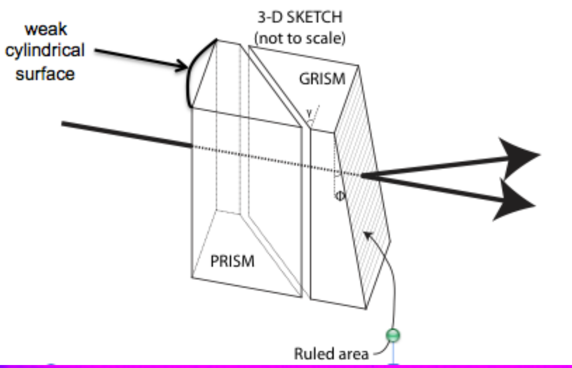
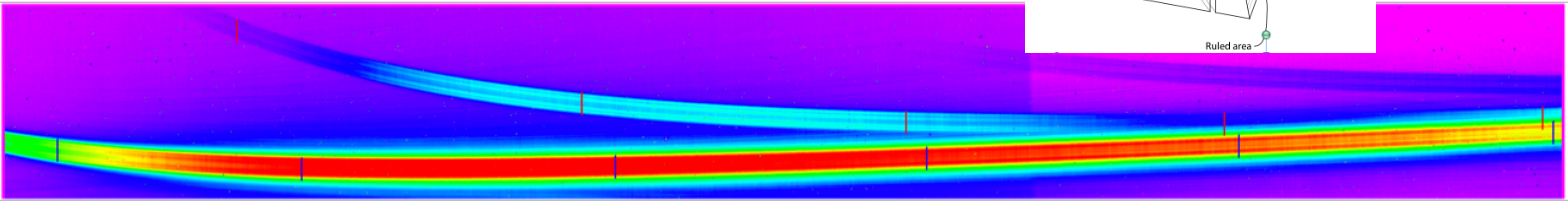
Exoplanet and brown dwarf atmosphere characterization with NIRISS SOSS – GTO program

David Lafrenière, for the NIRISS team

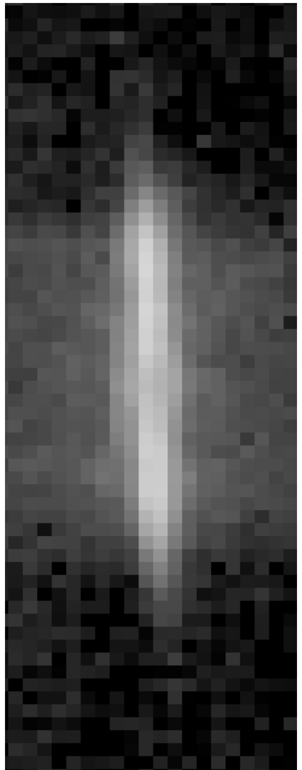
AAS 230th meeting, Austin, TX, 2017 June

NIRISS SOSS mode
(Single Object Slitless Spectroscopy)

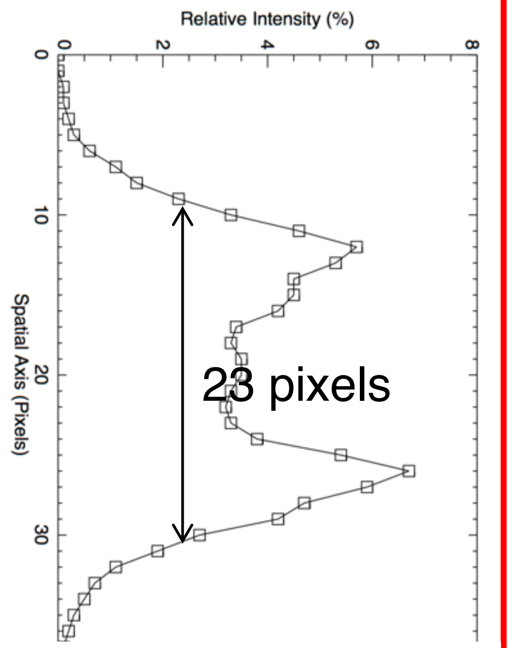




- **0.6-2.8 µm simultaneously @ R~1000**, through 2 orders over 256x2048 subarray
- Weak defocus along spatial axis
  - increase dynamic range
  - minimize systematic red noise due to undersampling and flat field errors
- Dispersion axis very slightly tilted



CV3 monochromatic PSF



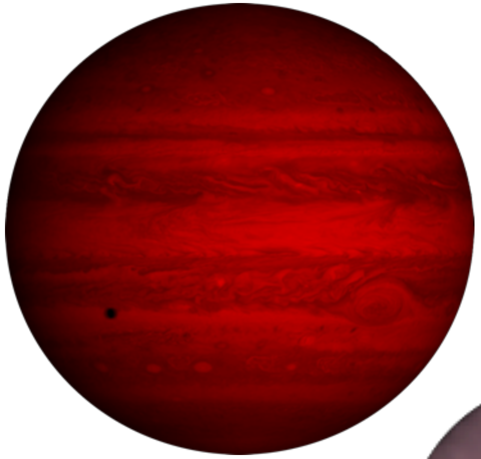
Spatial trace profile

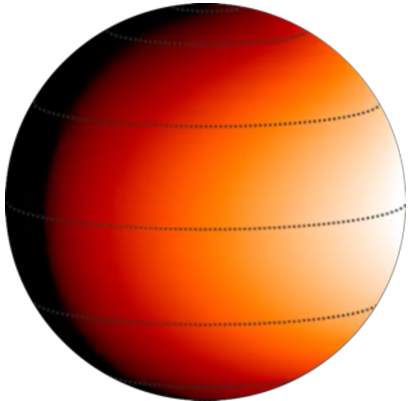
NEAT
(NIRISS Exploration of Atmospheric diversity of Transiting exoplanets) Program goals

- Determine abundances of major atomic and molecular constituents, C/O ratio, overall metallicity, atmospheric scale height, mean molecular weight, and temperature-pressure profile
- Investigate presence & properties of haze, clouds, patchy clouds
- Explore wide range of planet masses & temperatures
- Determine longitudinal/vertical thermal & composition structure of atmosphere
- Detect atmosphere of rocky planets and infer their bulk composition

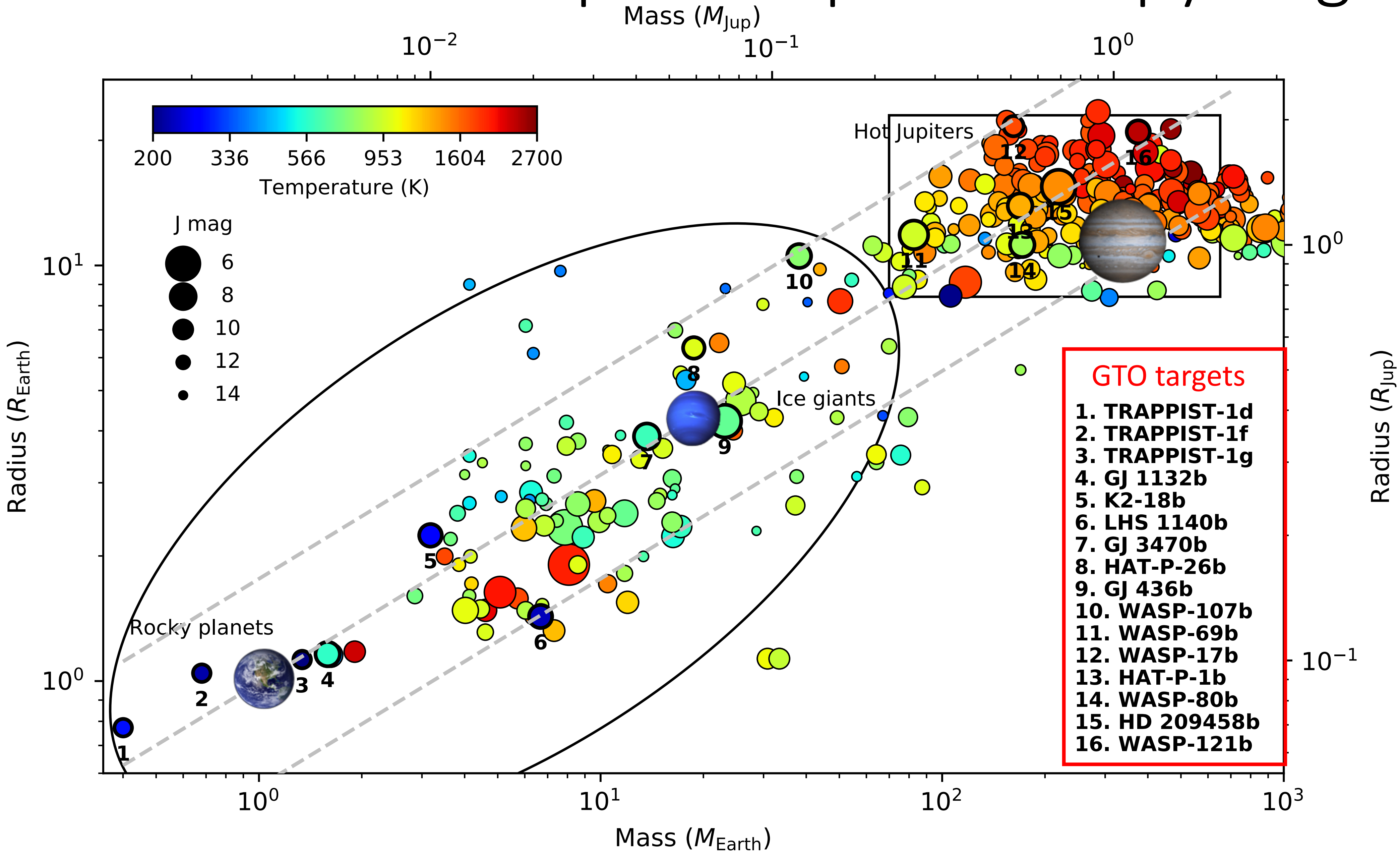
NEAT Program components

- Ice & gas giants
  - 9 targets for which a single visit is sufficient to achieve a robust detection of atmospheric signature at the native resolving power of the SOSS mode
- Rocky planets
  - 6 planets for which a detection will require multiple visits and binning down the spectra to lower resolution
- Phase curve program
  - Full phase curve spectroscopy of one target

