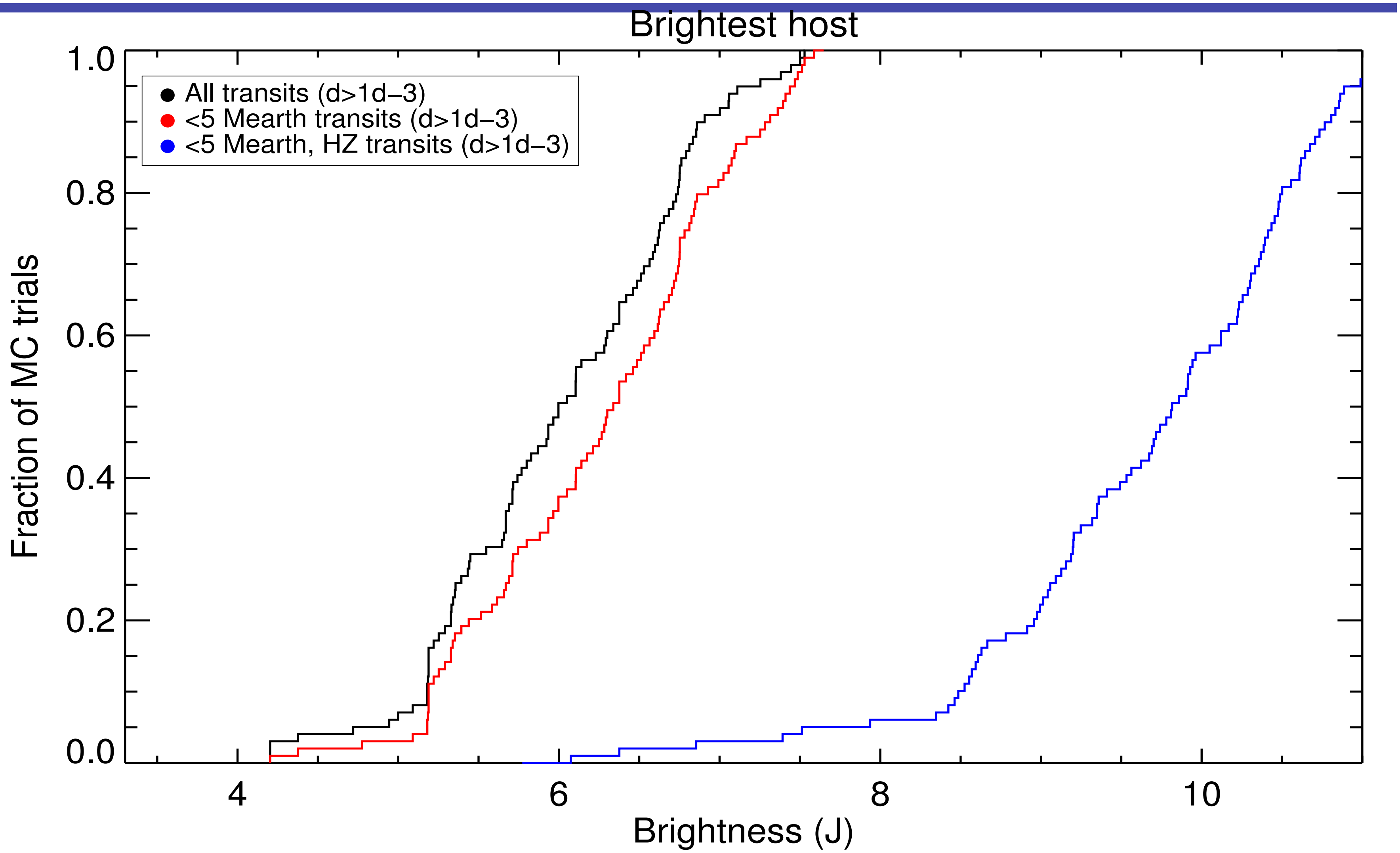
- Take all known M dwarfs within 10 pc
- Expand sample isotropically with same density and properties (sp types, abs mags, etc.) out to 50 pc
- Take 2MASS mags
- Planet statistics follows Bonfils et al. 2012
  - Eta_Earth~0.5
- Extrapolated at low masses
  - log normal distribution centered at 1 M_Earth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

TESS synthetic population

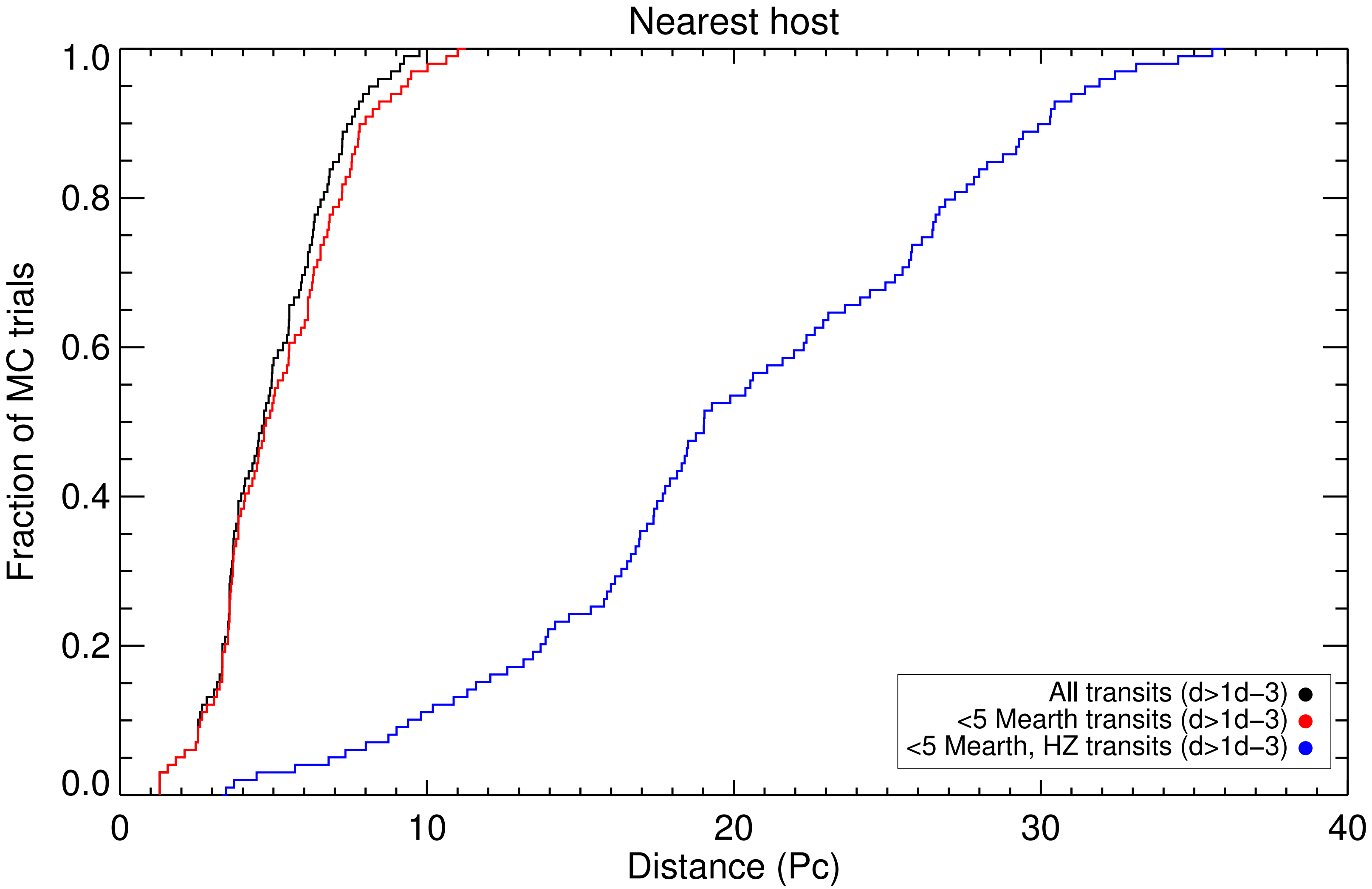


- Only 1-2 objects similar to GJ1214b
- Most transits at a few 0.1% depth, mostly early Ms with larger radii and lower-mass planets

