Simulation of Exoplanet Transit Observations with NIRSpec

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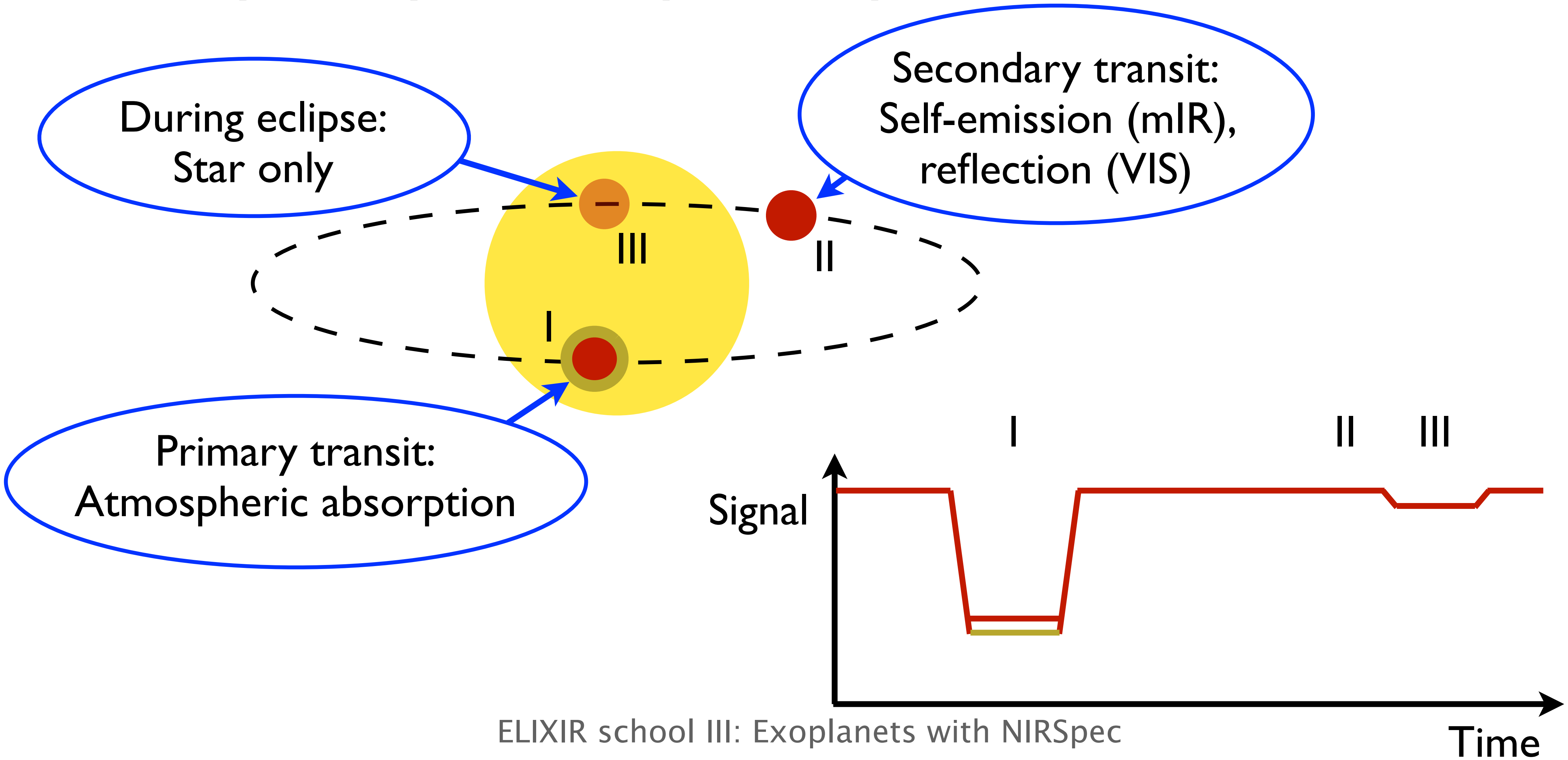
Science case: Planetary systems

- Characterization of planetary systems ("Origin of life", habitability)
- 834 planets known, 282 transiting (last week)
- Detection of absorption features in atmospheres (O_2, O_3, CO_2, H_2O, CO, CH_4, Na, K)
- Detection and spectroscopy of thermal emission from planets

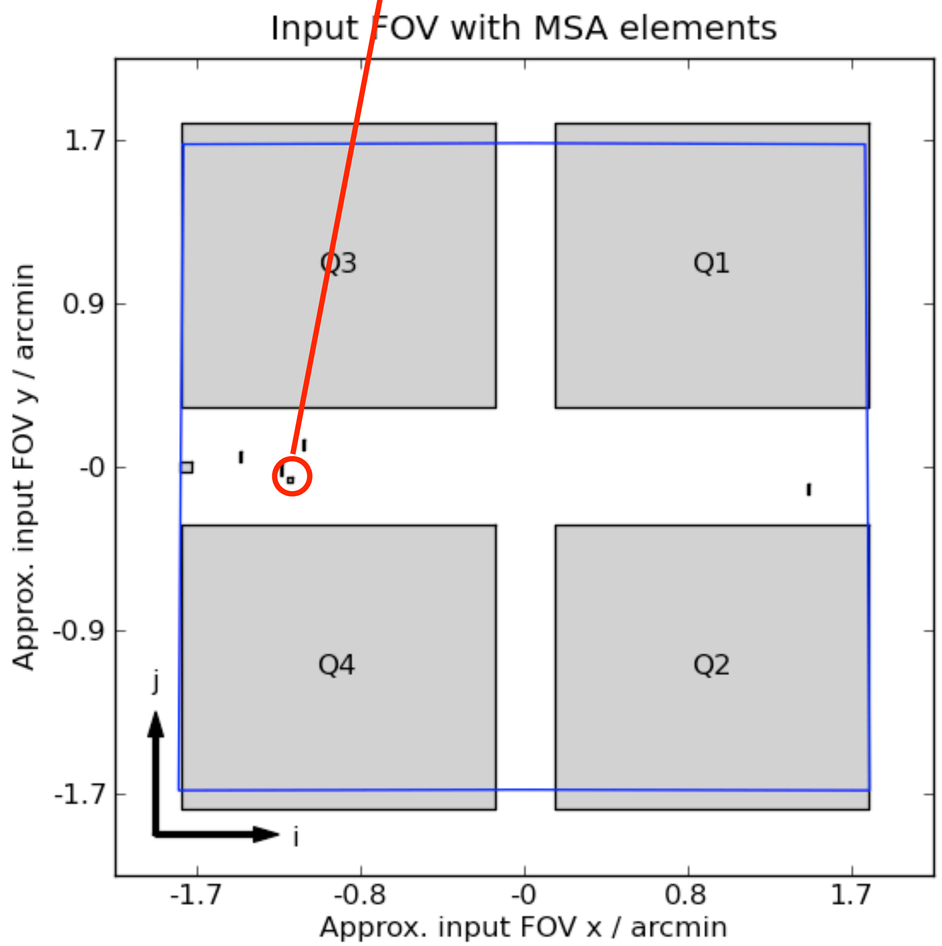
Transit observations

- Typical signal levels: 1:100,000
- Successful observations with HST, Spitzer, and from ground (Charbonneau et al., 2002, 2005, Bean et al., 2010)
- NIRSpec: special square aperture S1600A1