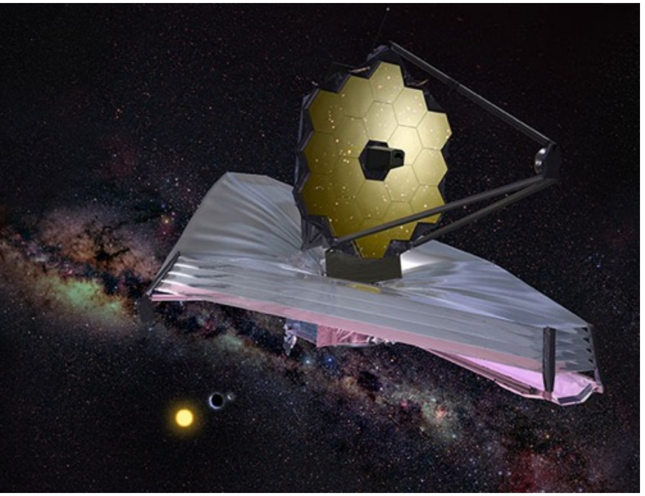


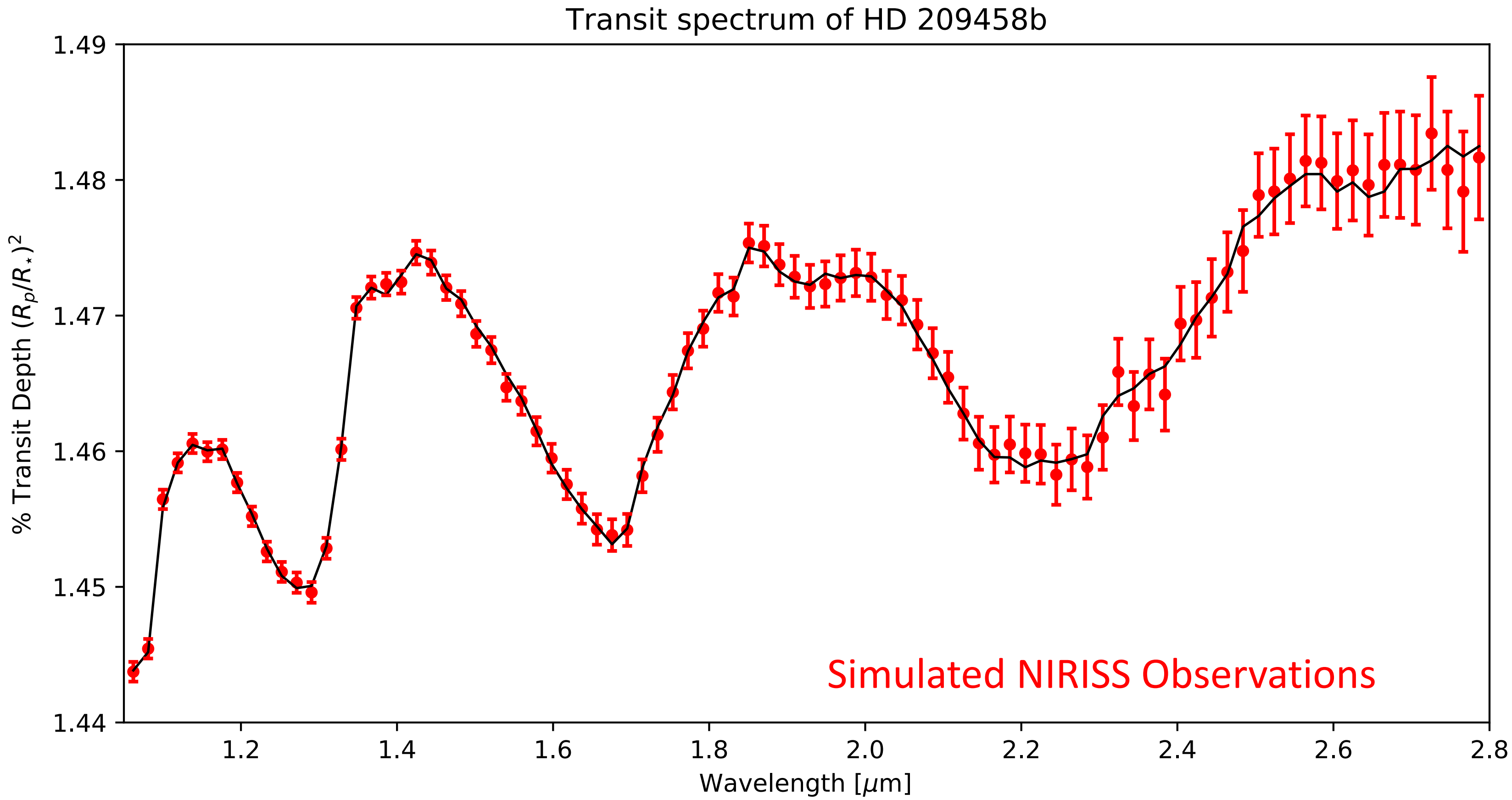
NIRISS team GTO exoplanet spectroscopy targets



Transit spectrum of HD 209458b

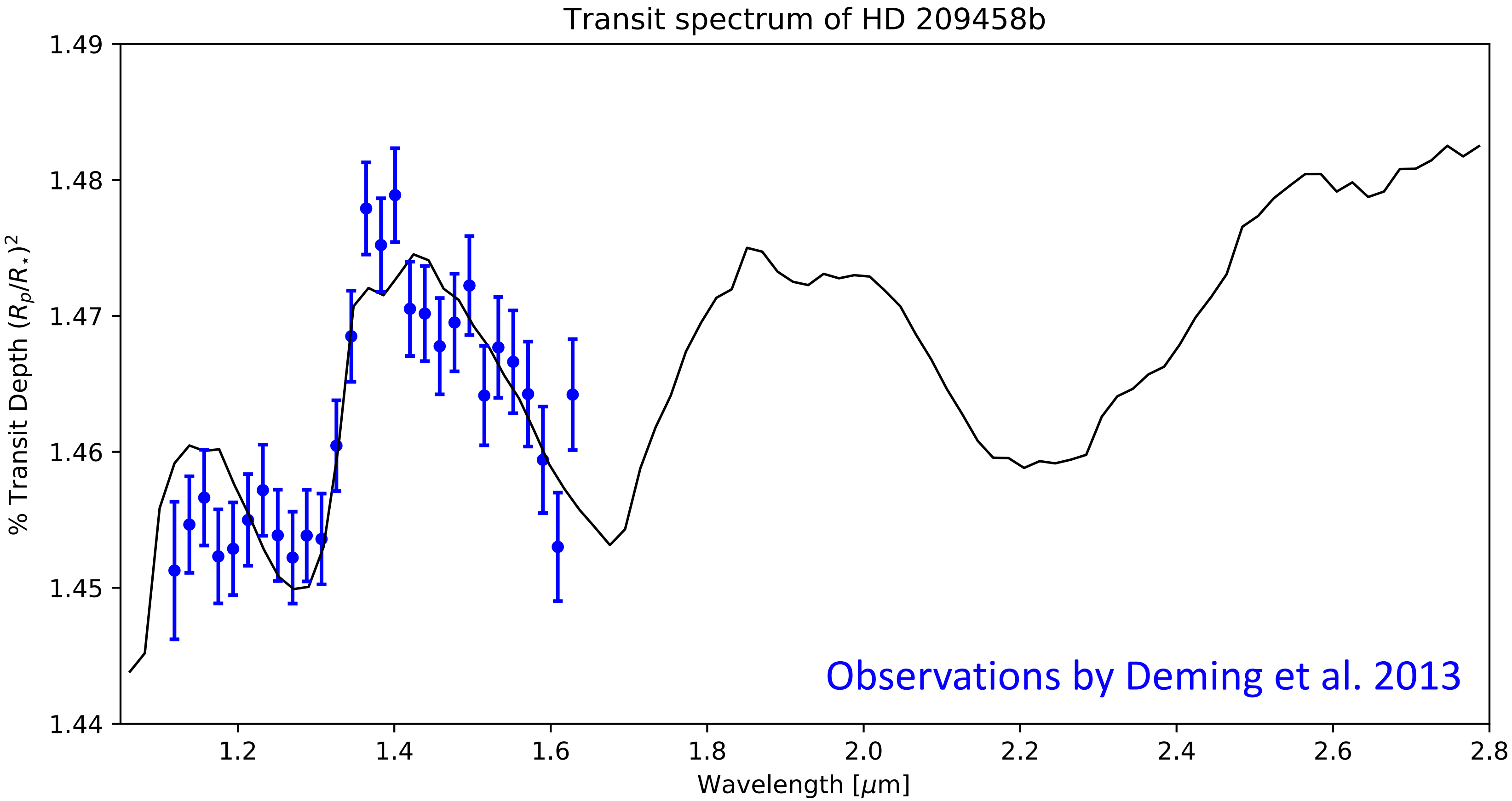


With JWST NIRISS

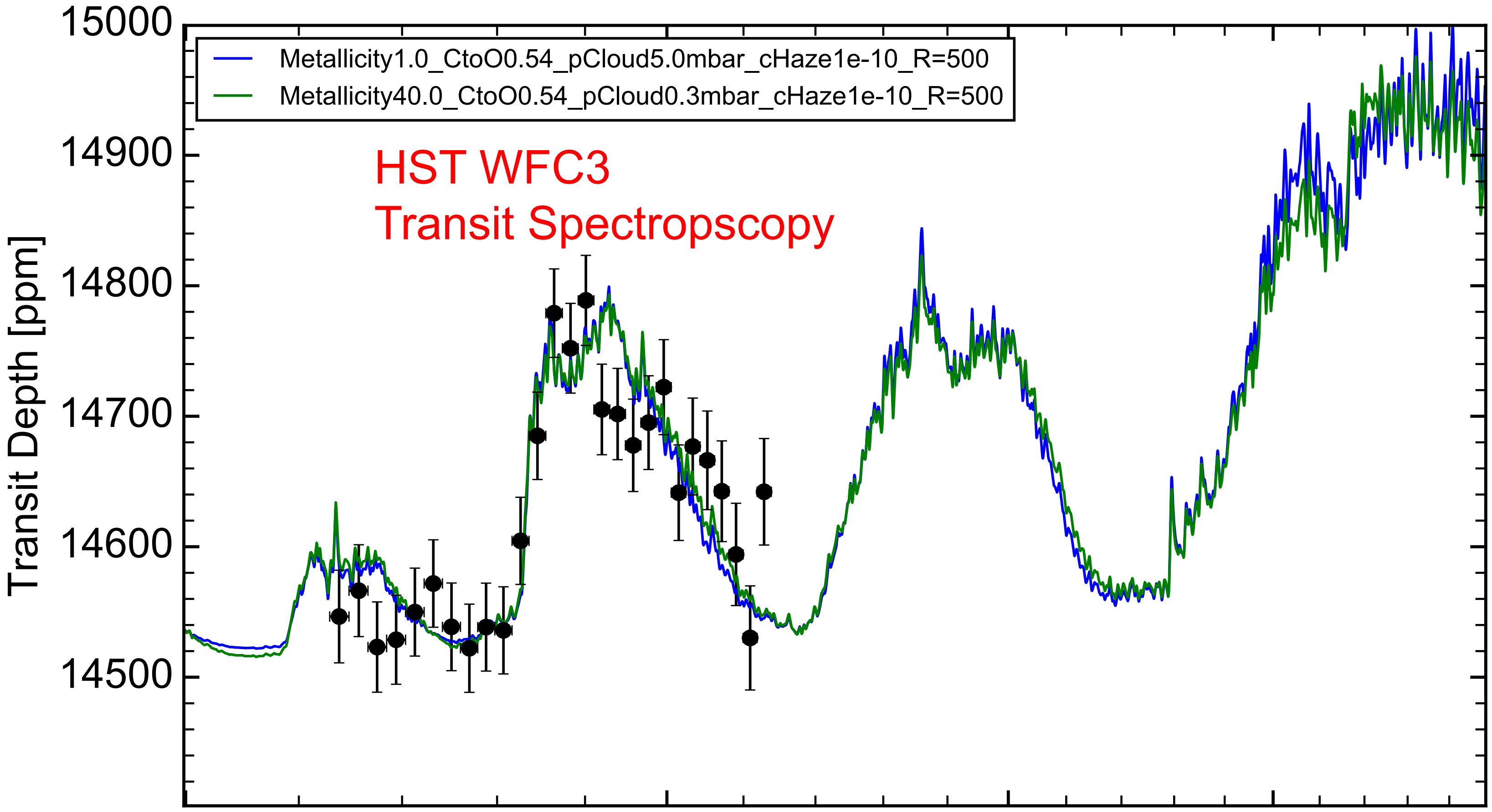


Transit spectrum of HD 209458b

With HST WFC3



Overall metallicity/clouds degeneracy in transit spectro.



HD 209458b

Figure/models: B. Benneke
Data points: Deming et al. 2013

Blue: solar metallicity, low clouds (5 mbar)

Green: 40X solar metallicity, high clouds (0.3 mbar)

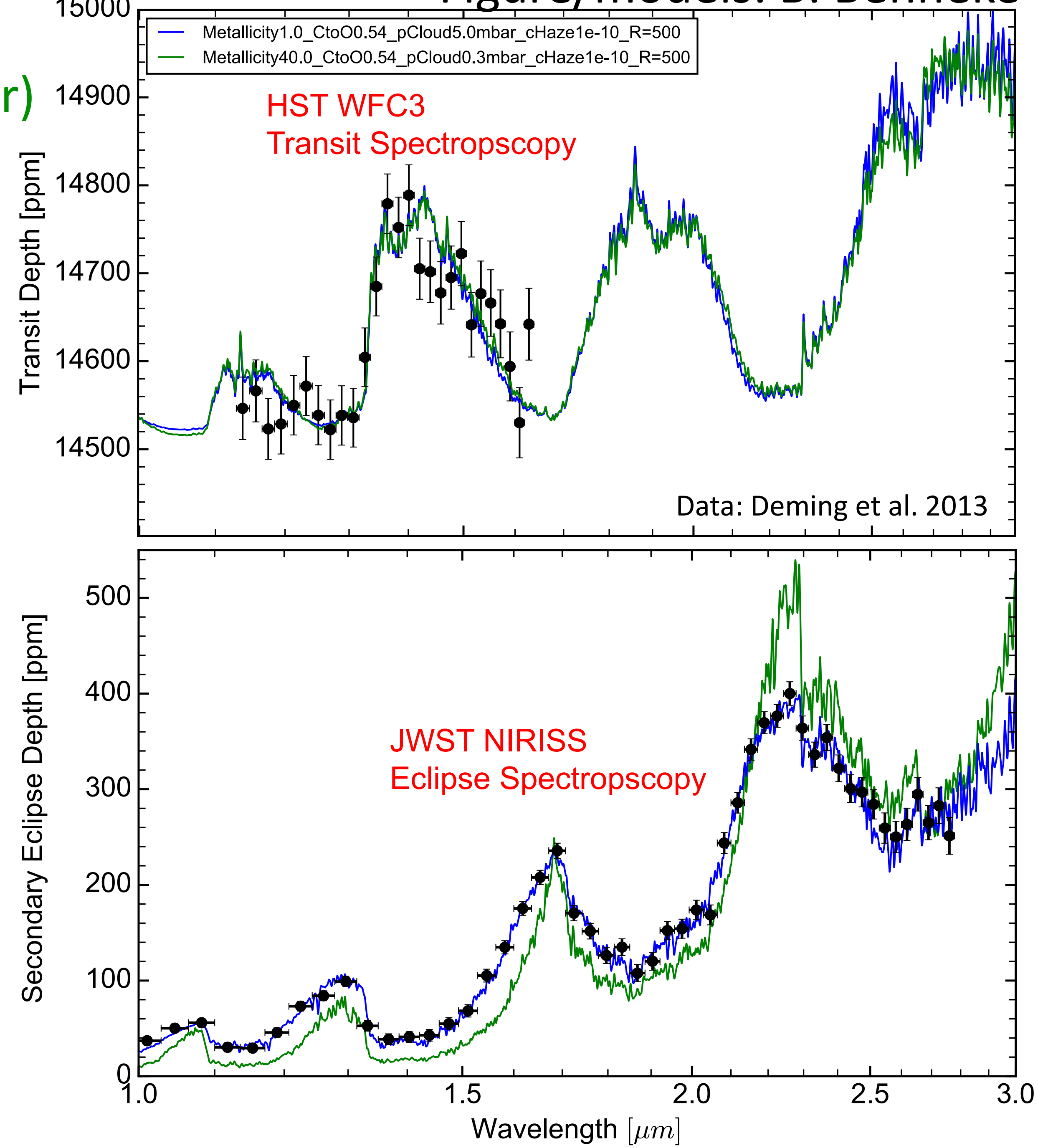
Figure/models: B. Benneke

Blue: solar metallicity, low clouds (5 mbar)