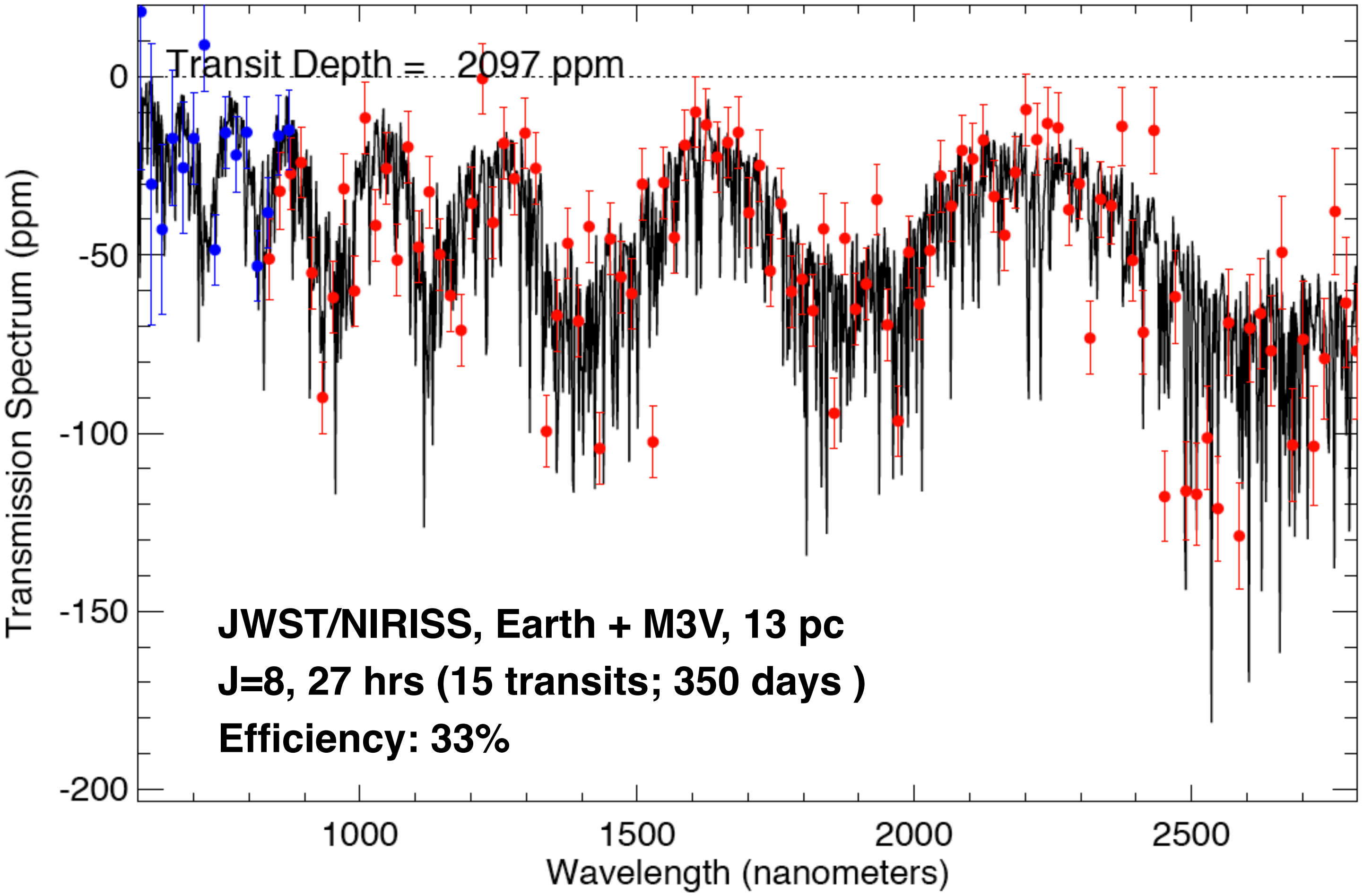
Most likely *brightest* host: J~6



Most likely distance

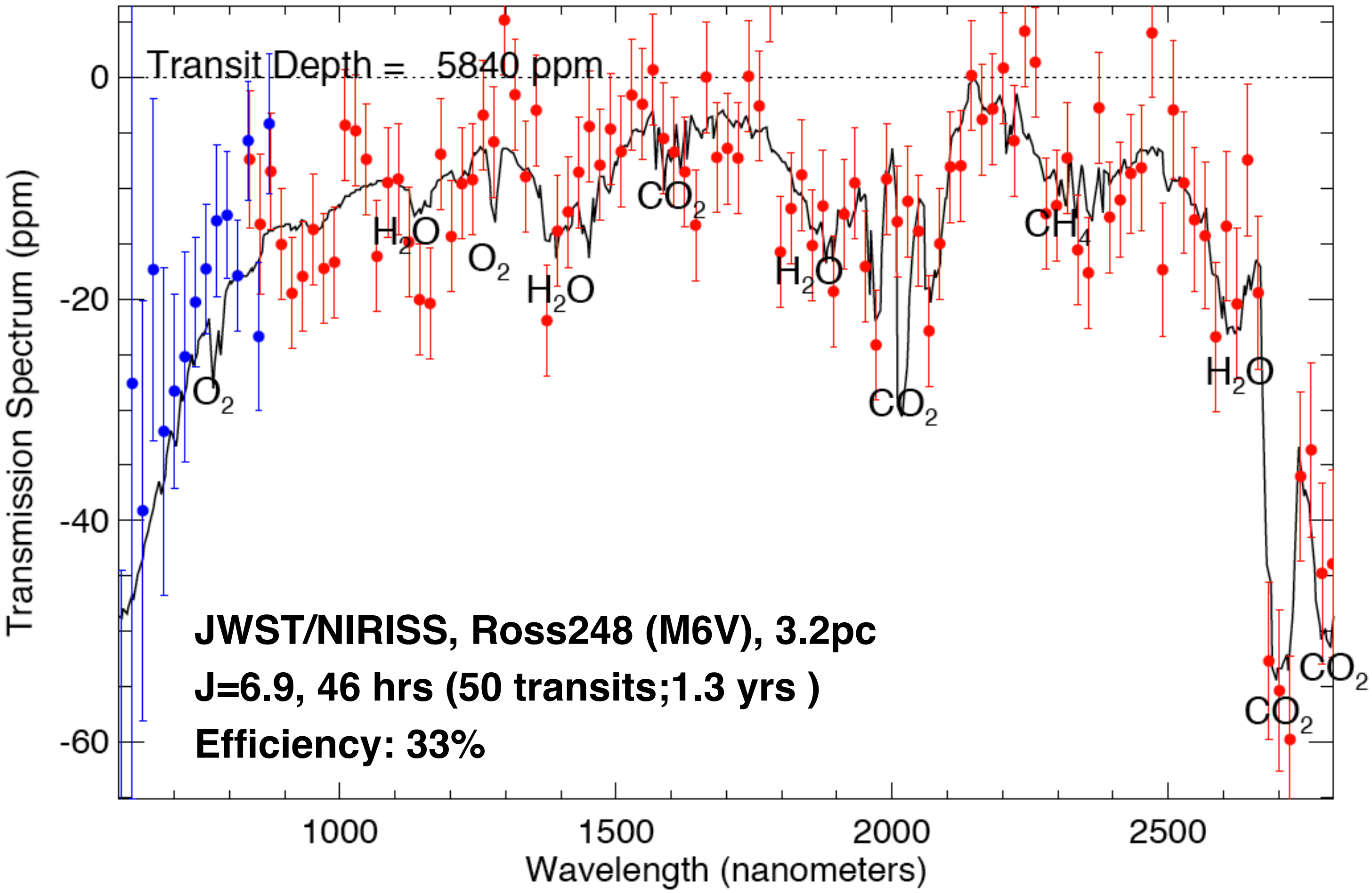


Earth size HZ water-world + M3V



Noise level: 10 – 20 ppm

Earth 2.0 around Ross248 (M6V)