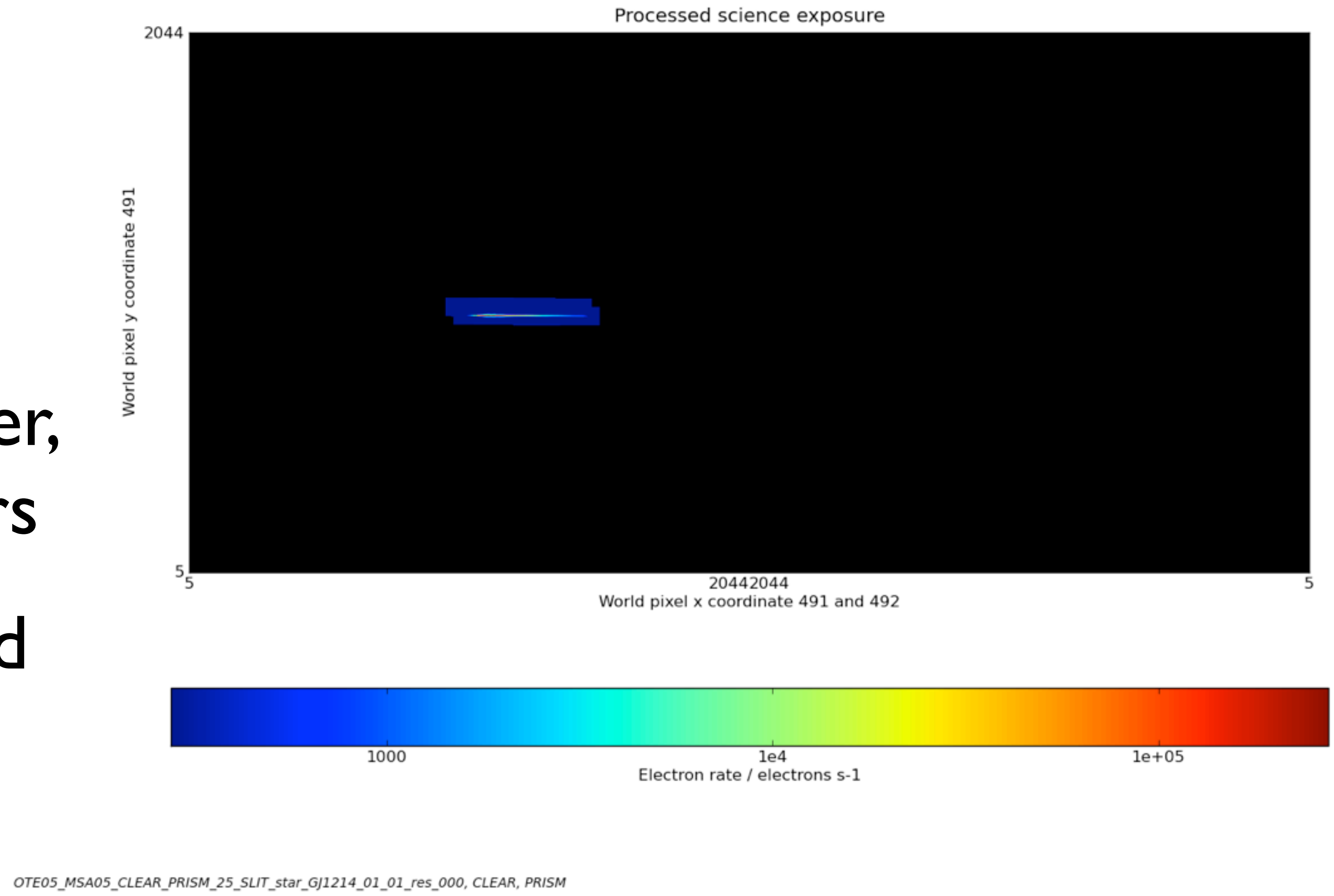
Observation setup

- Single star (point source) in 1.6" slit
- Different NIRSpec modes (filters, dispersers)
- Subarray readout
- No dithering



Spectra shapes and locations

- PRISM: short spectrum
- Gratings: longer, multiple orders
- Spectra curved
- Slit tilt: 4–12 degrees