Green: 40X solar metallicity, high clouds (0.3 mbar)

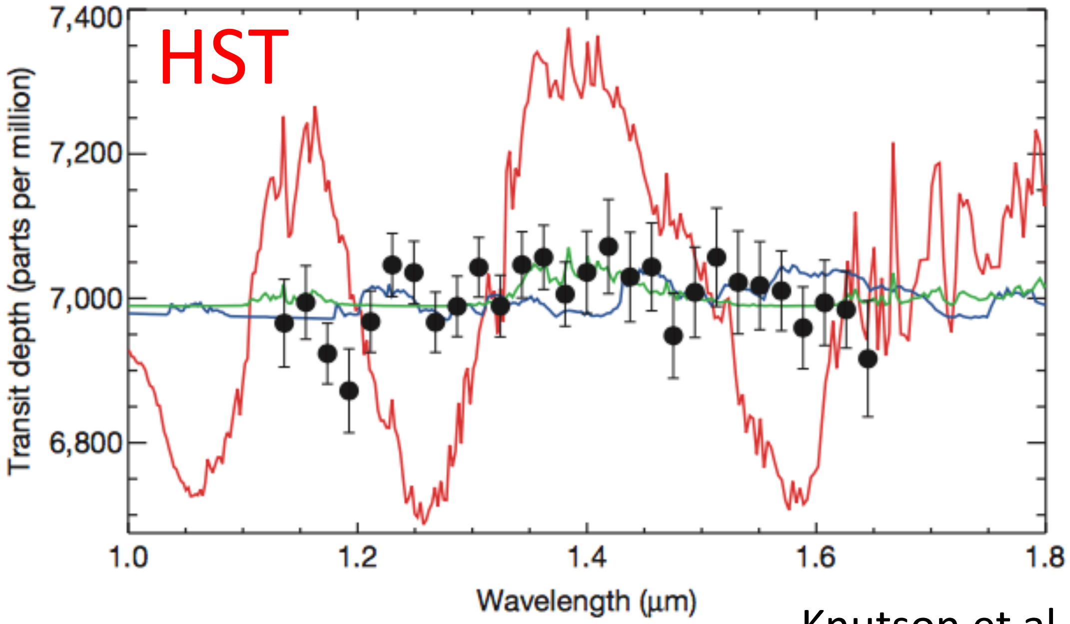
HD 209458b transit+eclipse

- Metallicity/cloud degeneracy can be lifted by NIRISS eclipse spectroscopy
- In turn, with Z constrained, clouds can be constrained from transit
- Eclipse gives better constraint of T-P profile

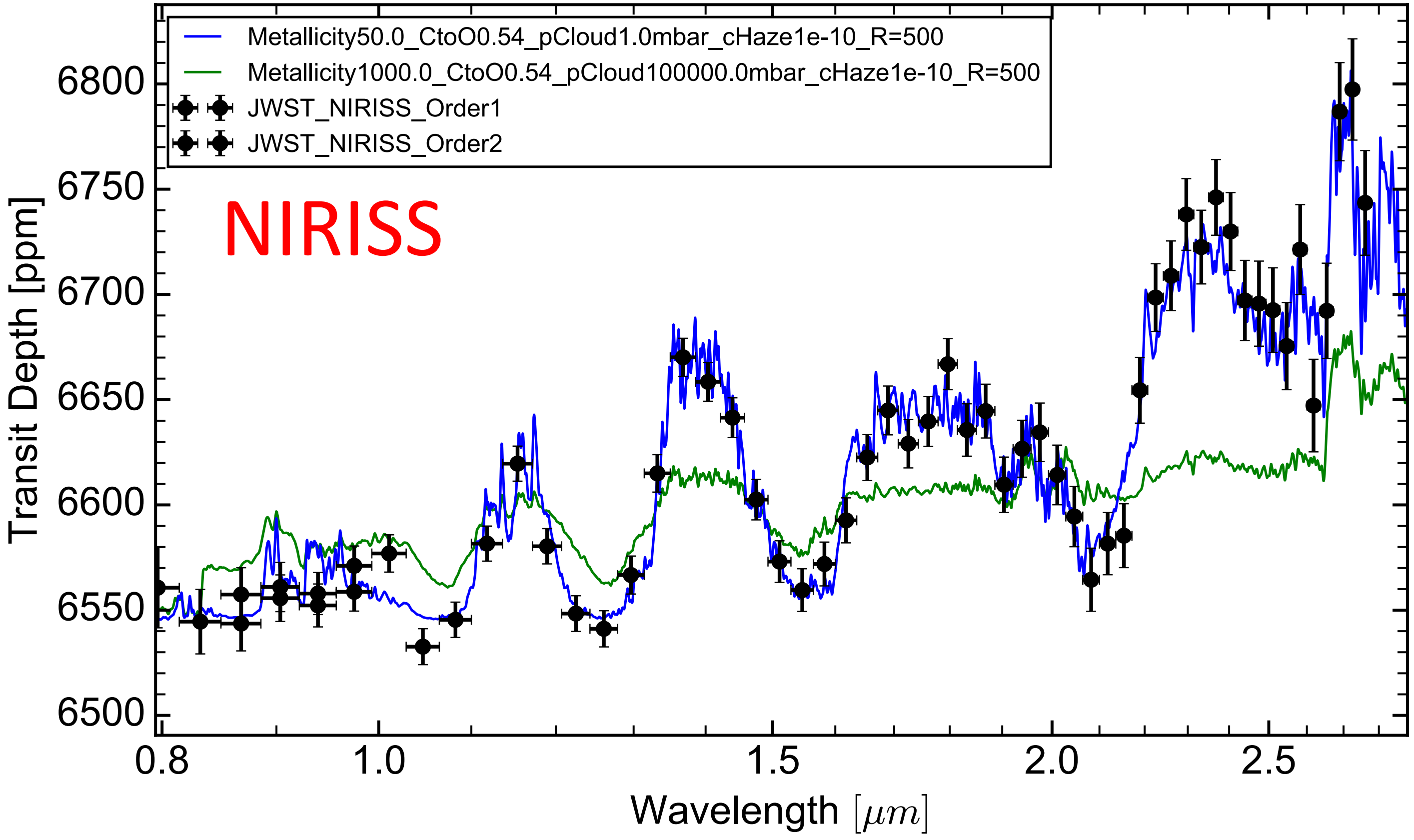


NIRISS transit of GJ 436b

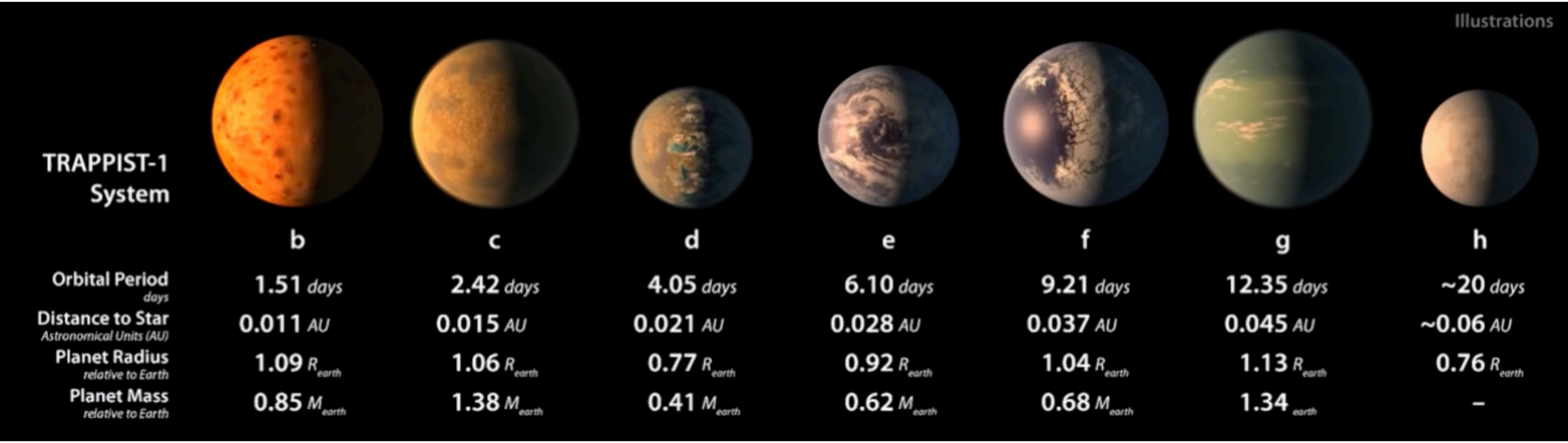
- Metallicity of smaller planets can get much higher, transit useful by itself



Knutson et al. 2014



Blue: 50X solar metallicity, high clouds (1 mbar)
Green: 1000X solar metallicity, ~no clouds
Model colors inverted in HST plot