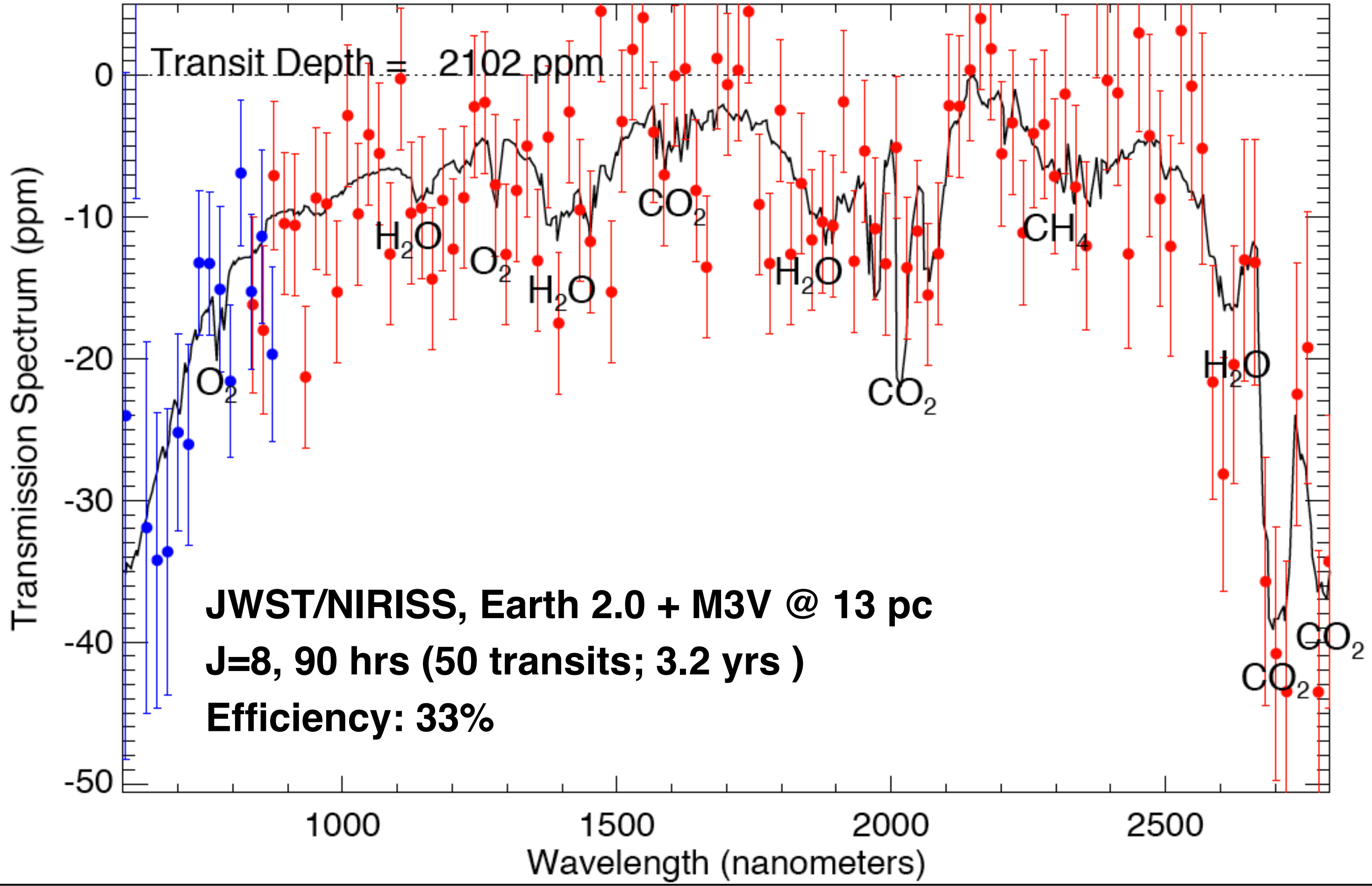


Noise level: 5 – 10 ppm

Model courtesy of L. Kaltenegger

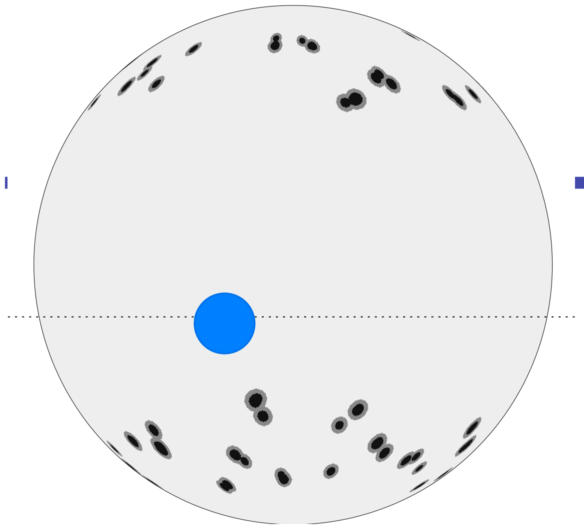
Earth 2.0 + M3V @ 13 pc (likely TESS HZ planet)

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



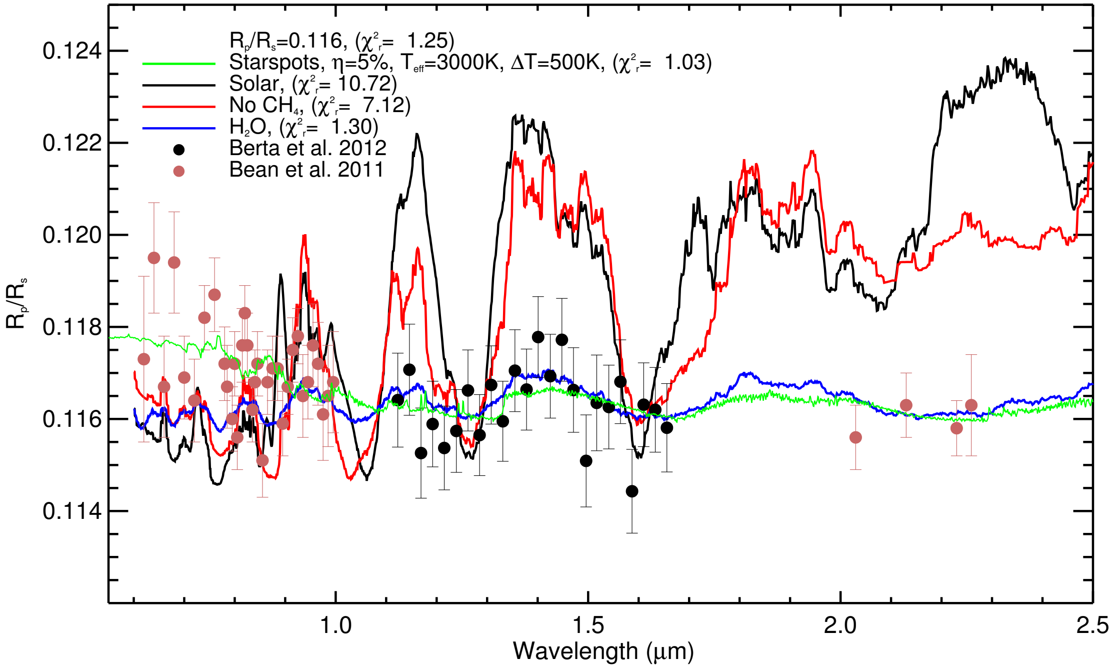
JWST/NIRISS, Earth 2.0 + M3V @ 13 pc
J=8, 90 hrs (50 transits; 3.2 yrs)
Efficiency: 33%