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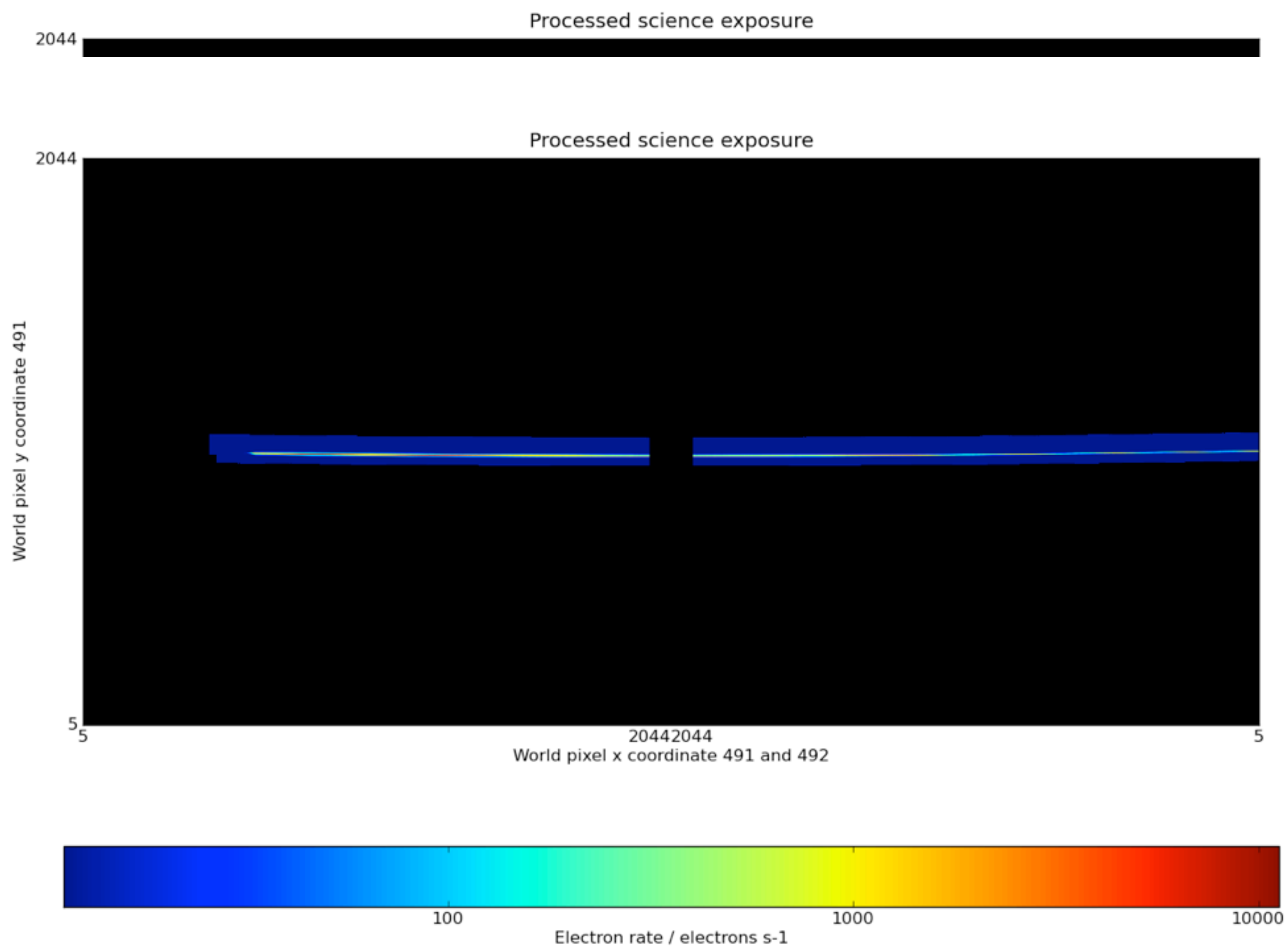

OTE05_MSA05_F100LP_G140M_25_SLIT_star_GJ1214_01_02_band1_res_000, F100LP, G140M

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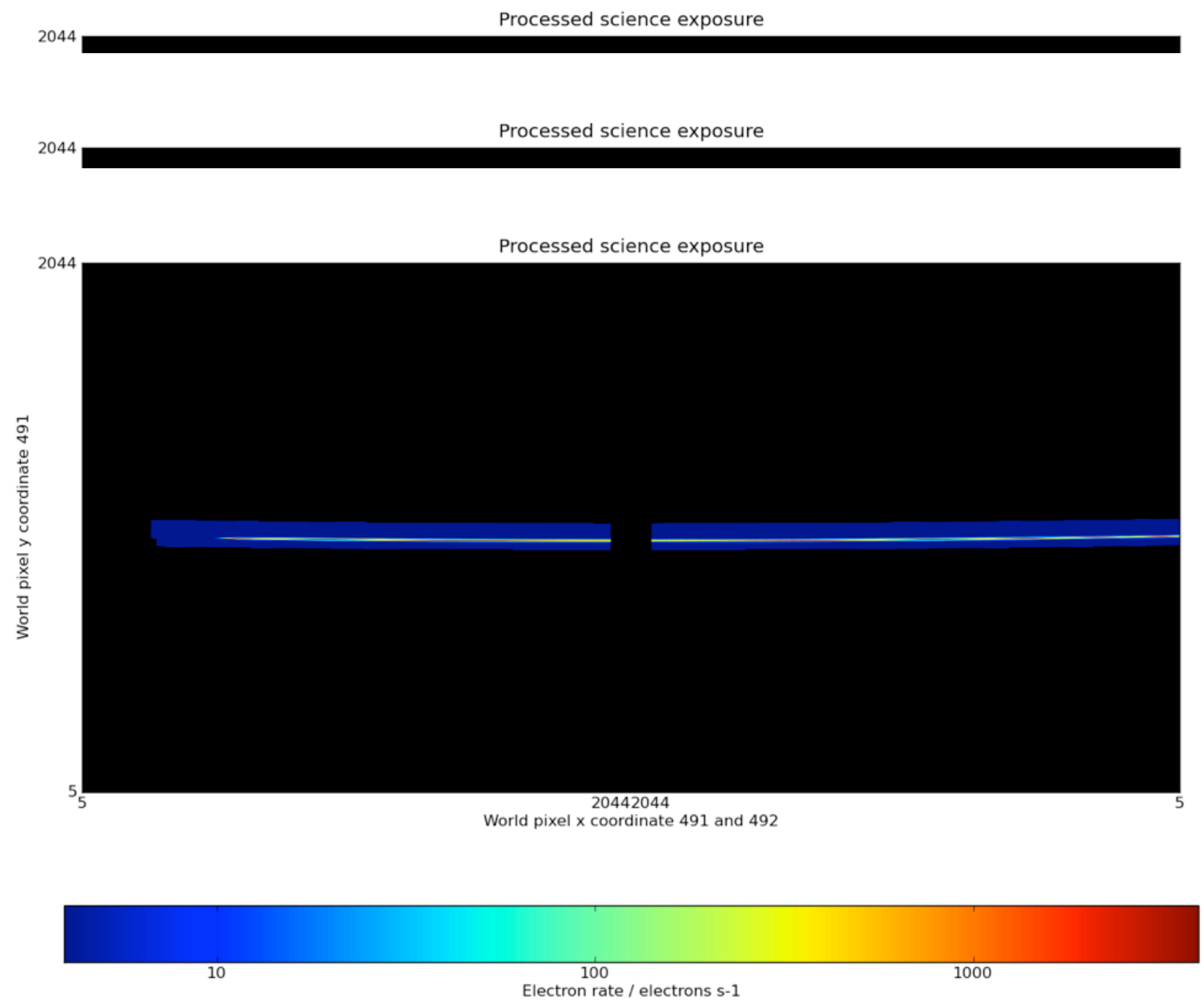
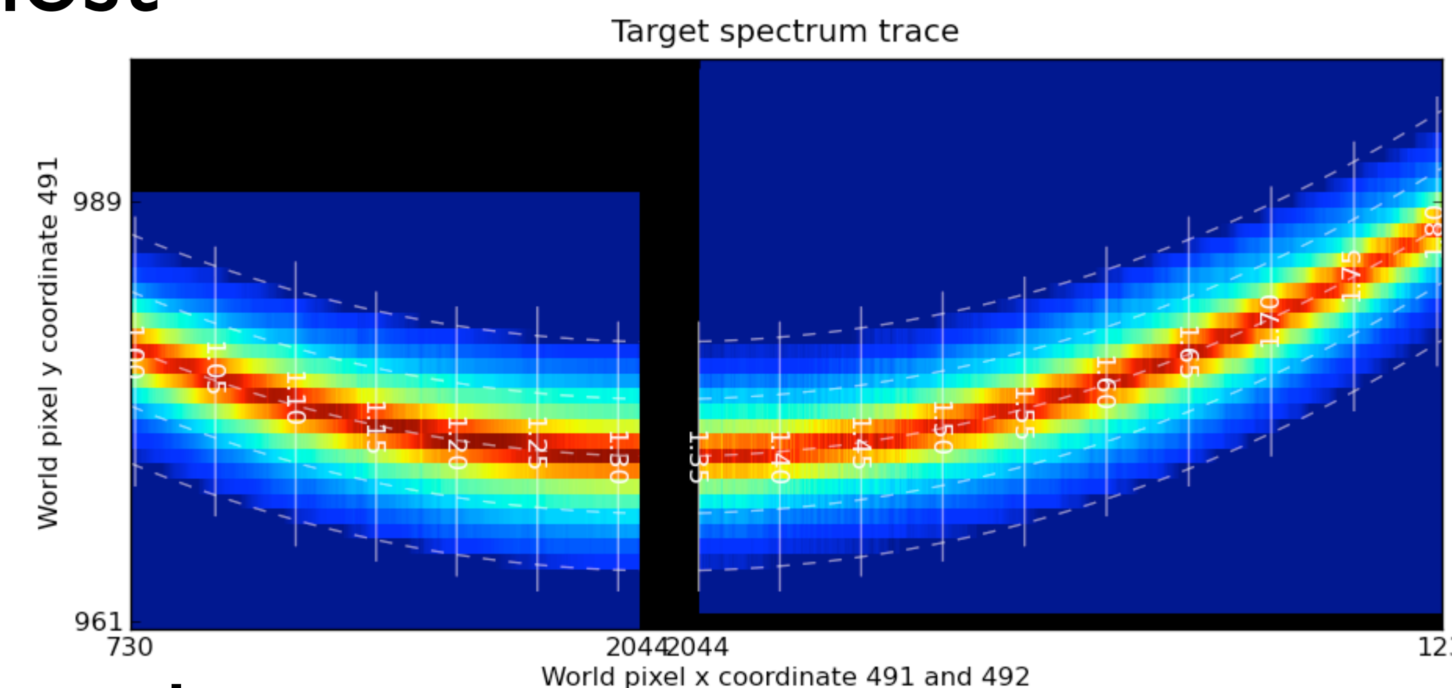