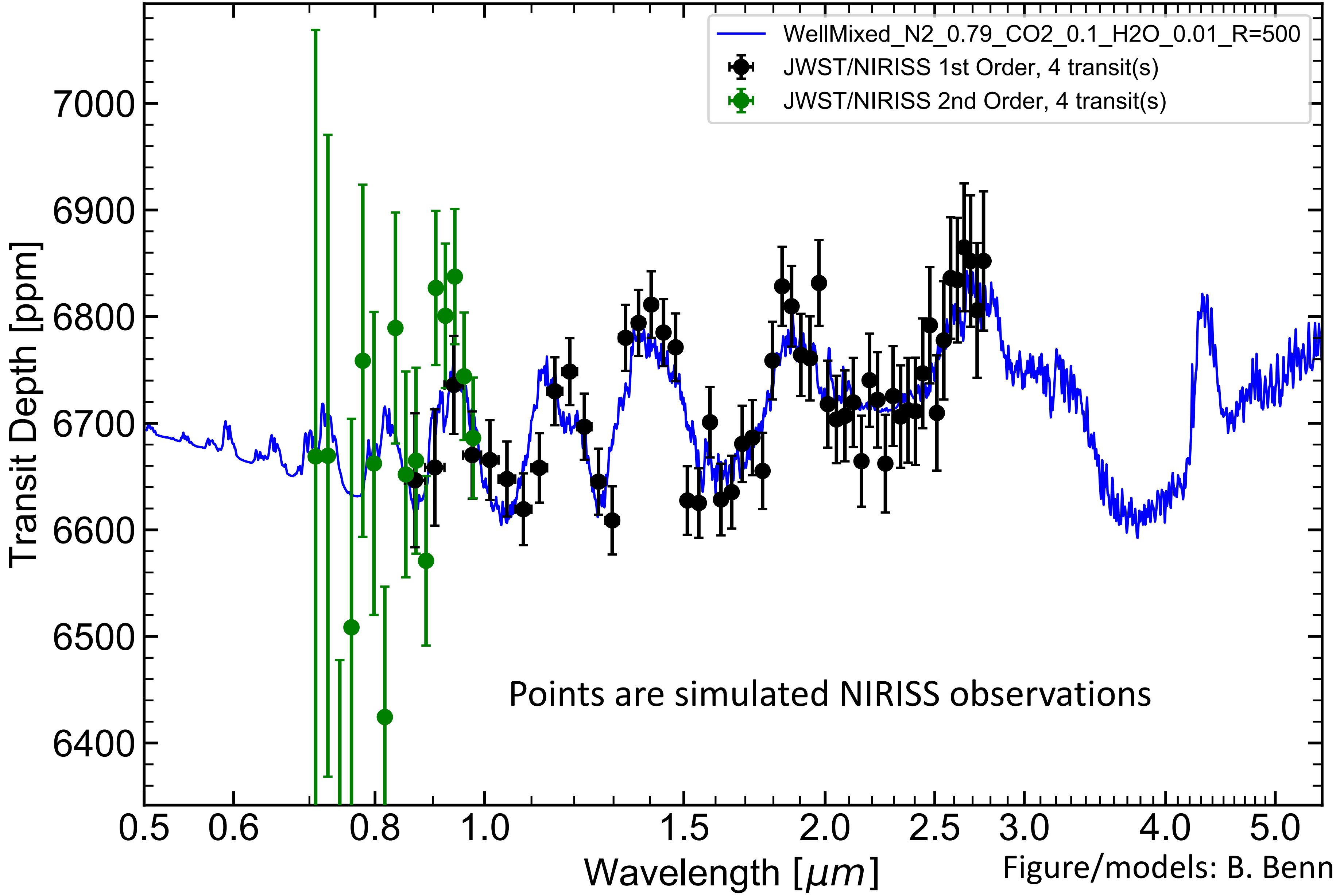


Gillon et al. 2017
Image: NASA/JPL

250 K   220 K   200 K

This one shown in
next example

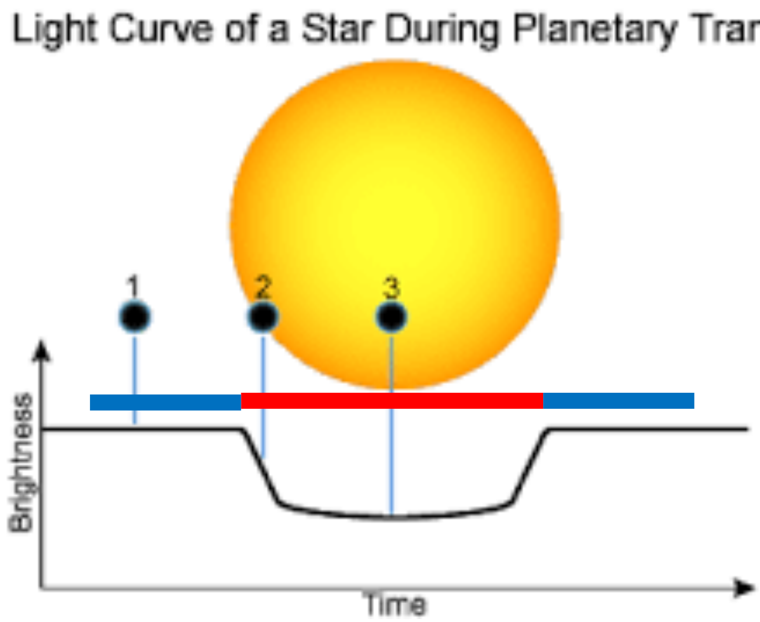
TRAPPIST-1f with Earth-like atmosphere



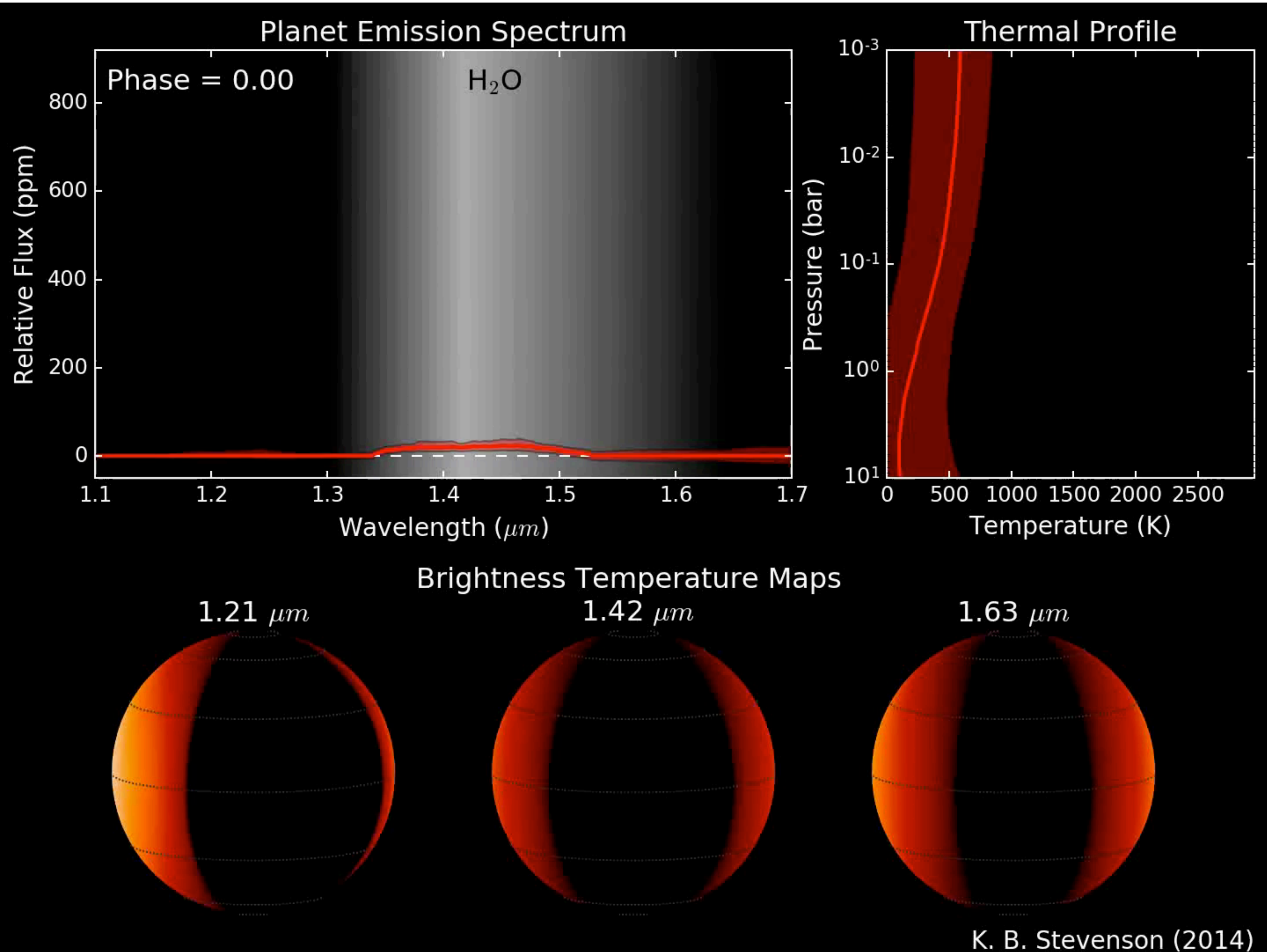
Figure/models: B. Benneke

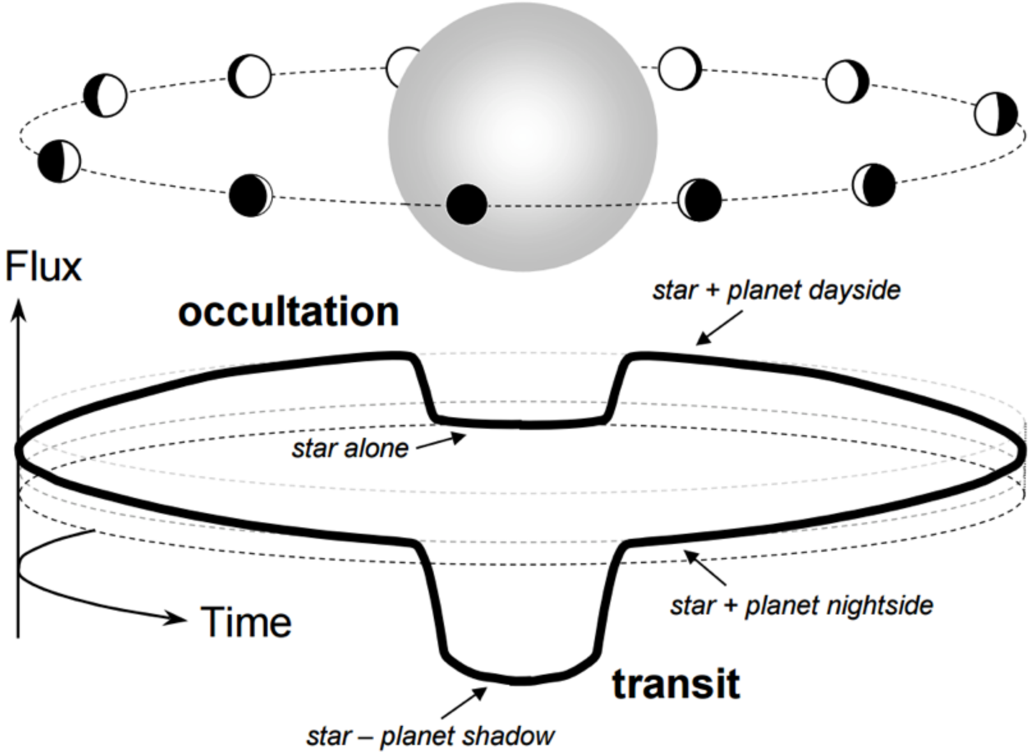
Observation strategy: transit/eclipse spectro

- For planet temperature >1200 K, observe transit and eclipse
  - To break the degeneracy between metallicity & clouds
- For planet temperature <1200 K, observe transit only
  - C part of CH_4 instead of CO, enable metallicity to be constrained from transit
  - Also for low masses, metallicity can be much higher, easier to differentiate from clouds
- Stare continuously for 2X a transit duration
  - Transit + half before & half after
- For shorter transits, we increase the out of transit baseline



Phase curve spectroscopy of hot Jupiters





WASP-43b
3 full planet orbits with HST/WFC3
Stevenson et al. 2014

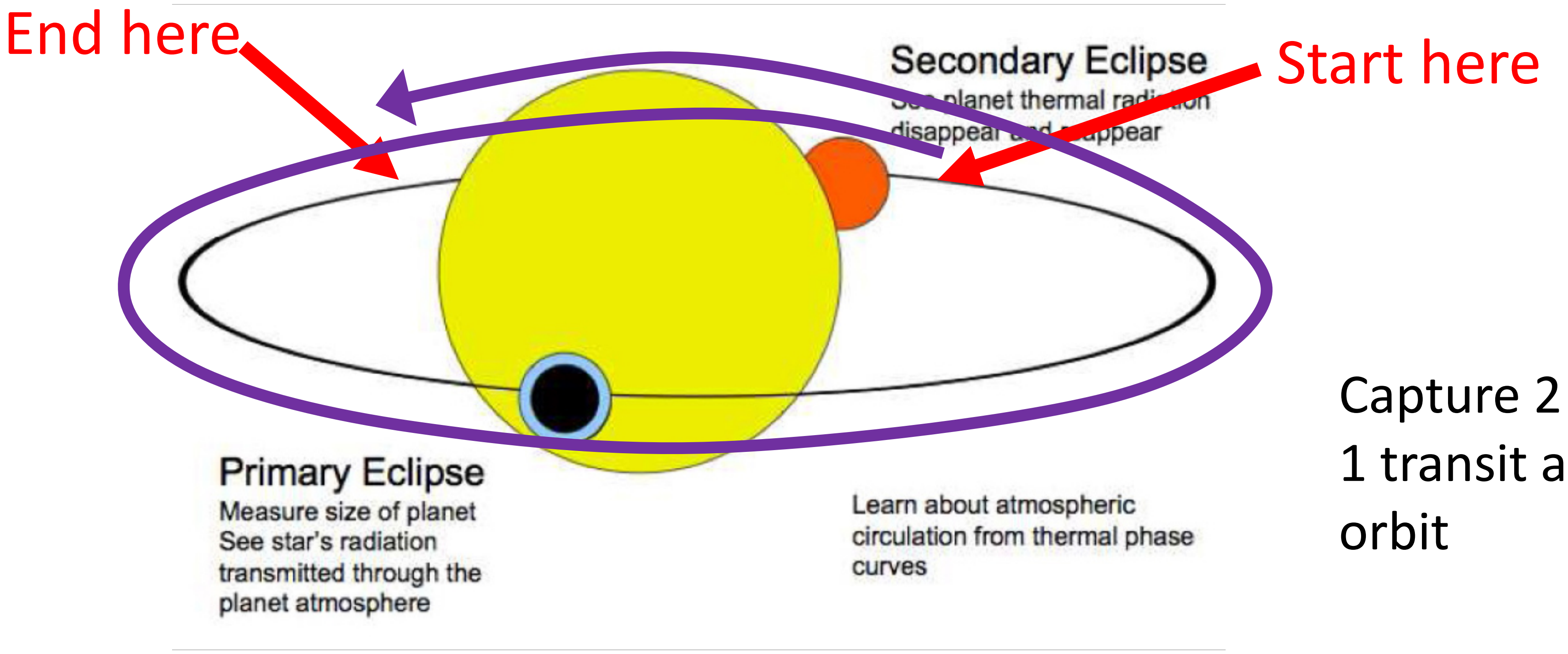
NEAT phase curve observation of WASP-121b

- WASP-121b (1.2 M_{Jup}, T_{eq}=2400 K)
  - Short orbital period (~30.6 hr)
    - Not too expensive target to demonstrate this science
  - Relatively bright, J=9.6, good precision possible
  - Has a temperature inversion (Evans et al. 2017, 2016)
    - Present at all phases?