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



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

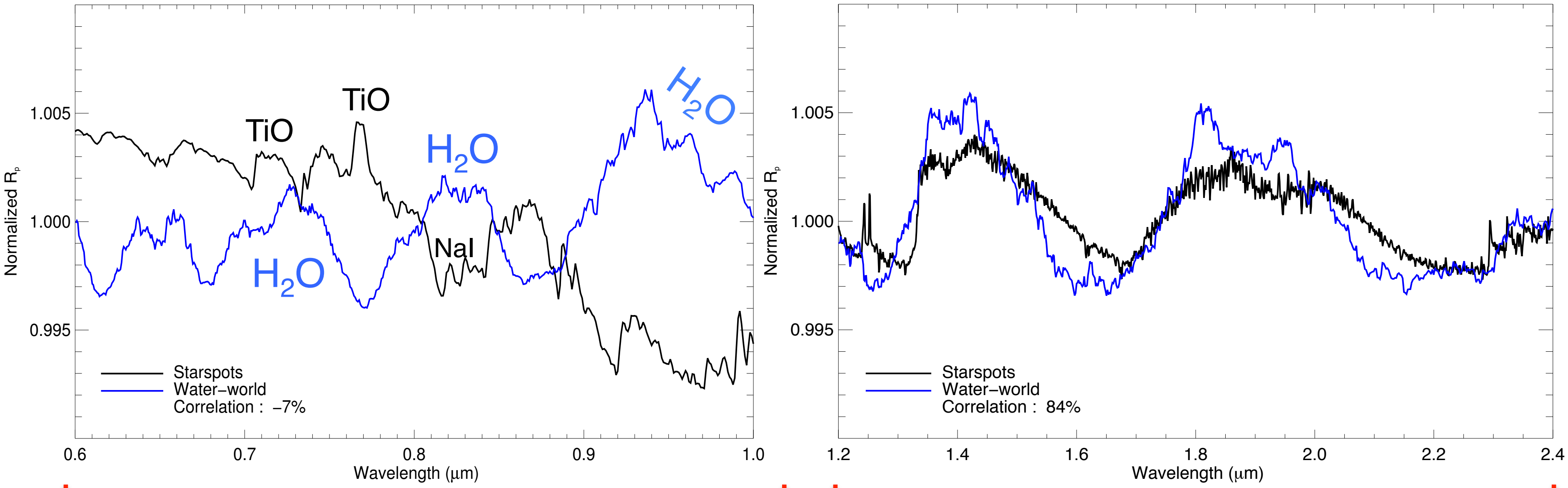
- If GJ1214 is spotted over 5% of its surface and GJ1214b happens to transit a spot-free area …
- Out-of-transit spectrum : 95% star, 5% spots
- In-transit spectrum: 93.6% star, 5% spots
- Spot spectra, 500 K cooler than photosphere, has significantly deeper water bands and a redder overall SED.
- In-transit/out-of-transit 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.



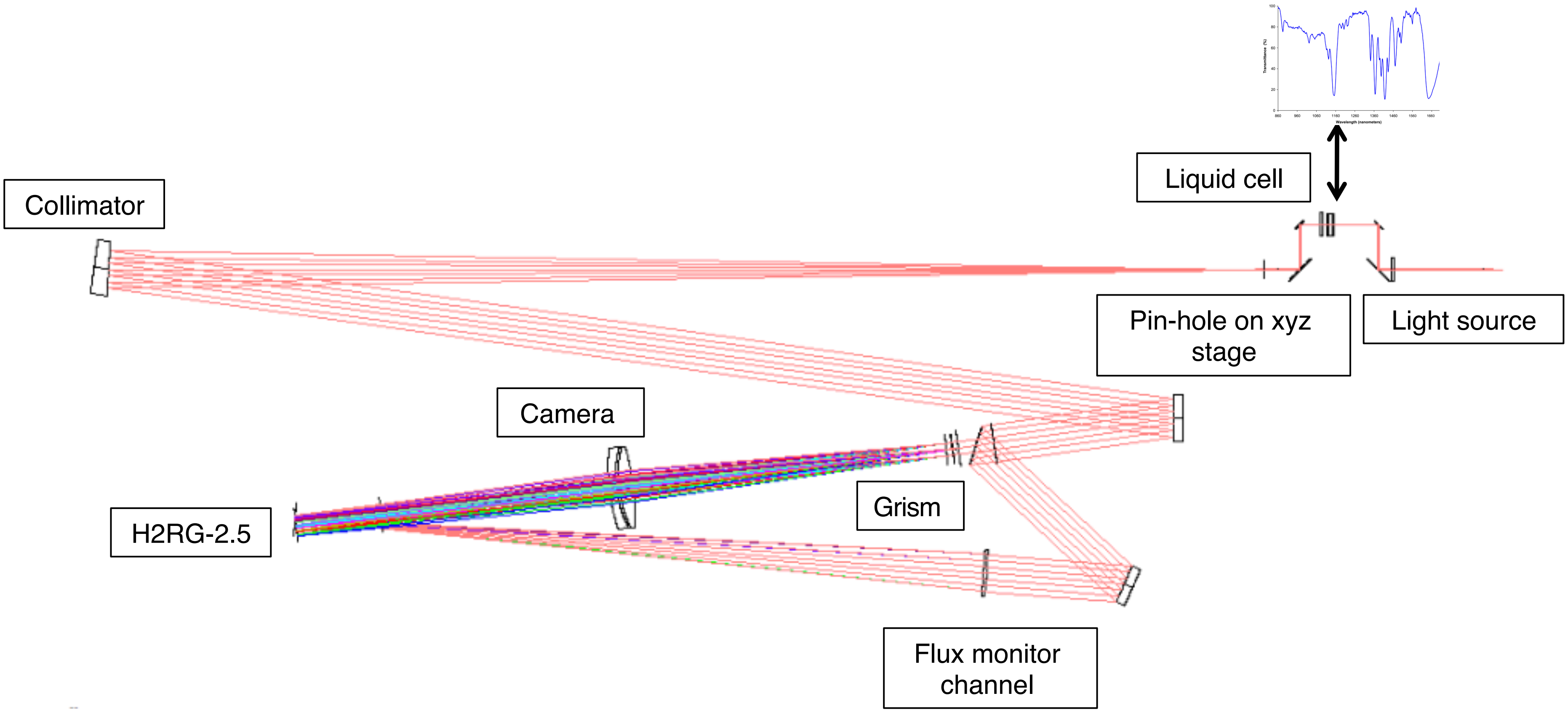
- TiO, NaI, FeH dominate the star spot-induced spectrum.
- Water absorption dominates the planetary features.
- Good spectral resolution needed to detect some features (e.g. NaI, KI)

- 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).