OTE05_MSA05_F100LP_G140H_25_SLIT_star_GJ1214_01_02_band1_res_000, F100LP, G140H

General observation properties

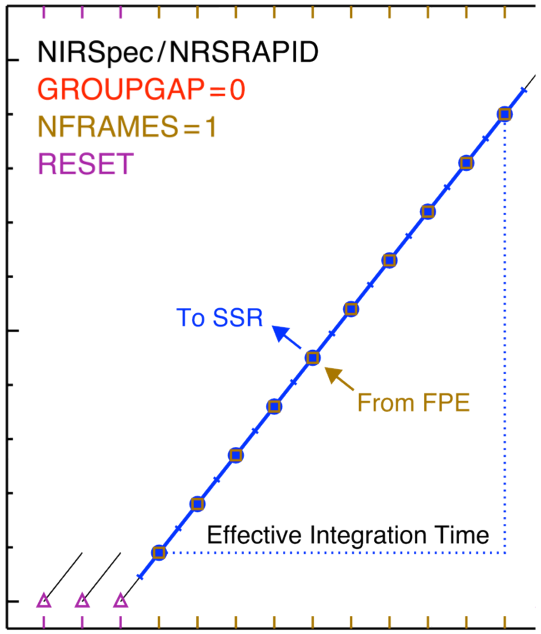
- Wavelength coverage:
  - PRISM + R1000: full bands
  - R2700: detector gap lost
    - 1.31 – 1.35 μm
    - 2.20 – 2.26 μm
    - 3.72 – 3.83 μm



- Subarray of 2048 x 32 pixel
  - Accommodate spectrum curvature
  - Reference pixels needed