  - Hot, dayside ~2700K, NIRISS will capture >80% of dayside flux
  - Wider wavelength range probes a greater vertical extent of atmosphere

Observation strategy: phase curve

- Stare continuously for entirety of WASP-121b's orbit starting before its secondary eclipse, and ending with additional phase overlap extending slightly beyond its secondary eclipse

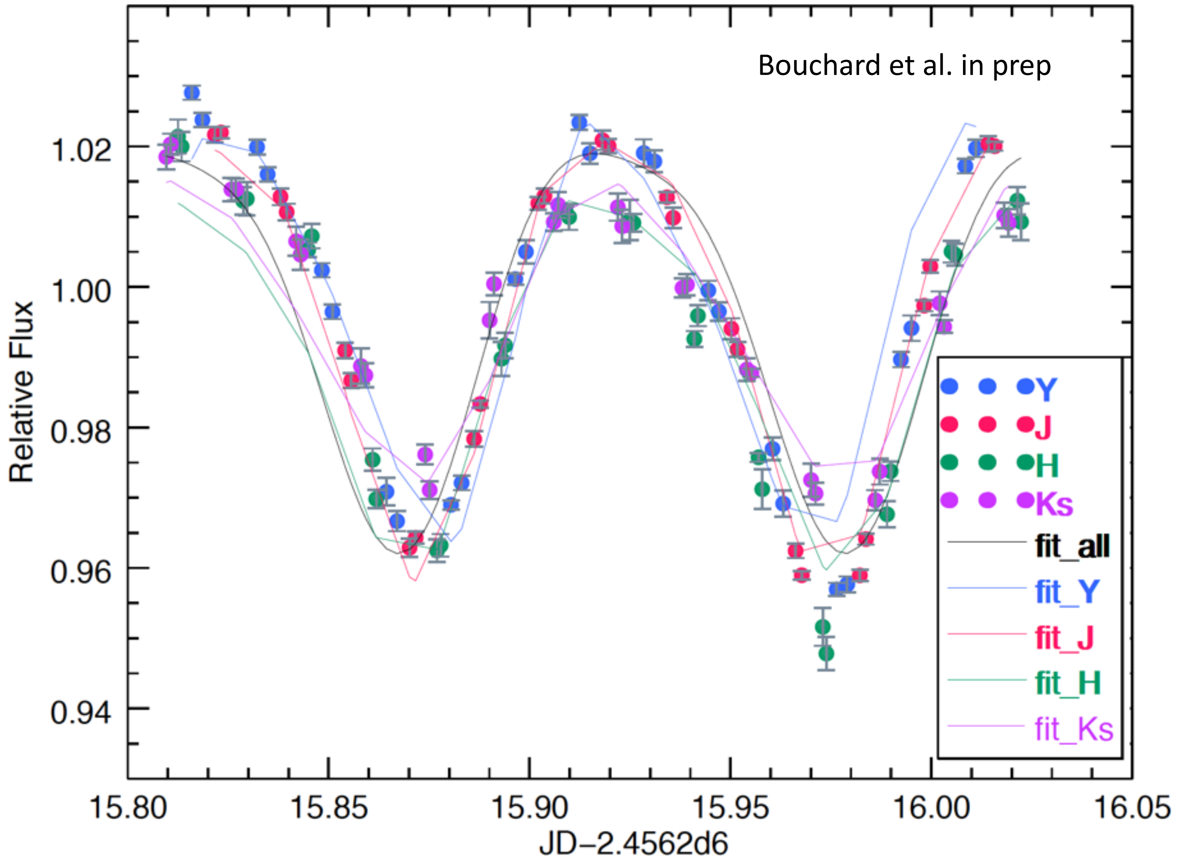


Capture 2 eclipses, 1 transit and full orbit

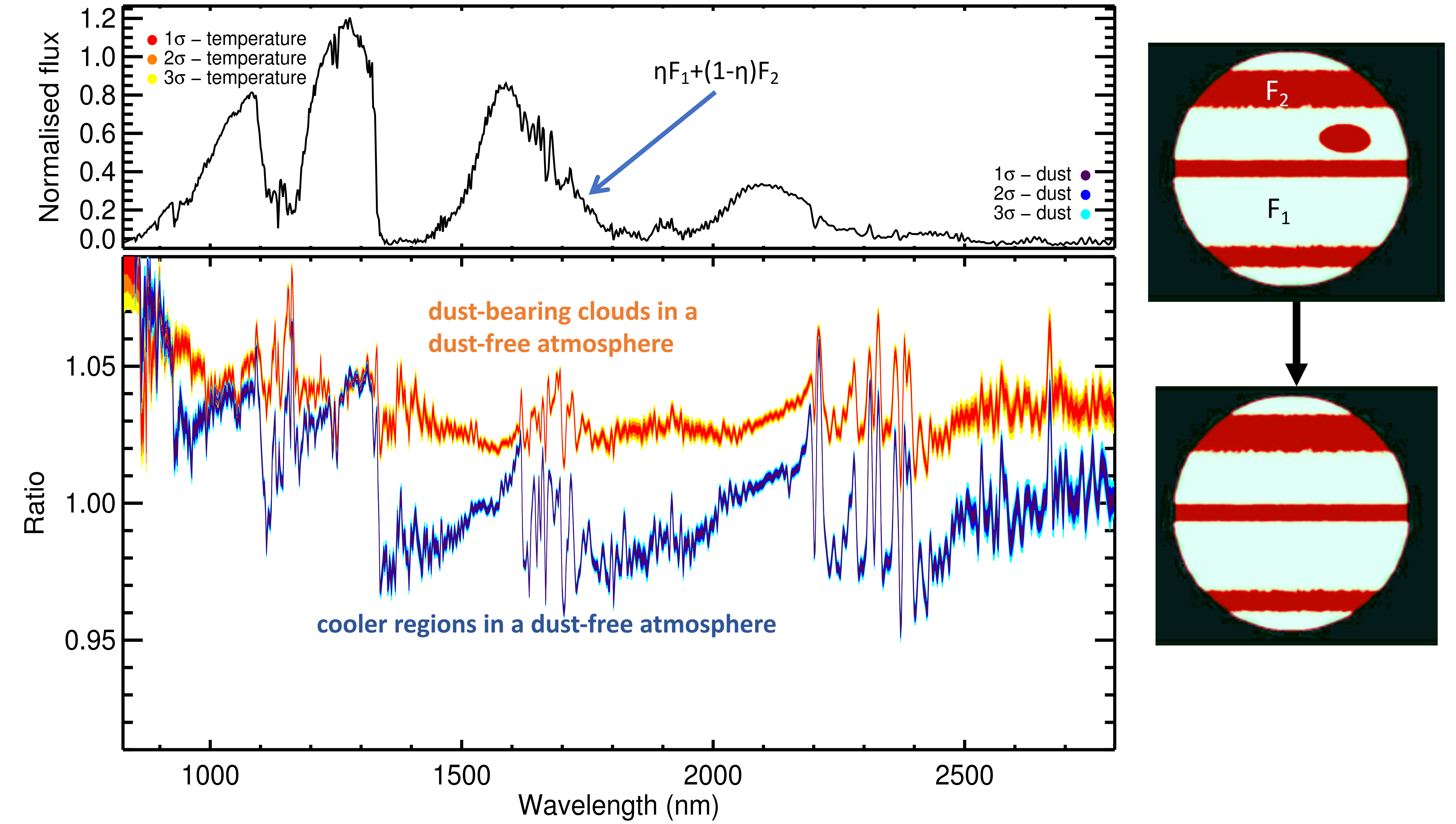
BD variability: SOSS time series of SIMP0136

- T2.5 SpT, T_{eff}=1200 K
  - Likely ~12 M_{Jup} mass
- 2.4 h rotation period
- 2-7% variability amplitude
- Bright, J=13.45

- Expect precision of 0.001 per resolution element in 5 min
  - Detection of variability >20-70 σ per resolution element



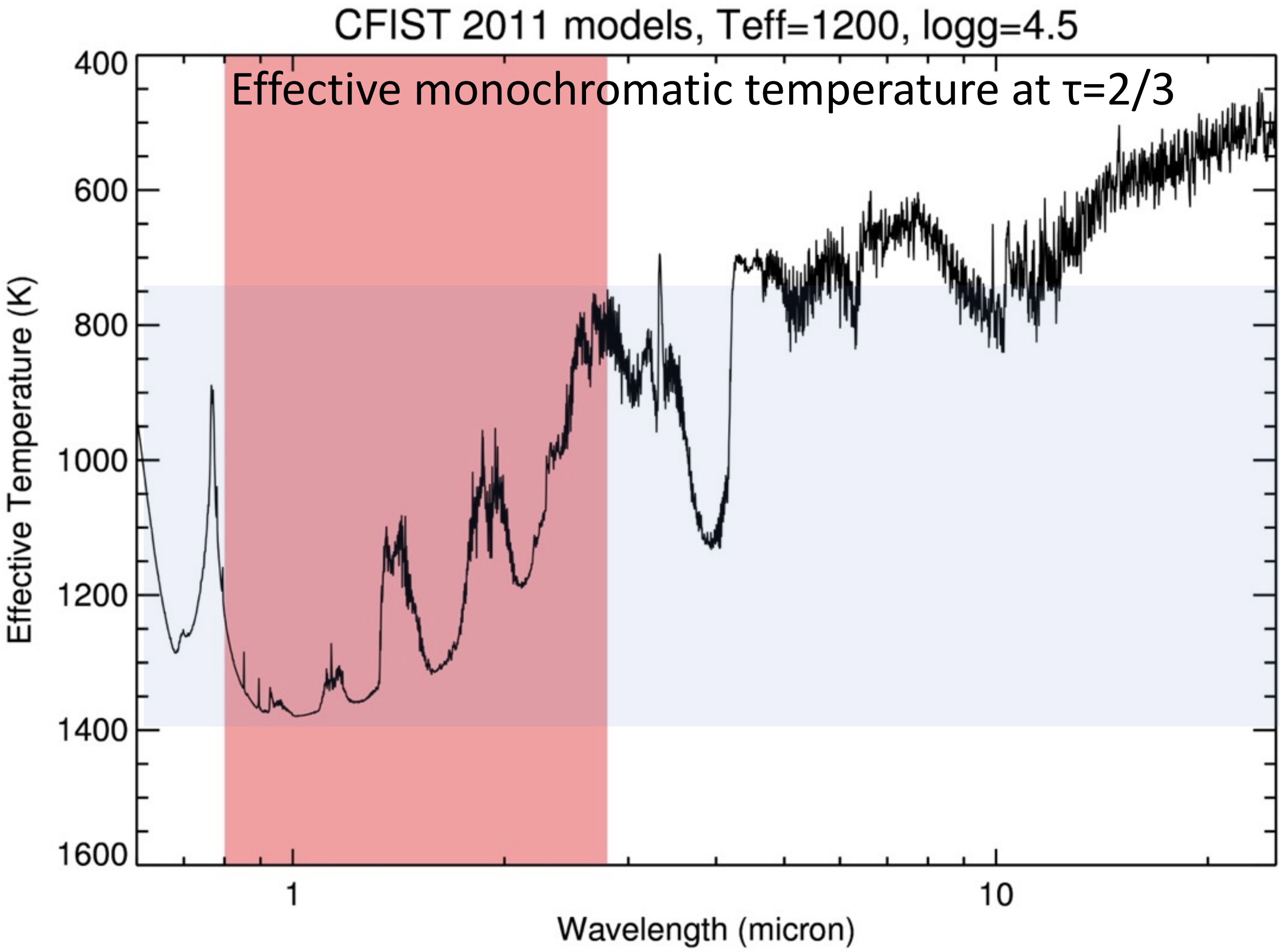
Program lead: É. Artigau (U Montreal)



Normalised flux
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1σ – temperature
2σ – temperature
3σ – temperature
ηF1+(1-η)F2
1σ – dust
2σ – dust
3σ – dust
Ratio
1.05
1.00
0.95
dust-bearing clouds in a
dust-free atmosphere
cooler regions in a dust-free atmosphere
1000
1500
2000
2500
Wavelength (nm)
F2
F1

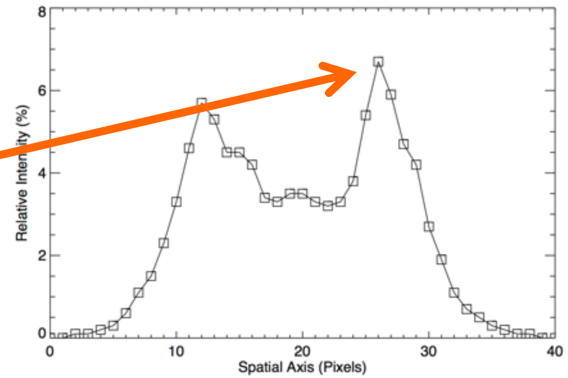
Why NIRISS SOSS for SIMP0136?