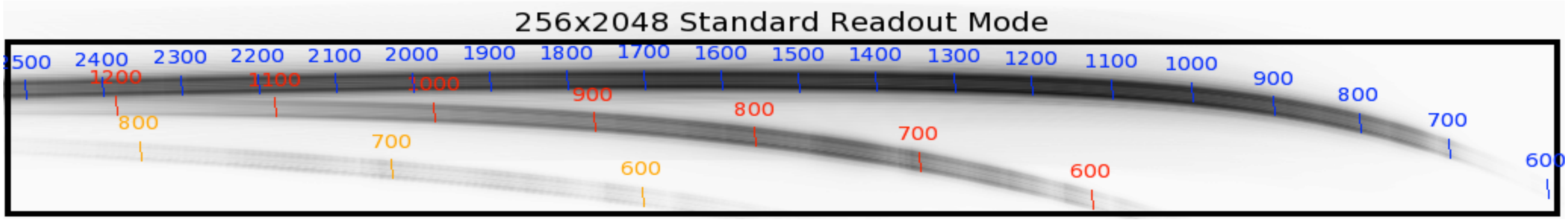
On-going work

- 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



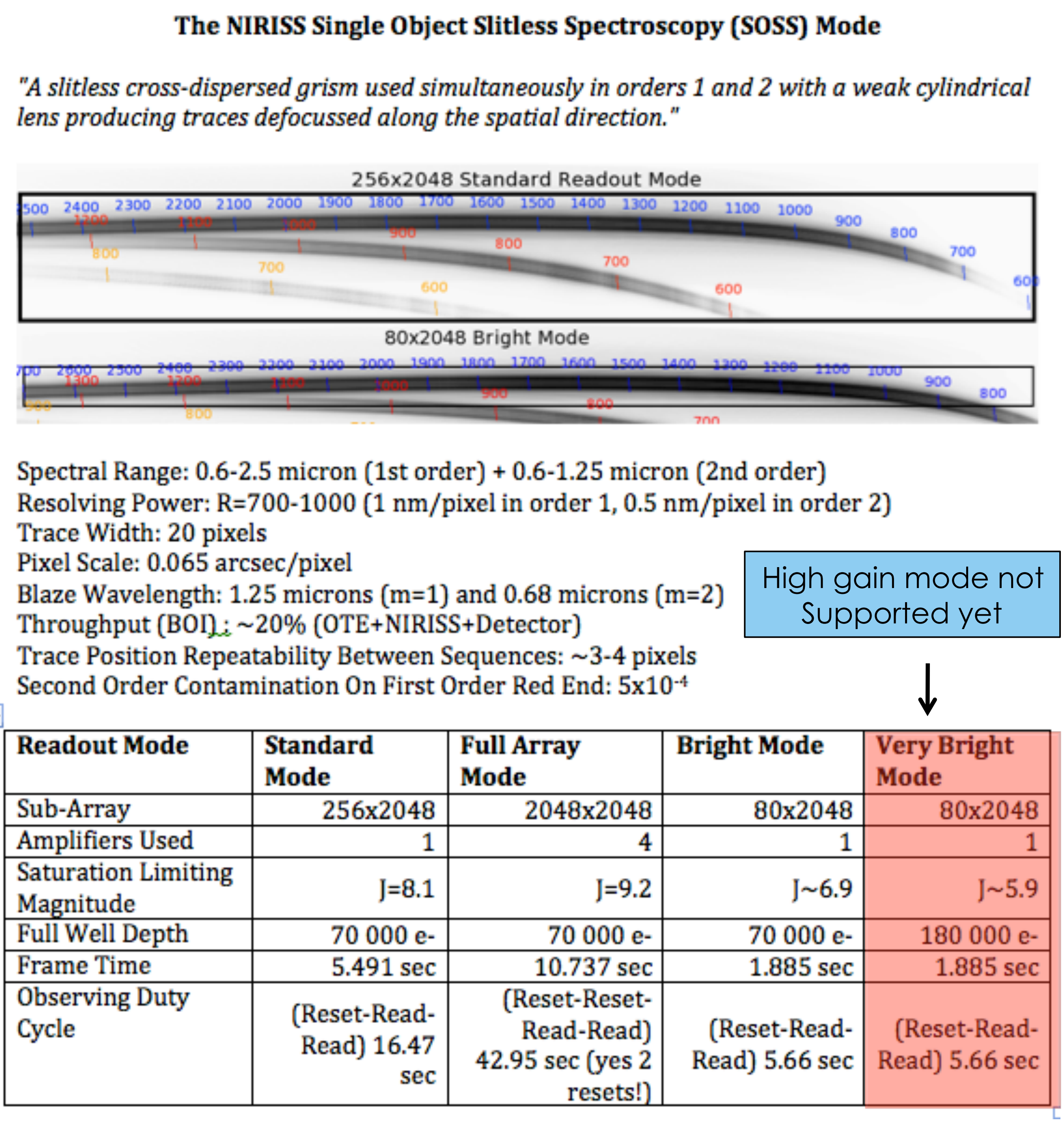
VII. B.

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 (BOI) : ~20% (OTE+NIRISS+Detector)
Trace Position Repeatability Between Sequences: ~3-4 pixels
Second Order Contamination On First Order Red End: 5×10^{-4}

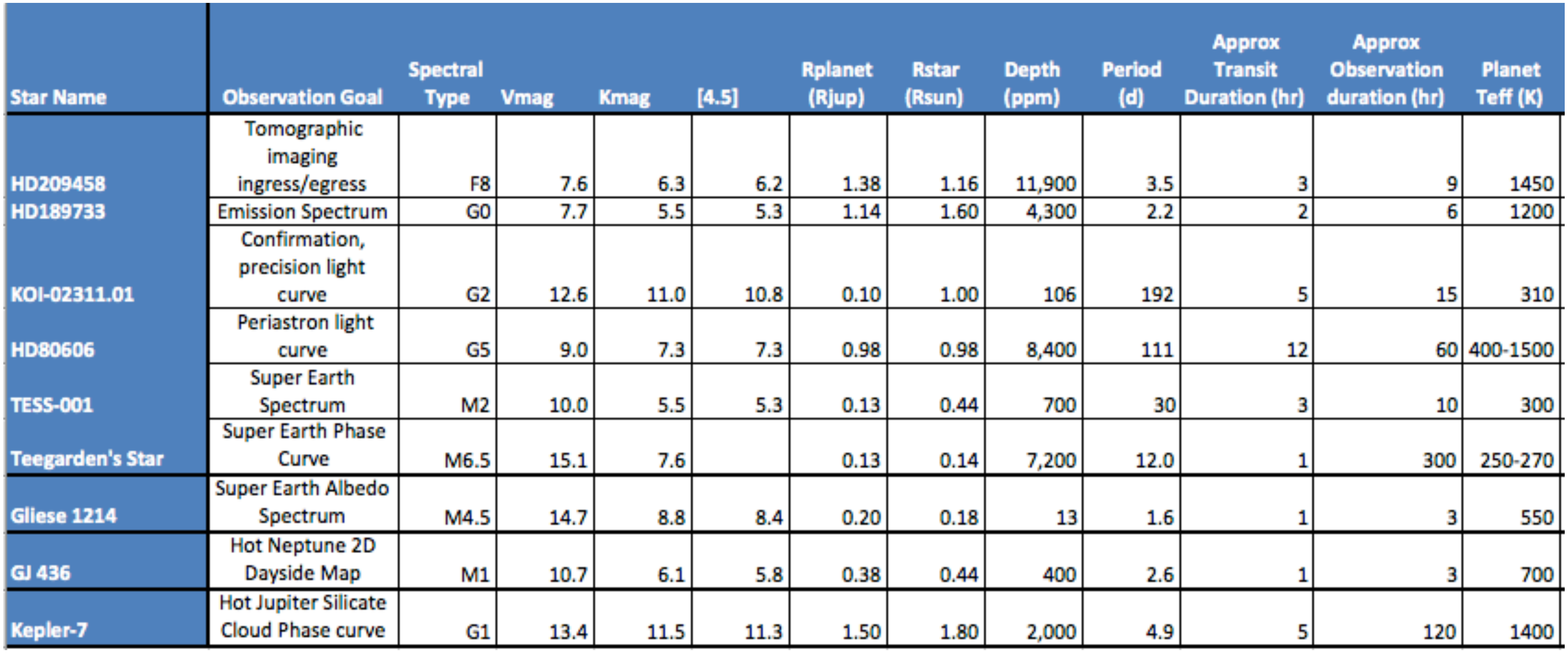
High gain mode not Supported yet

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)