Host star brightness limits

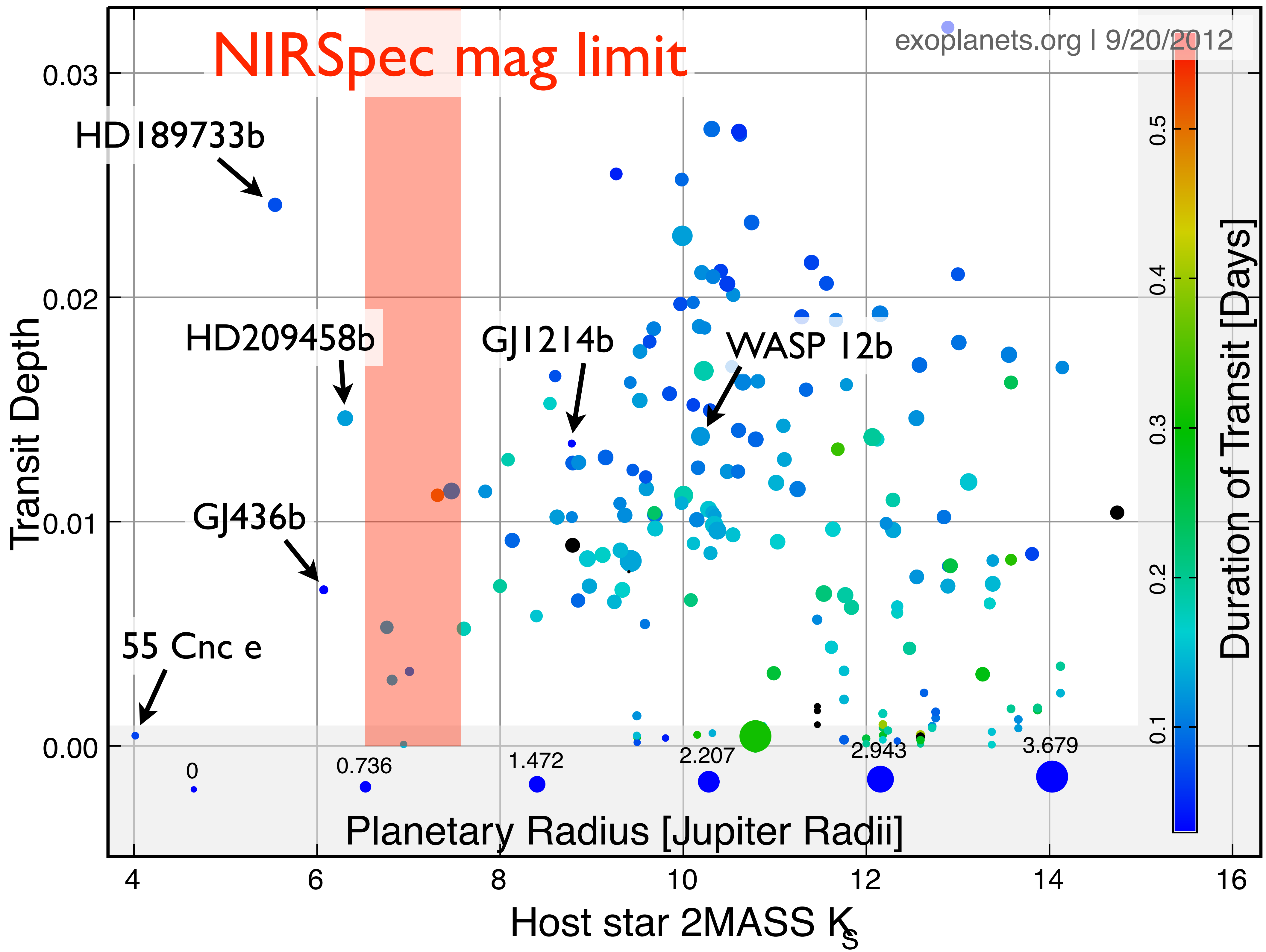
- Saturation limit: 55,000 ADU
- Subarray readout: 2048x32 pixels
- At least 2 non-saturated groups needed
- Minimum magnitudes in bands:



Resolution	J	K	L
R100	12.2	10.3	8.5
R1000	8.8	7.6	6.7
R2700	7.7	6.6	5.7

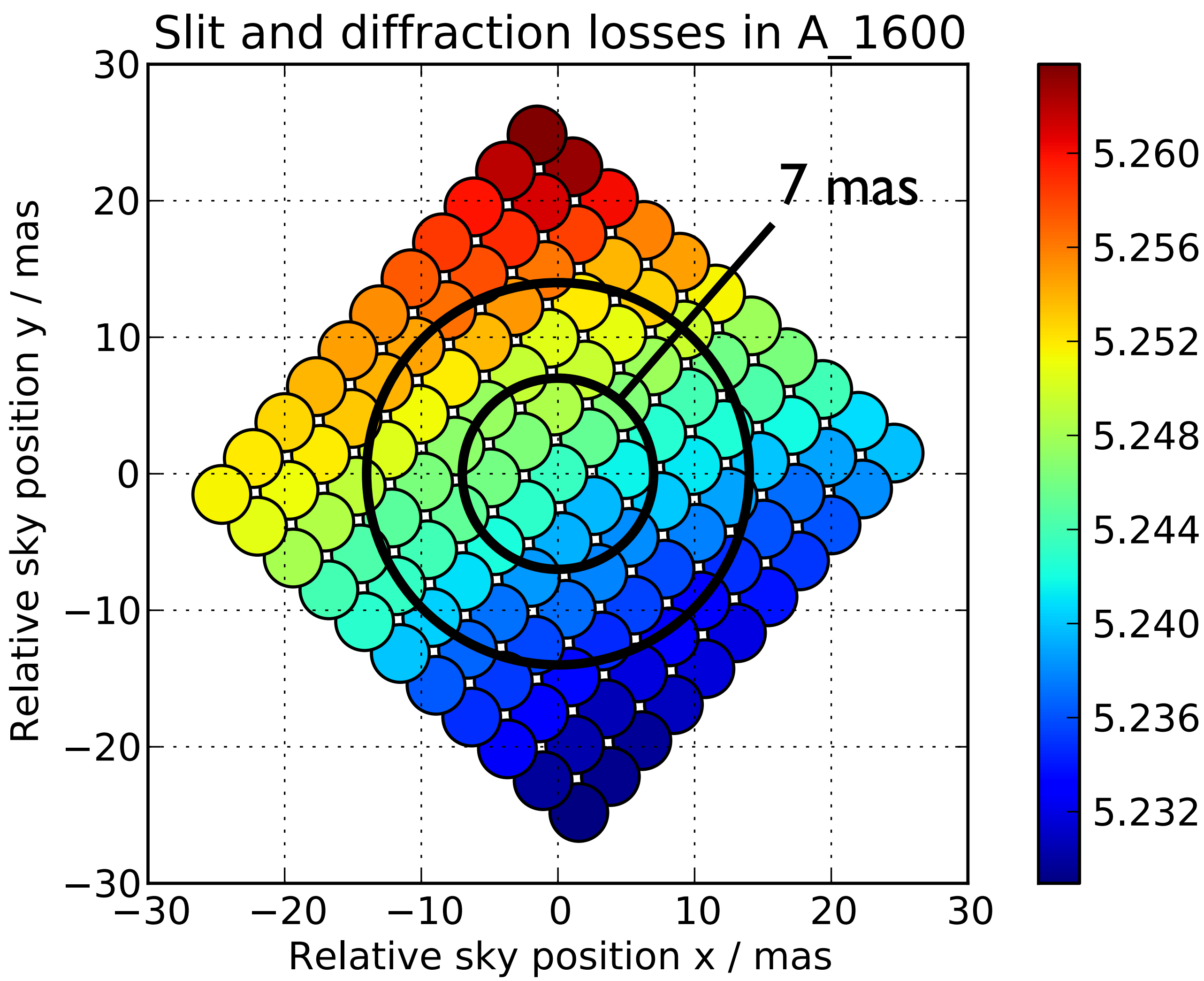
Severe restriction on observable systems