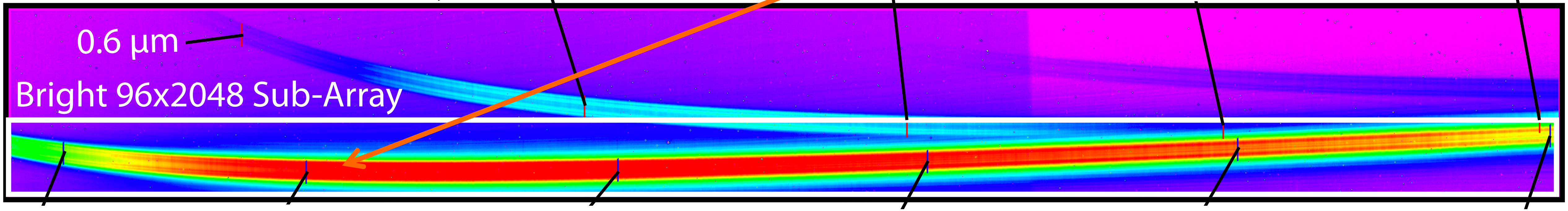
- Covers (nearly) the entire temperature range accessible between 0.5 and 20μm
- Resolution sufficient to resolve atomic features (Cs, K, Na)
- Covers deep water bands inaccessible from the ground



Practical considerations to develop your own SOSS program

SOSS saturation limits

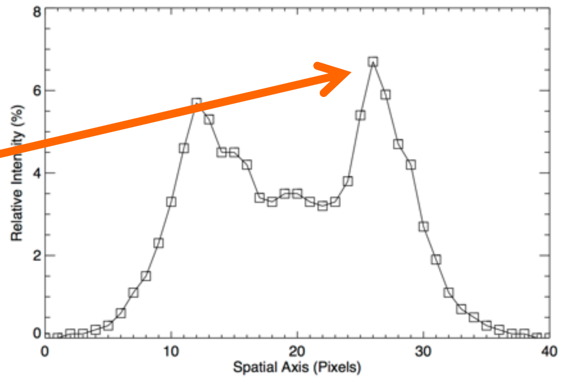


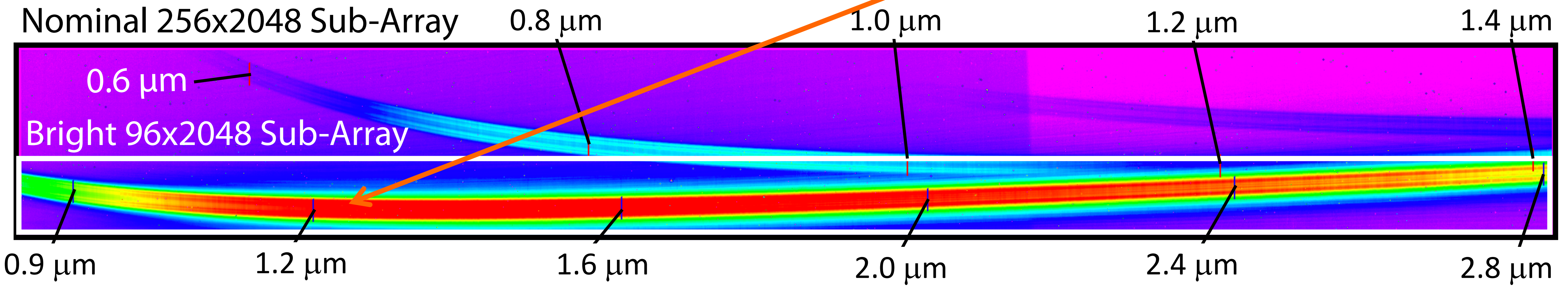


- **Standard Mode**, 256x2048 subarray, orders 1&2
  - Wavelength coverage: **0.6-2.8 μm**
  - Saturation limits:
    - **J=8.25** (Ngroup=2, CDS, 33% efficiency)
    - **J=7.5** (Ngroup=1, reset-read, 50% efficiency)

SOSS saturation limits

Saturation first occurs here and there





- **Bright Mode**, 96x2048 subarray (shown in white), order 1
  - Wavelength coverage: **0.9-2.8 μm**
  - Saturation limits:
    - **J=7.25** (Ngroup=2, CDS, 33% efficiency)
    - **J=6.5** (Ngroup=1, reset-read, 50% efficiency)

http://maestria.astro.umontreal.ca/niriss/simu1D

SOSS Simulation Tools
by the NIRISS Instrument Team

SOSS 1D Simulator | SOSS 2D Simulator | SOSS Trace Contamination

The NIRISS Single Object Slitless Spectrograph (SOSS) 1-D Simulator:

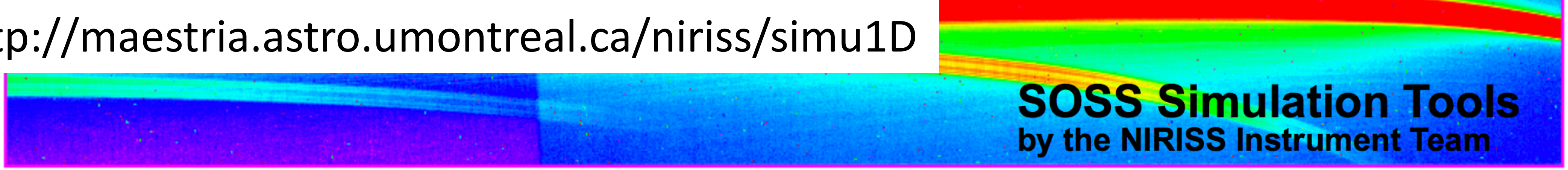
This tool prepared by the NIRISS Instrument Team simulates spectra produced with the SOSS observing mode of NIRISS doing transit spectroscopy. It computes signal and noise from first principles, based on our best knowledge of the instrument and observatory. This is a 1-D tool, i.e., we deal with flux per pixel row extracted from the detector and assume that the extraction was done optimally, not introducing errors. We encourage the user to read the Simulator Guide.

(Version 1.0)

Here is a SOSS Simulator Guide (in pdf).

Astrophysical Inputs	
Planet Name	Press to Resolve **NOTE: To resolve, the same formatting as the NASA Exoplanet Archive might be needed (ex : CoRoT-1 b).**
Planet Atmosphere Model	HD209458b_fortney2014.fits
	Check this box to scale the model by changing the scale height using actual temperature and gravity. Otherwise, the model will directly be used.
Star Radius	Rsun
Star Teff	Kelvin (rounded to 100 K)
Star J Mag	(Vega System)
Transit Duration	hours (t_14)
Planet Density	g/cm3
Planet Teq	Kelvin
Planet Solid Radius	Rjup
Instrument Setup and Observing Strategy	
Out to In Factor	1 (Ratio of time spent outside transit and during transit)
Number of Transits	1

http://maestria.astro.umontreal.ca/niriss/simu1D



SOSS 1D Simulator | SOSS 2D Simulator | SOSS Trace Contamination

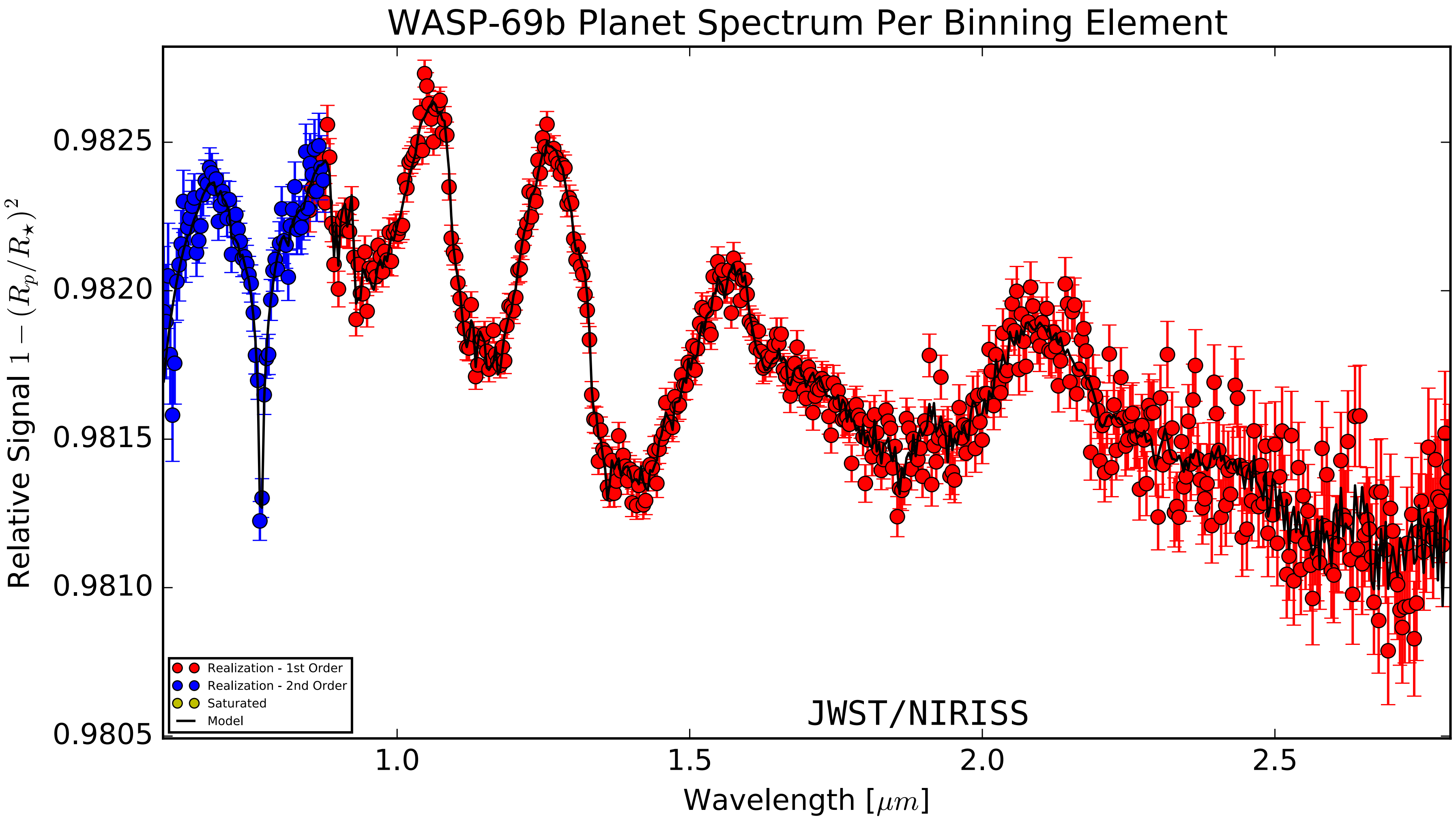
The NIRISS Single Object Slitless Spectrograph (SOSS) 1-D Simulator:

This tool prepared by the NIRISS Instrument Team simulates spectra produced with the SOSS observing mode of NIRISS doing transit spectroscopy. It computes signal and noise from first principles, based on our best knowledge of the instrument and observatory. This is a 1-D tool, i.e., we deal with flux per pixel row extracted from the detector and assume that the extraction was done optimally, not introducing errors. We encourage the user to read the Simulator Guide.