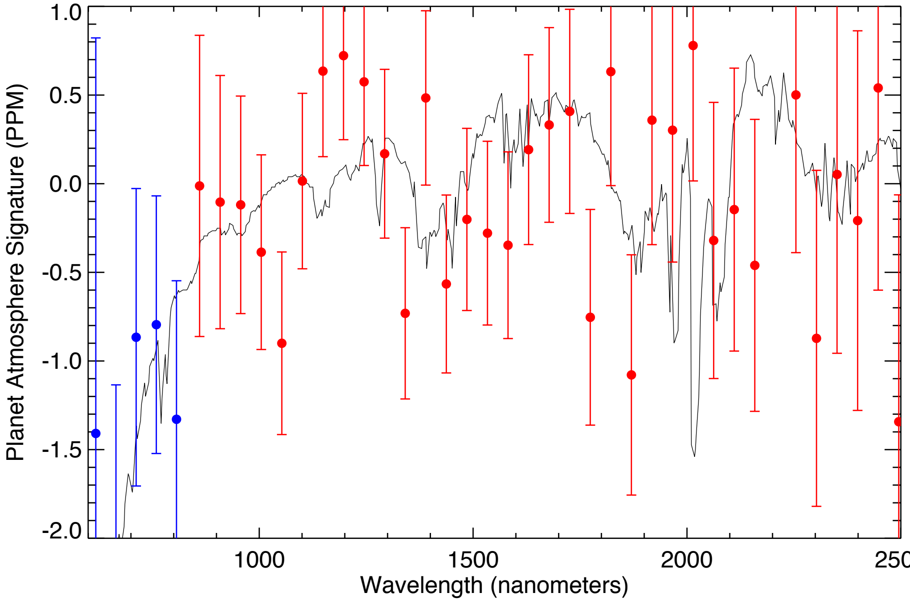
Simulation methodology

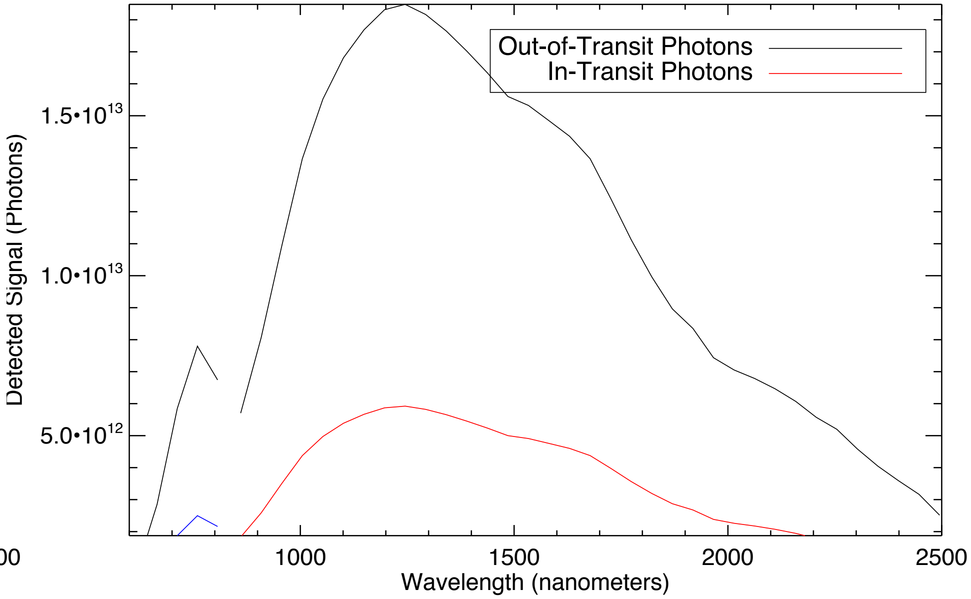
- **Photon-Noise Limited**
- **1-D** Simulation (2-D in the works)
- Star Model Atmospheres**: BT-Settl**
- Use **Measured Throughputs** for the Observatory and Instrument (OTE+2 TMAs + Grism Blaze) – no conservative fudge factor.
- Assume a Full-Well Depth of **70 000 e-** and Use the Measured Spectral 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

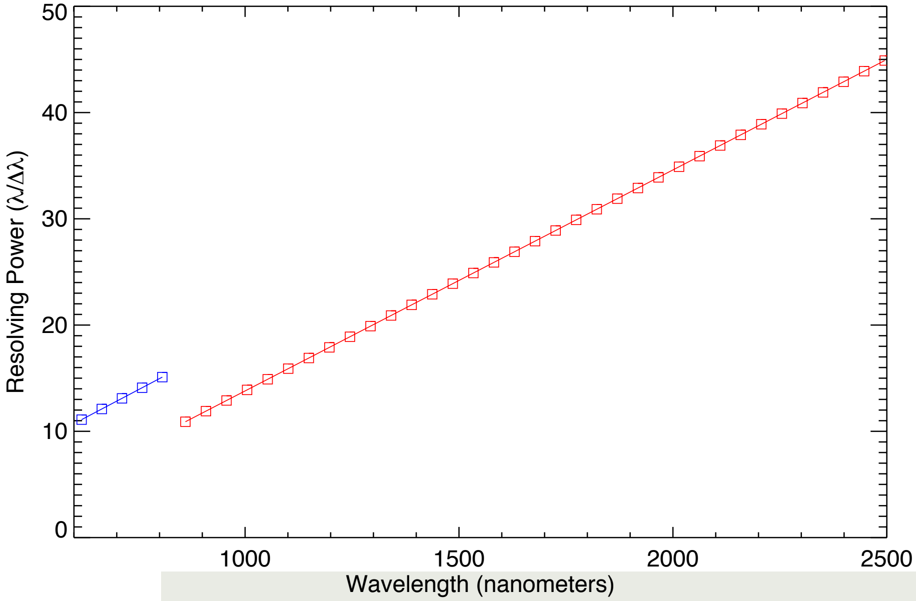
TESS-01 Input Parameters

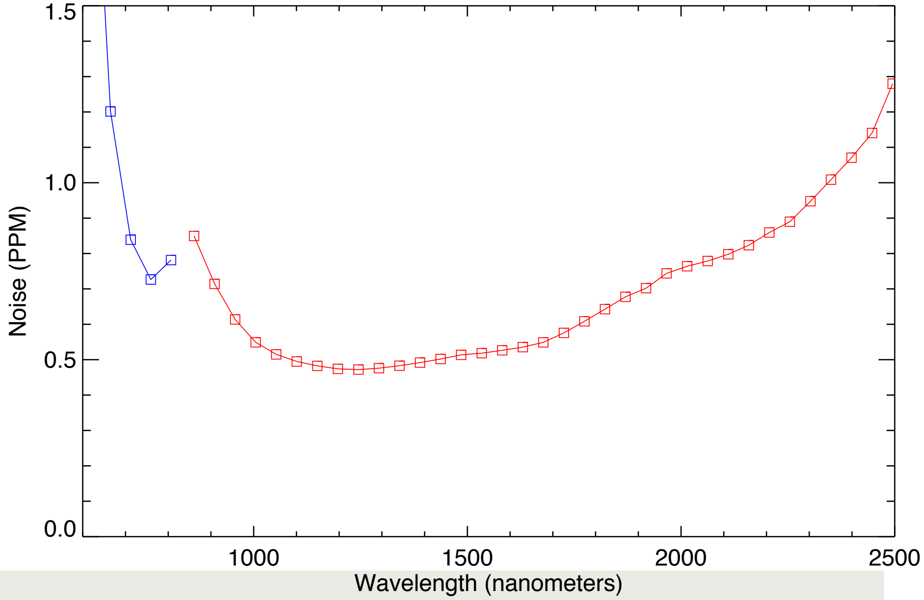
System: TESS-01
Planet Model: ./PlanetModels/Earth_kaltenegger2009.txt
Star Model: ./InputSpectra/lte036-4.5-0.0.BT-Settl.fits
Star J magnitude: 6.33 (K=5.5) (per assignment)
Grism: LLNL_Coated
Average Transit Depth: 0.08%
Efficiency (Integration Time/Elapsed Time): 50.0%
Readout Scheme: 80 x 2048 *** 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)
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
1000
1500
2000
2500
Wavelength (nanometers)


Detected Signal (Photons)
1.5•10^13
1.0•10^13
5.0•10^12
Out-of-Transit Photons
In-Transit Photons
1000
1500
2000
2500
Wavelength (nanometers)