Today's transiting planets



Slit and diffraction losses

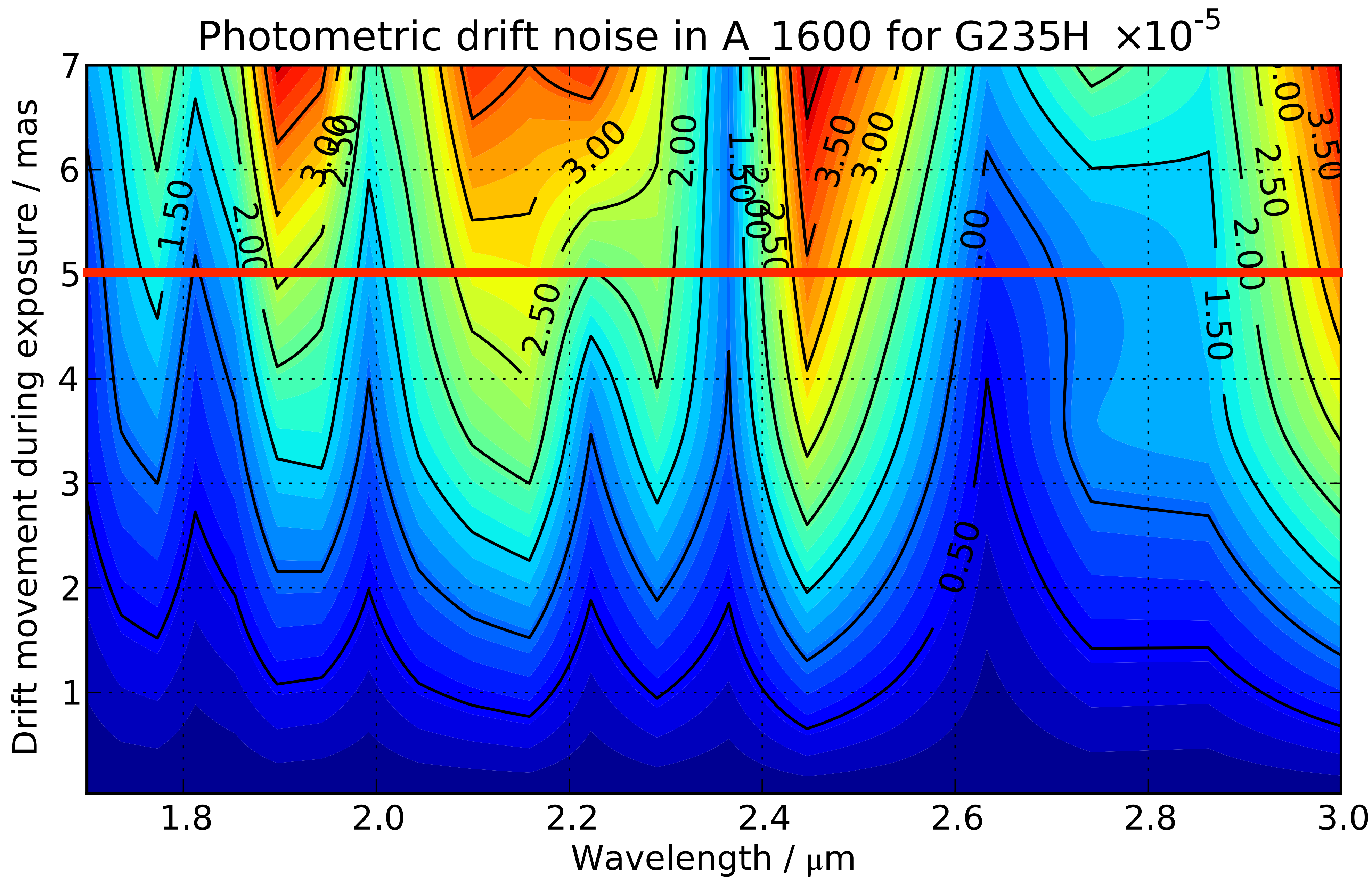
- Truncation of PSF in slit and pupil at disperser
- Random jitter in slit: <7 mas (1σ) during 10,000 sec (requirement)
- Simple drift on very short timescales
- Expected drift during one exposure: 5 mas
- Characterize with RMS in radial distance