(Version 1.0)

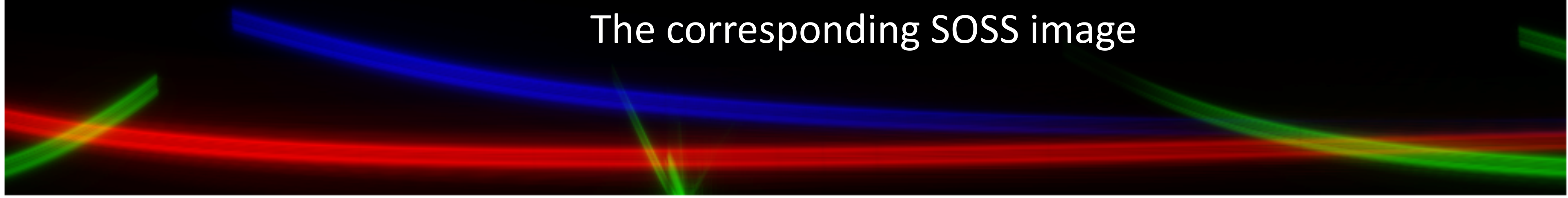
- Noise & S/N calculation
  - Different instrument parameters, visit duration, number of visits
- Saturation warning & wavelengths affected
- Simulated transit spectrum, with noise
  - Several atmosphere models available
- Diagnostic information
- Tabulated data export available

Sample output




```
Model : WASP_69_b_SolarNoCloud_Benneke20161111.fits
           STAR RADIUS (Rsun)    = 0.8100000
                STAR TEFF (K)    = 4715.0000000
                   STAR JVEGA    = 8.0319996
     TRANSIT DURATION (hours)    = 2.2296000
      PLANET DENSITY (g/cm^3)    = 0.2910000
           PLANET EQTEMP (K)     = 963.0000000
   SOLID PLANET RADIUS (Rjup)    = 1.0570000
            SCALE ATMOSPHERE     = 1
            OUT TO IN FACTOR     = 1.0000000
                   NTRANSIT      = 1
        AVERAGE TRANSIT DEPTH    = 0.9816994195
                 PIXELBIN M1     = 4
                 PIXELBIN M2     = 8
              FLOOR PPM (ppm)    = 20.0000000
          READOUTMODE (x2048)    = 256
                       NREAD     = 1
     READOUT NOISE (electrons)   = 45.0
                  EFFICIENCY     = 0.5000000
                  SATURATION     = 72000
                     TINT IN     = 1.115
           MEDIAN NOISE (ppm)    = 50.268586546549635
```

Slit-less = possible contamination



Red=target order 1

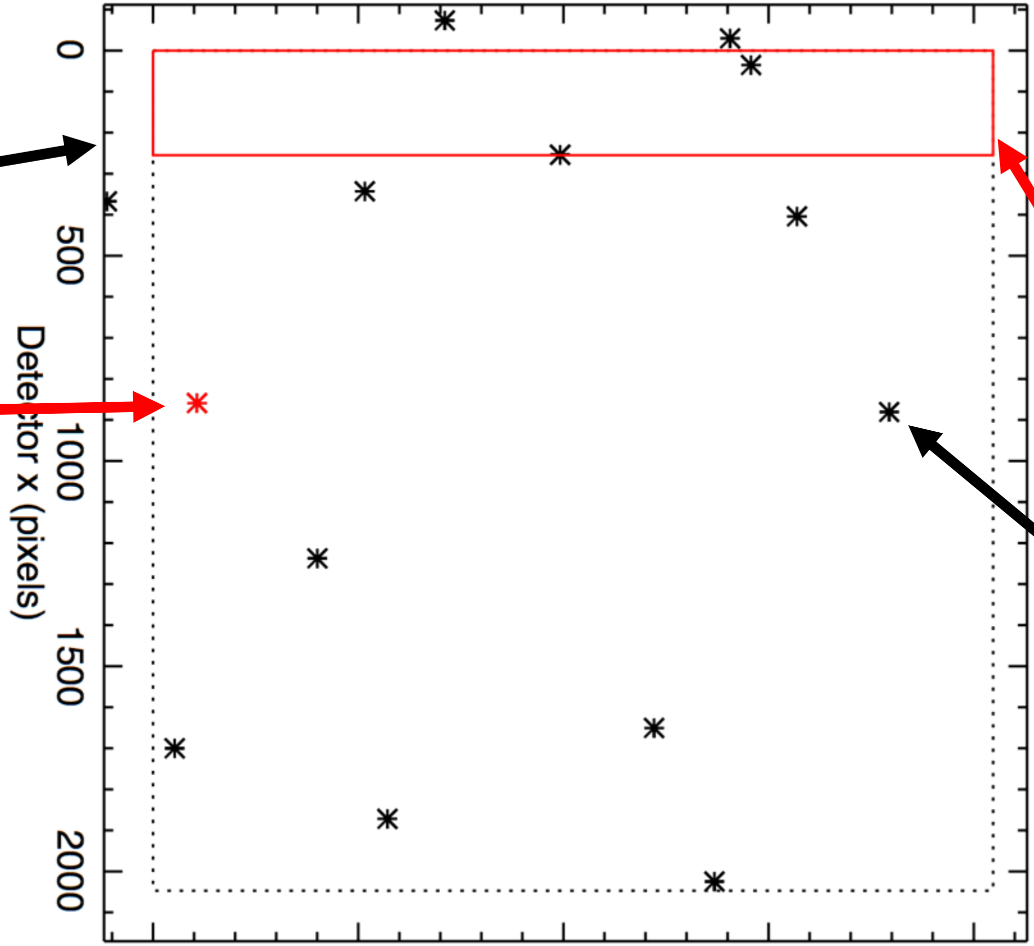
Blue= target order 2

Green=all orders of other stars in FOV

NIRISS pick-off mirror FOV

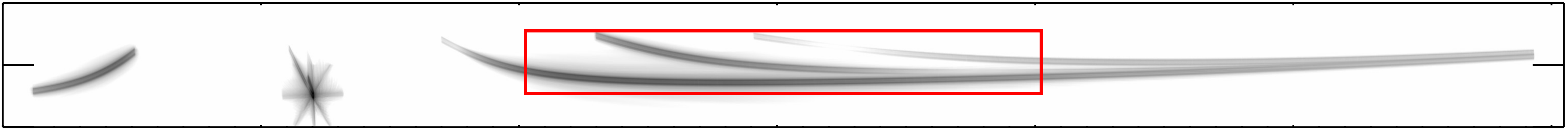
The target dispersed spectrum goes here in 256x2048 subarray

The target direct image is here



This star introduces contamination

Full dispersed trace (for reference)



http://maestria.astro.umontreal.ca/niriss/SOSS_cont

NIRISS SOSS planning tool

As its name suggests, the Single-Object Slit-less Spectroscopy (SOSS) mode of NIRISS is slit-less and thus the spectrum of a target star may be contaminated by partly overlapping spectra of nearby stars. For a given target, the details of this potential contamination are a function of the Aperture Position Angle (APA) at which the observations are taken. This tool simulates SOSS observations of a given target and produces an estimate of the level of contamination as a function of the APA of the observation; it may be used to plan observations at the optimal APA. The tool also computes the JWST accessibility windows of the target, along with the corresponding accessible PAs for NIRISS observations.

Important! Before September 26, 2017, there was an inconsistency in the definition of the APA used for this tool and and that used in APT. This has now been fixed, i.e. the APA here and in APT are the same. If you had used this tool prior to 2017 September 26 to plan observations, please re-do your calculations. Sorry for the inconvenience.

Usage notes:

- The "calculate contamination" button computes both the contamination and the visibility of a target. If you wish, you may calculate only the visibility using the "calculate visibility" button.
- The field stars used for this analysis are retrieved from the 2MASS point source catalogue. Contamination from stars missing from the 2MASS PSC is thus not modelled; this may be important for faint targets.
- For comments and questions, contact david.lafreniere@umontreal.ca

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Input information

Target name: Resolve name

Coordinates: RA (HH:MM:SS.S) DEC (DDD:MM:SS.S)

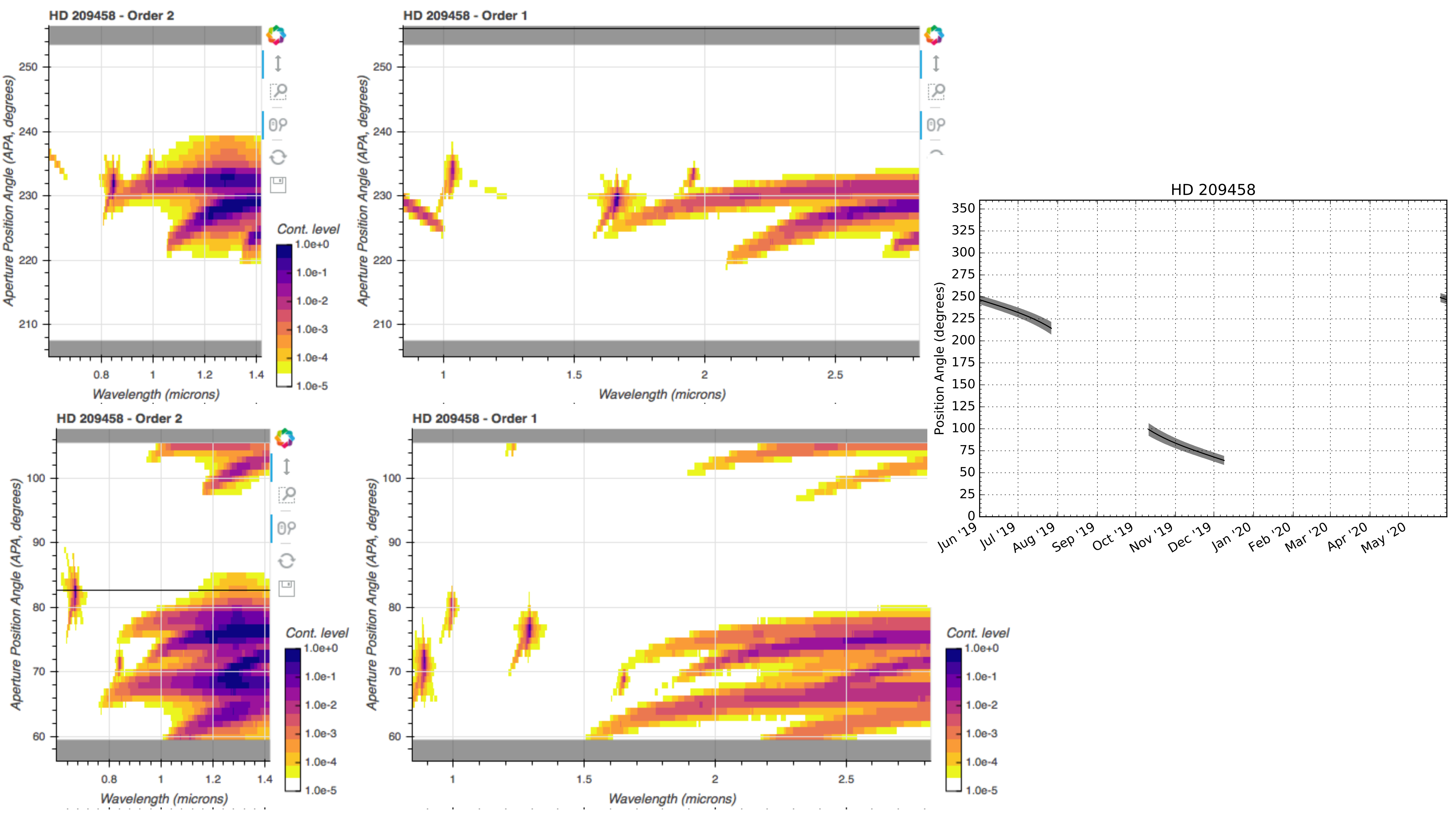
☐ Add a close binary companion not present in 2MASS, using information below:

RA offset ("), DEC offset ("), 2MASS J (mag), H (mag) and Ks (mag) [comma separated]

Actions

Calculate contamination (Be patient, this may take up to 30 seconds...)

Calculate visibility (This is quick, about 2 seconds.)

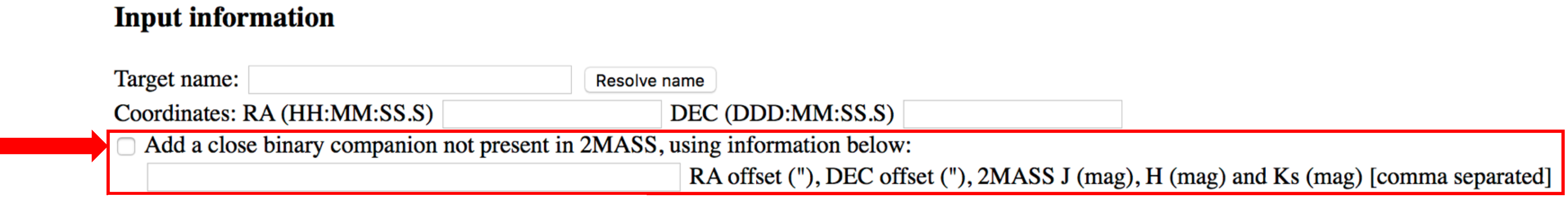


HD 209458 - Order 2
HD 209458 - Order 1
Aperture Position Angle (APA, degrees)
Wavelength (microns)
Cont. level
1.0e+0
1.0e-1
1.0e-2
1.0e-3
1.0e-4
1.0e-5
HD 209458 - Order 2
HD 209458 - Order 1
Aperture Position Angle (APA, degrees)
Wavelength (microns)
Cont. level
1.0e+0
1.0e-1
1.0e-2
1.0e-3
1.0e-4
1.0e-5
HD 209458
Position Angle (degrees)
Jun '19
Jul '19
Aug '19
Sep '19
Oct '19
Nov '19
Dec '19
Jan '20
Feb '20
Mar '20
Apr '20
May '20

Contamination tool warning

- Currently based on 2MASS PSC
- If a source is not in the PSC (unresolved, too faint) then its effect on contamination is not included.