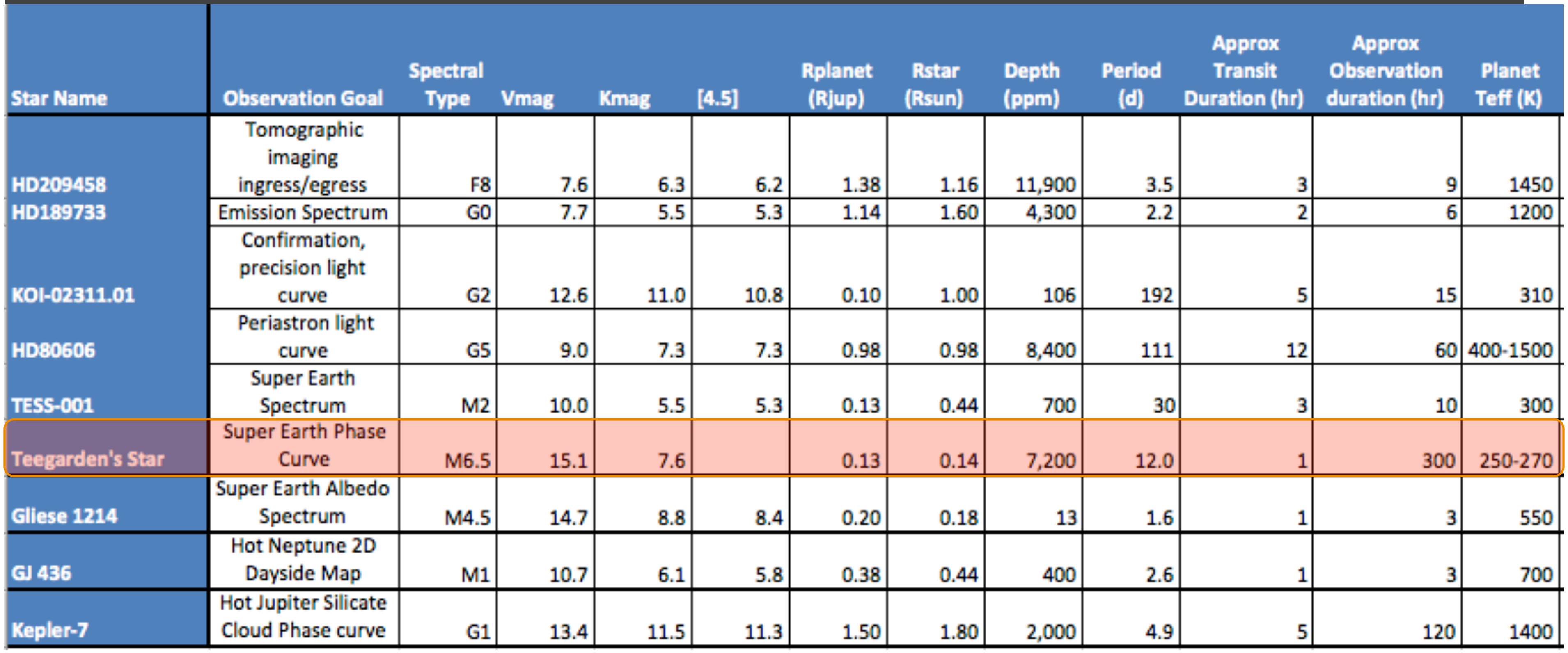

Resolving Power (λ/Δλ)
50
40
30
20
10
0
1000
1500
2000
2500
Wavelength (nanometers)


Noise (PPM)
1.5
1.0
0.5
0.0
1000
1500
2000
2500
Wavelength (nanometers)

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



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

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

Teegarden's Star Input Parameters

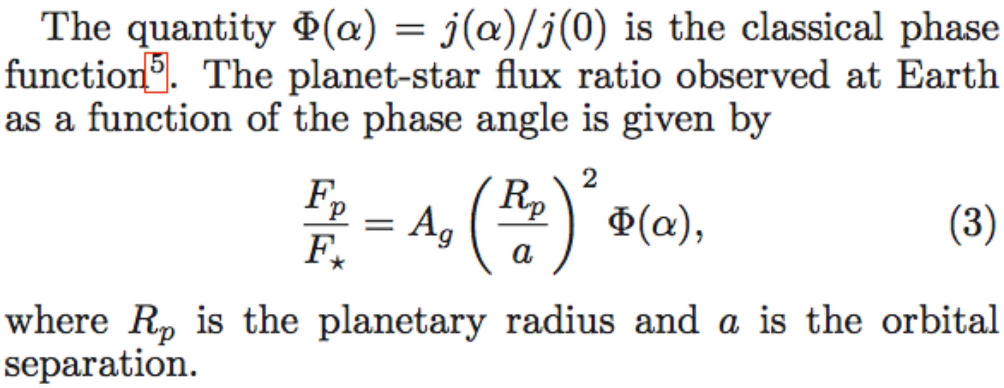
System: TeegardenPhaseCurve
Planet Model: ./PlanetModels/Earthshine_Turnbull/F7_alldata.txt
Star Model: ./InputSpectra/lte028-4.5-0.0.BT-Settl.fits
Star J magnitude: 8.39
Star Radius: 0.14 Sun Radii
Star Mass: 0.10 Sun Mass
Grism: LLNL_Coated
Planet Radius: 1.43 Earth Radii
Semi-Major Axis: 0.049 AU
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

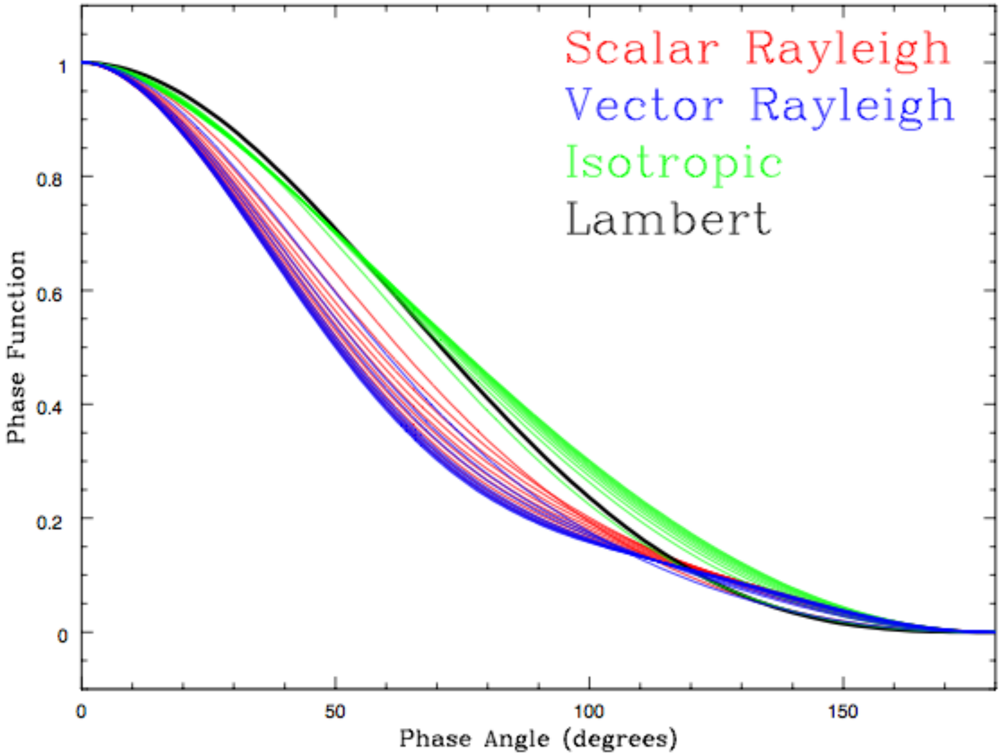
- Flux ratio given by Eqn 3 of Madhusudhan & Burrows 2011
- Use Turnbull 2006 (fig 7) Earth Shine Reflection Spectrum for the Geometric Albedo (A_g)
- Assume Lambertian Scattering
- Photon-Noise Limited Simulation