G235H, 2.45 μm

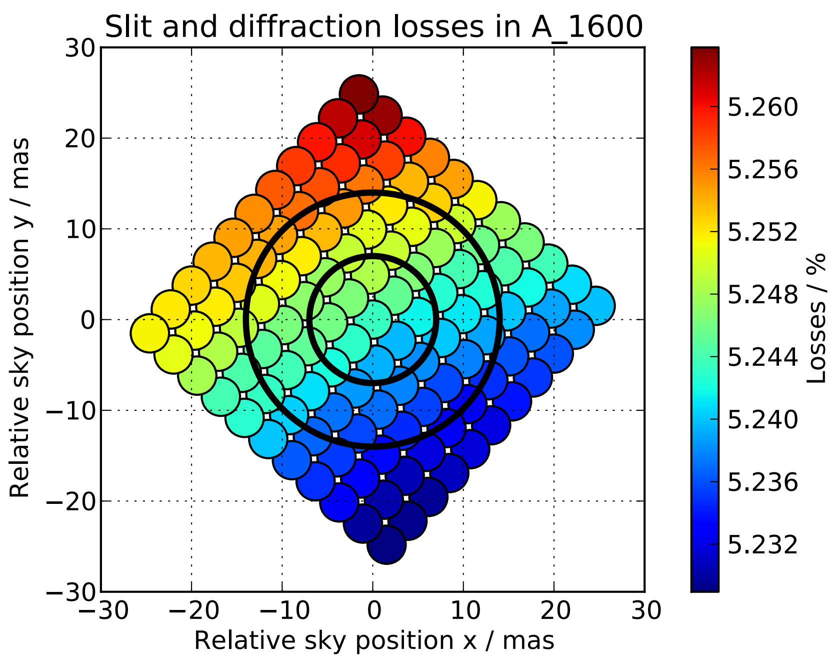
Slit and diffraction losses

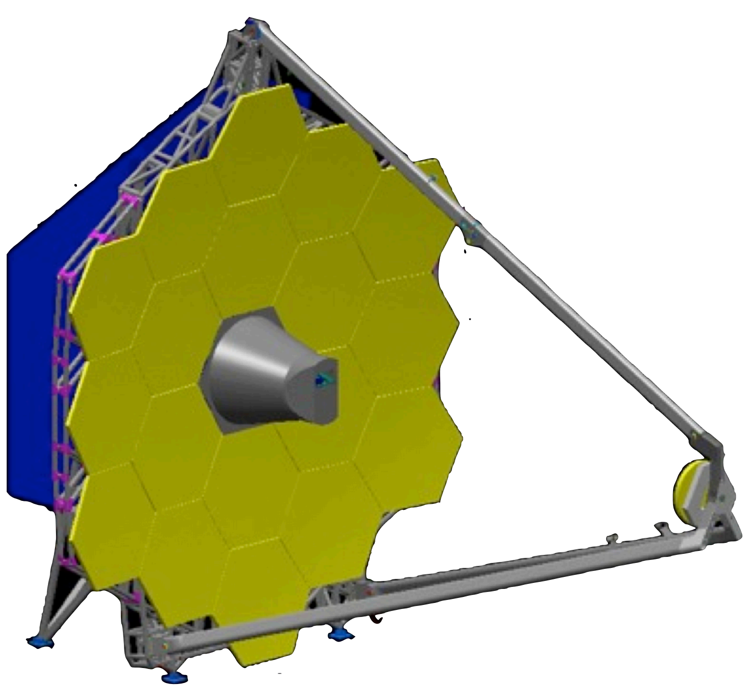
- Relative error of throughput typically $2 \cdot 10^{-5}$



Additional noise in transit observations

- Pointing jitter
  - Variation of throughput $\approx 2\cdot 10^{-5}$
  - Negligible compared to shot noise
- Intra-pixel sensitivity variation, PSF stability
  - Mostly in low spatial frequencies
  - No impact expected/simulated
- Background/dark subtraction
  - SNR change $<10^{-4}$
- Readout noise
  - $\sigma_{read} \approx 20e^{-}$ per pixel, significant





→ left with photon and readout noise

Simulated cases

- Hot Jupiter around G5 MS star: HD189733b
  - Typical HST case (optical, UV)
- Super-Earth around M4.5 dwarf: GJ1214b
  - Ground based (optical, near IR)
- Earth-sized planet in habitable zone around M4.5 dwarf
  - So far inaccessible / not found
- No stellar activity!