- For unresolved binaries, option to add them manually.



Input information

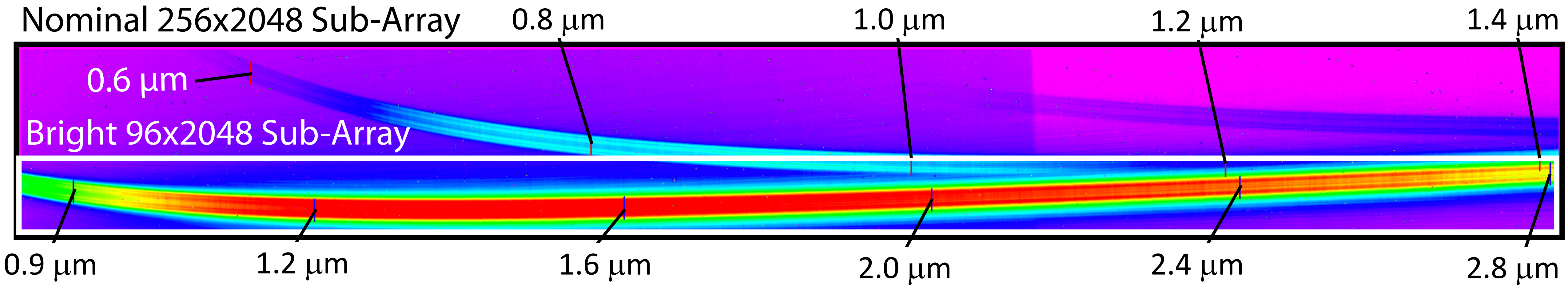
Target name: Resolve name

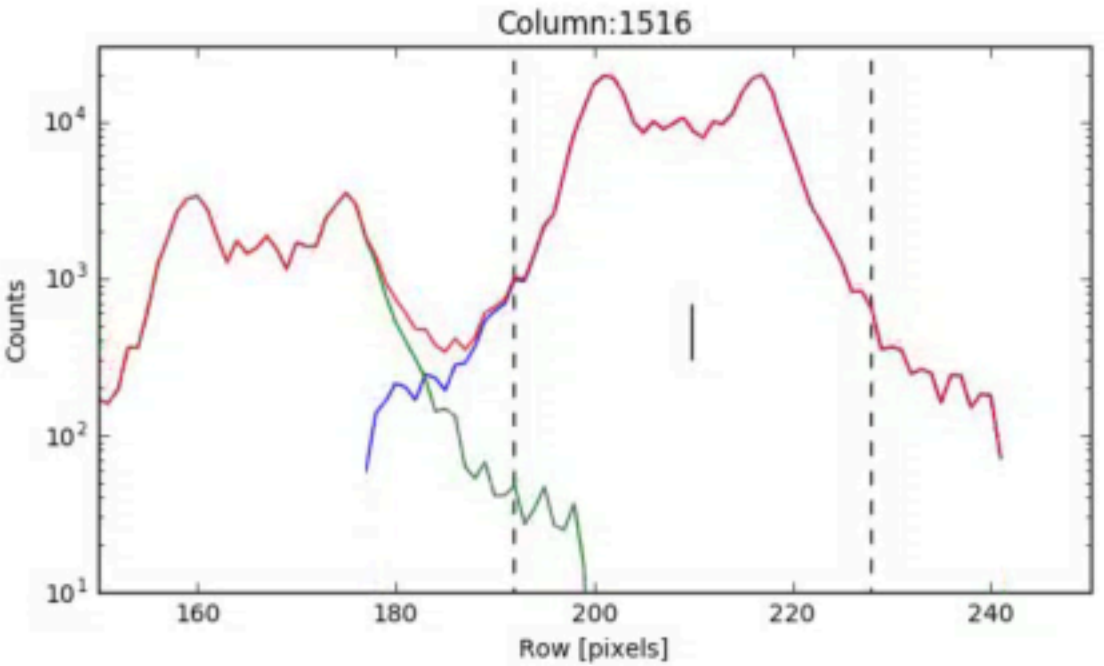
Coordinates: RA (HH:MM:SS.S) DEC (DDD:MM:SS.S)

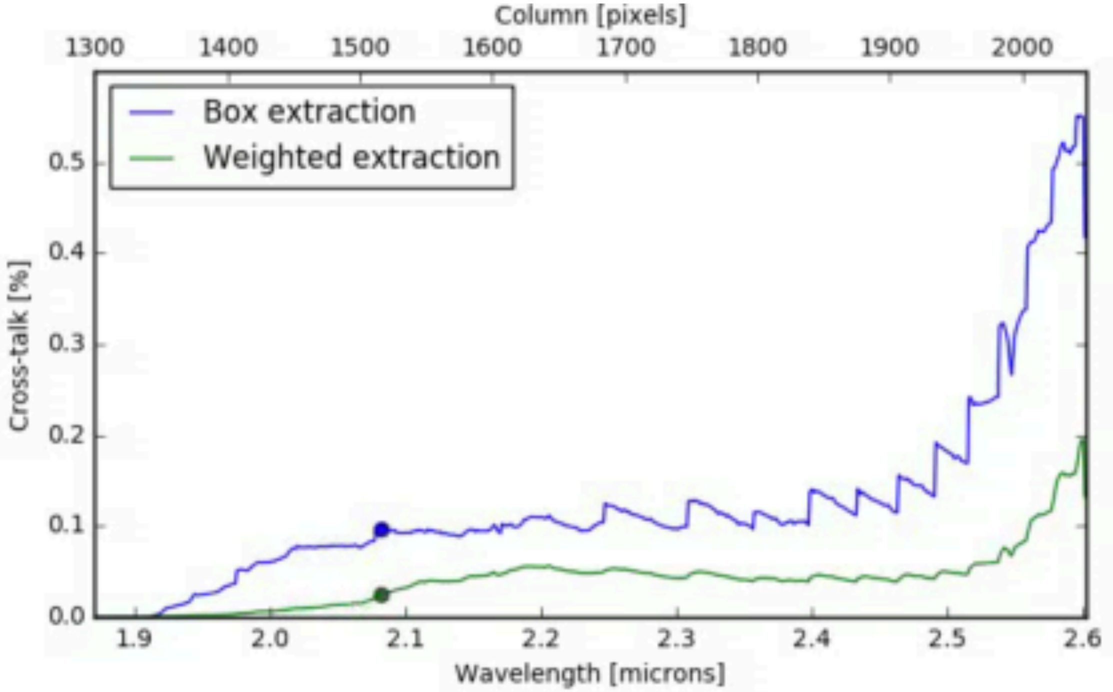
Add a close binary companion not present in 2MASS, using information below:

RA offset ("), DEC offset ("), 2MASS J (mag), H (mag) and Ks (mag) [comma separated]

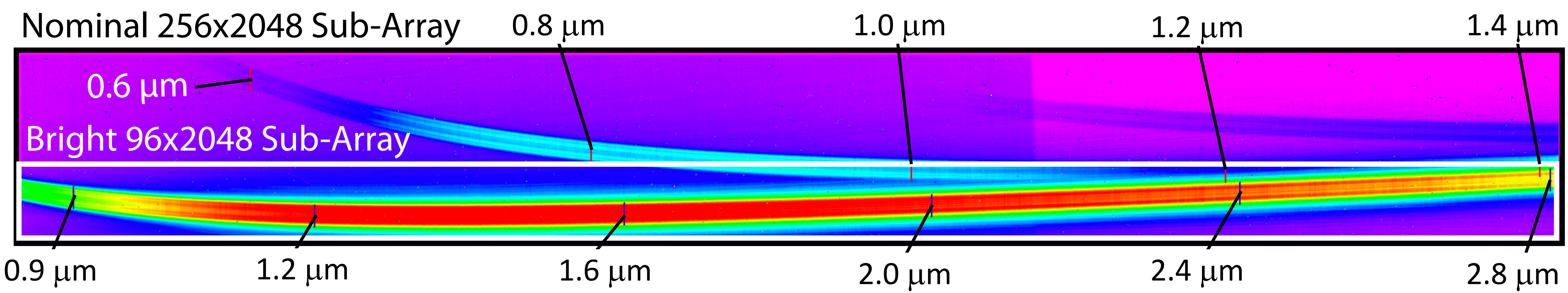
Order 2 overlap: contamination

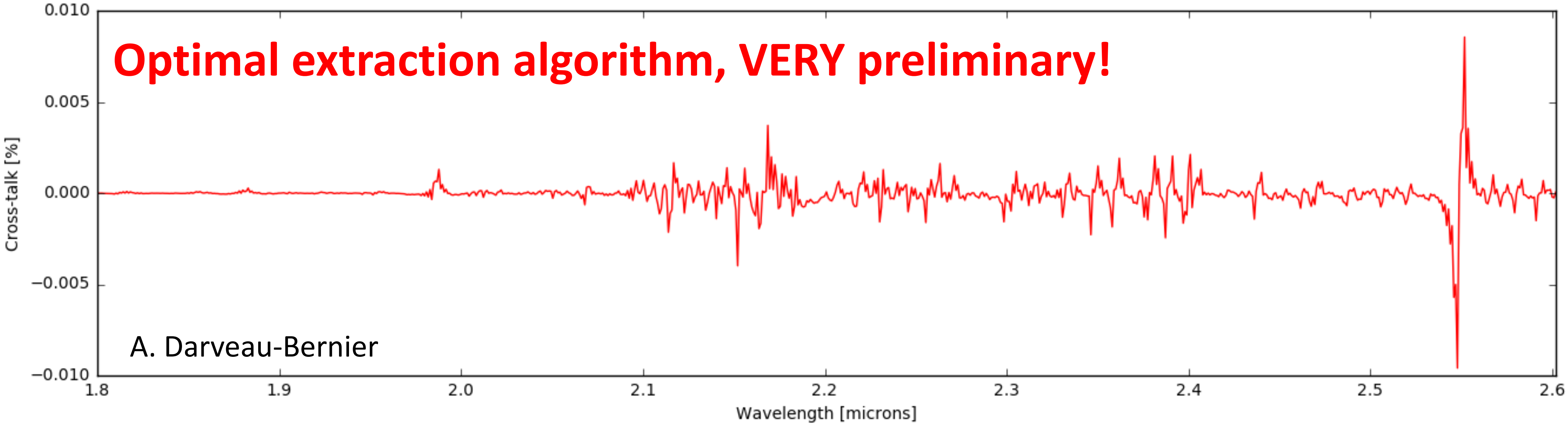






Order 2 overlap: contamination





Contact us for any question/help with NIRISS SOSS

- Loïc Albert (albert@astro.umontreal.ca)
- David Lafrenière (david@astro.umontreal.ca)

- NIRISS information & tools: http://jwst.astro.umontreal.ca

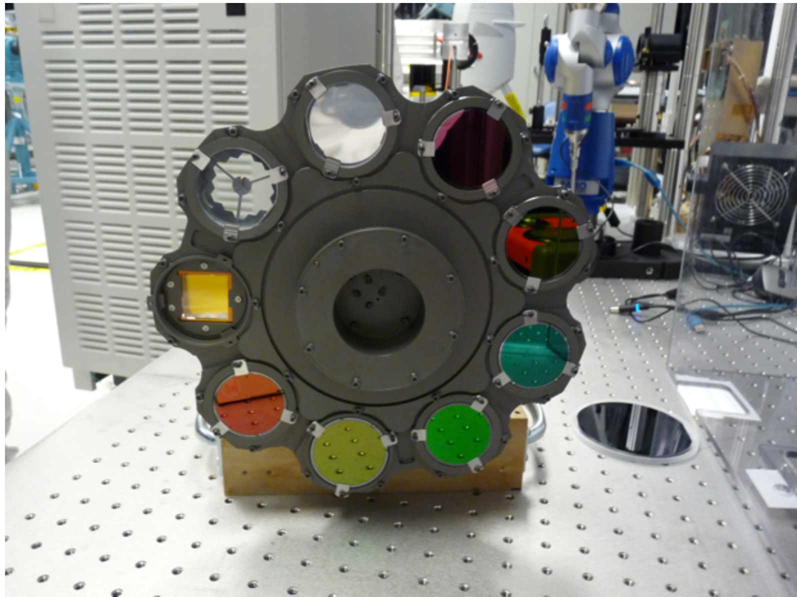
END

Backup slides

Instrument overview

- FGS (Fine Guidance Sensor)
  - Provides fine guiding to observatory, 4 mas
  - 0.6-5 µm camera, no filters, FOV 2.3’x2.3’

- NIRISS (Near-Infrared Imager and Slitless Spectrograph)
  - 0.6-5 µm camera, four observing modes:
    - Wide-Field Slit-less Spectroscopy (WFSS)
    - **Single-Object Slit-less Spectroscopy (SOSS)**
    - Aperture Masking Interferometry (AMI)
    - Broad+median band imaging



SOSS spectral response function