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

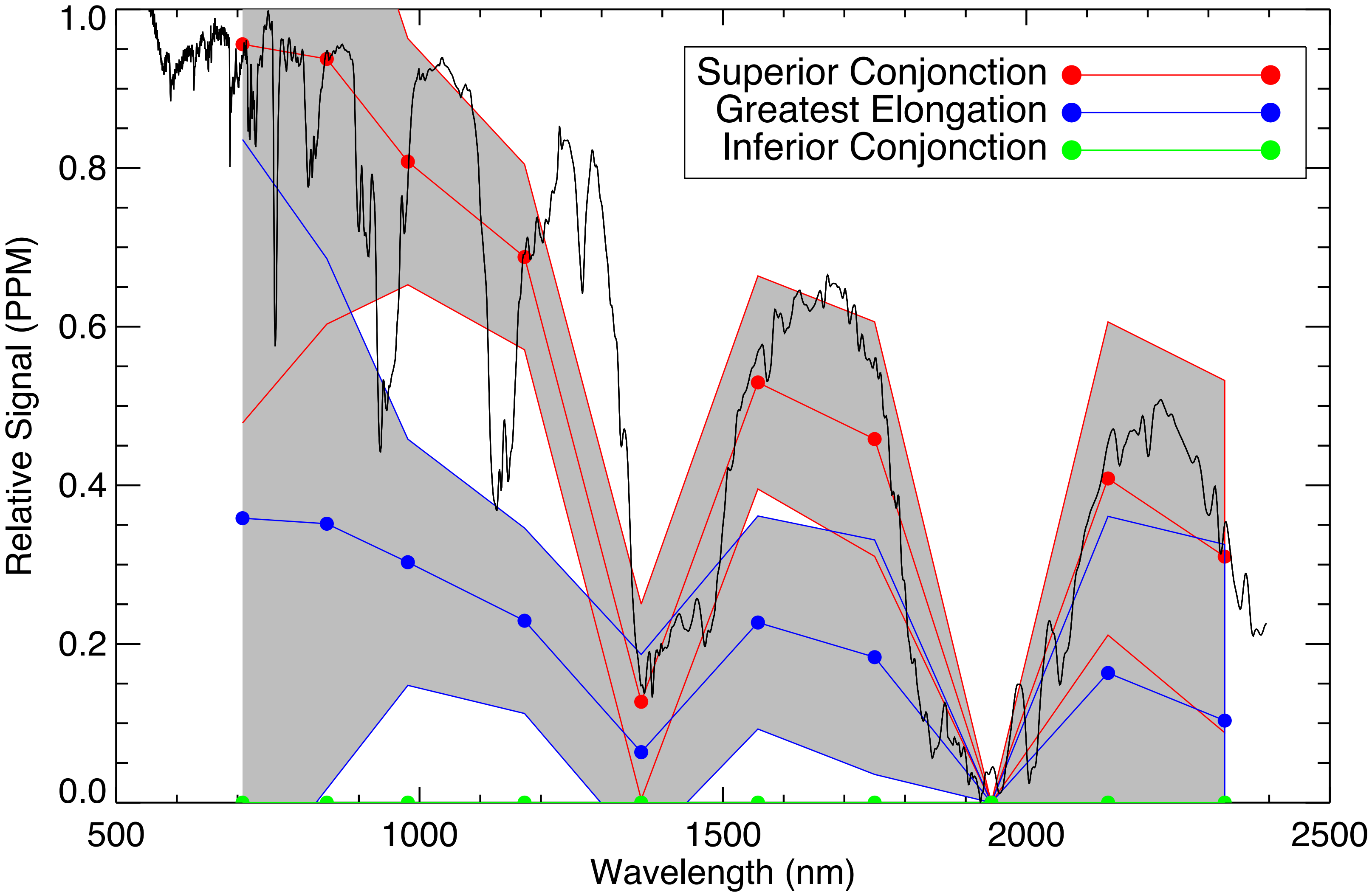
$$\frac{F_p}{F_\star} = A_g \left(\frac{R_p}{a}\right)^2 \Phi(\alpha), \qquad (3)$$

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

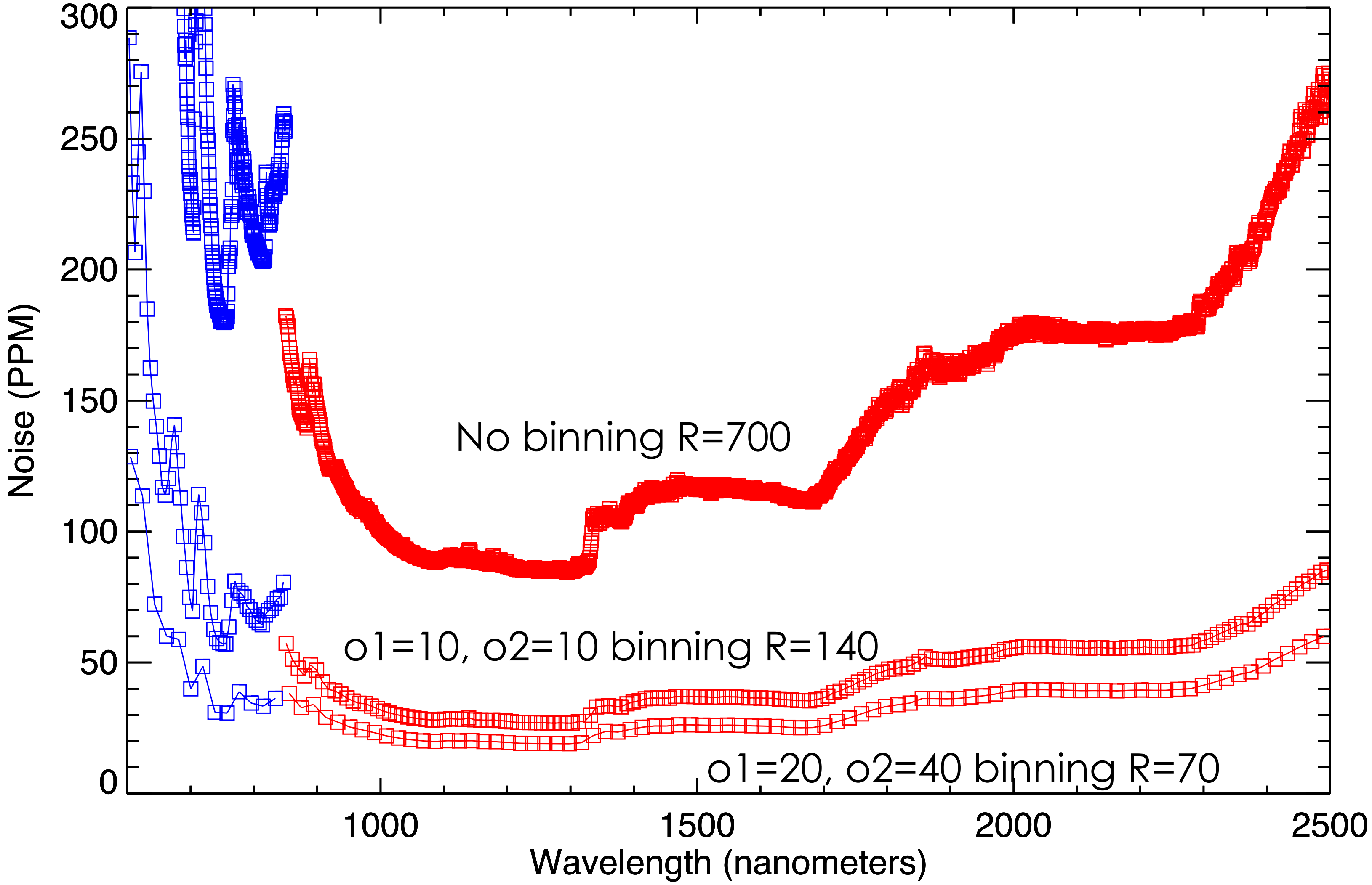


Teegarden's Star Phase Curve

(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