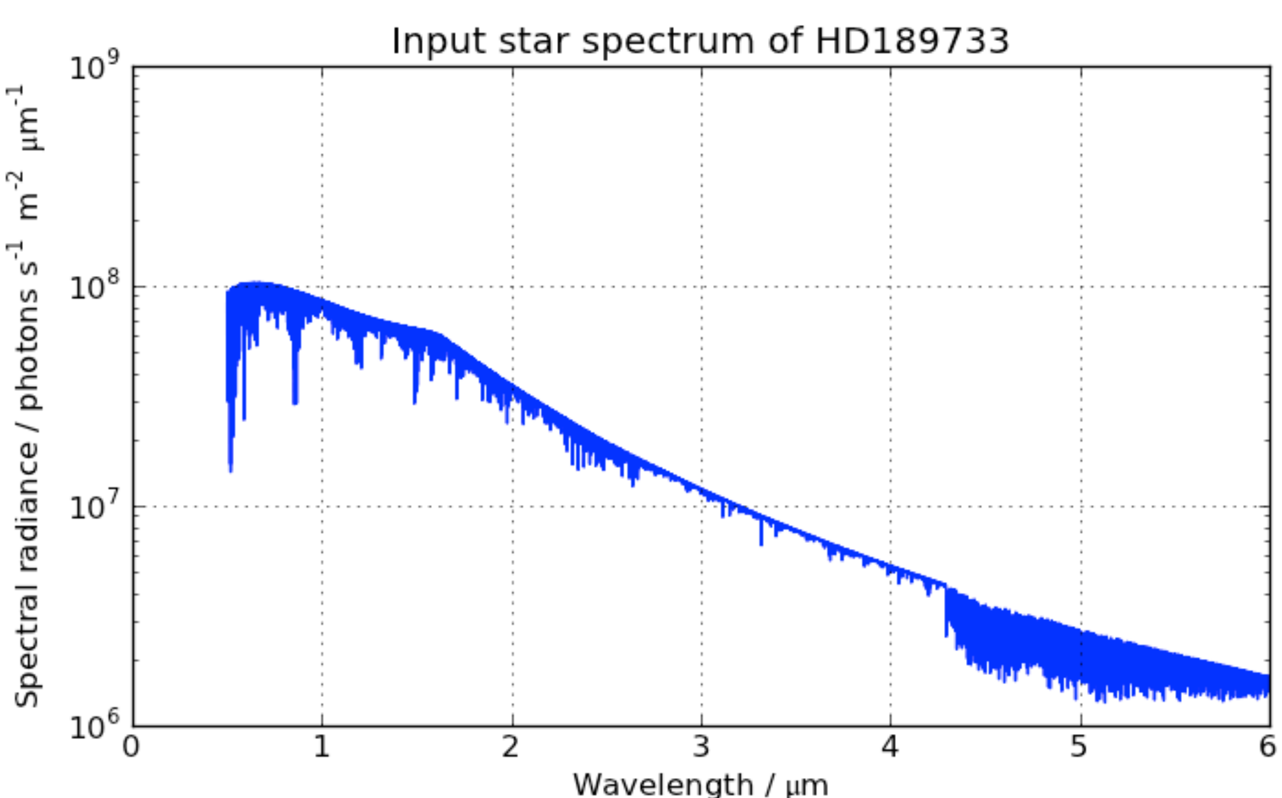
Example host stars

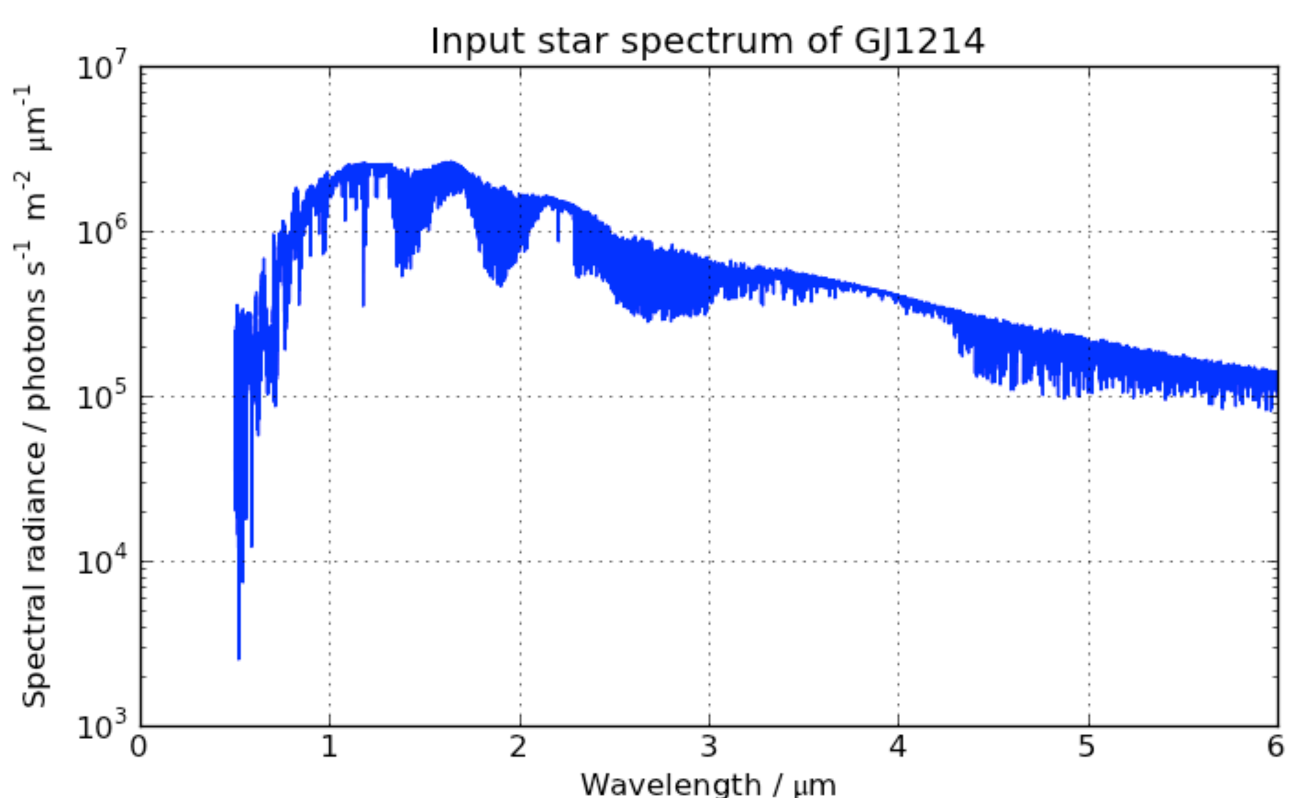
Hot Jup.: HD189733

- G5, 19.45 pc
- 0.757 r_{Sun} (Torres et al. 2008)
- mag_K=5.54
- Kurucz model

Super Earth: GJ1214

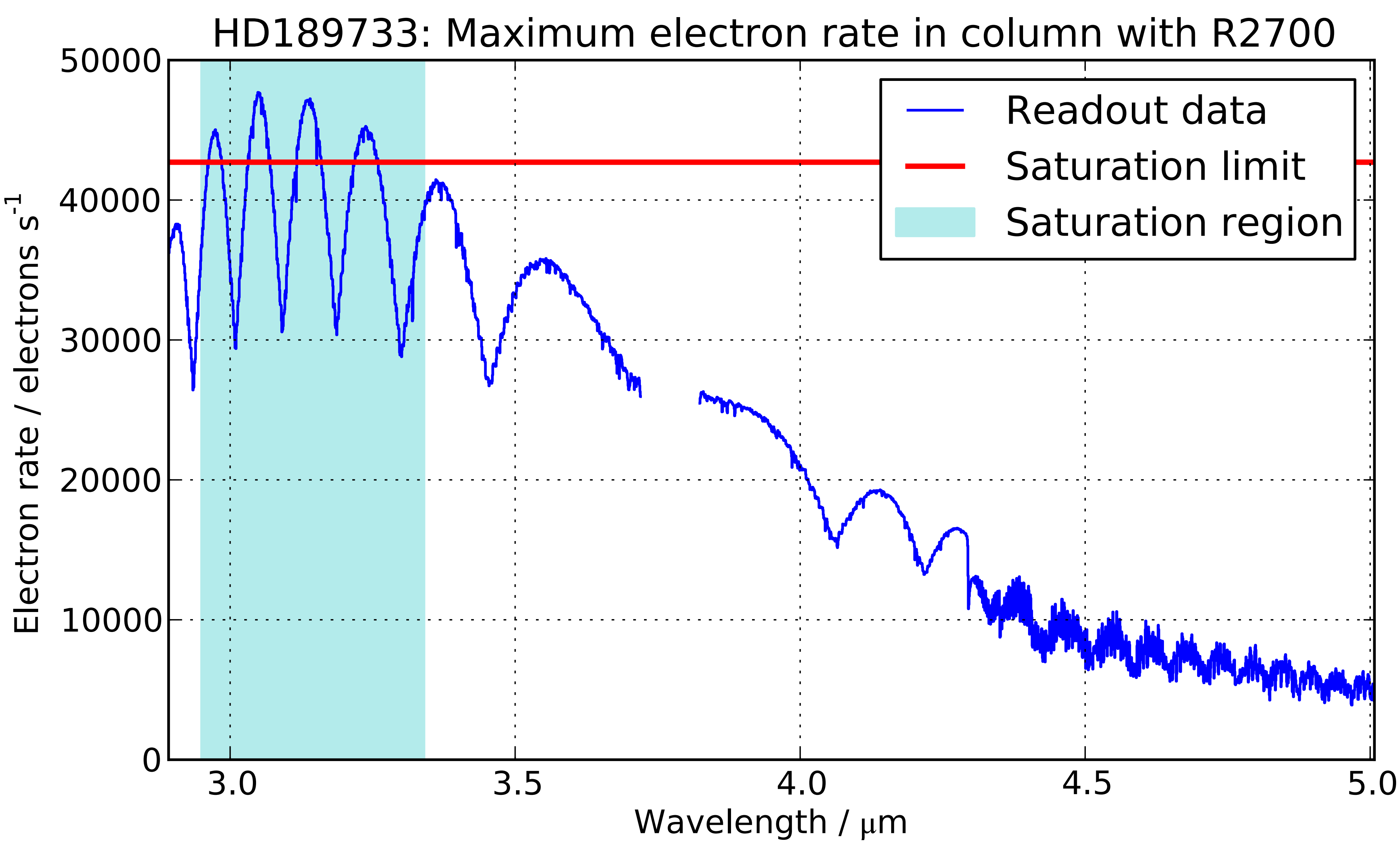
- M4.5V, 12.95 pc
- 0.2064 r_{Sun} (Berta et al. 2010)
- mag_K=8.78
- NextGen model





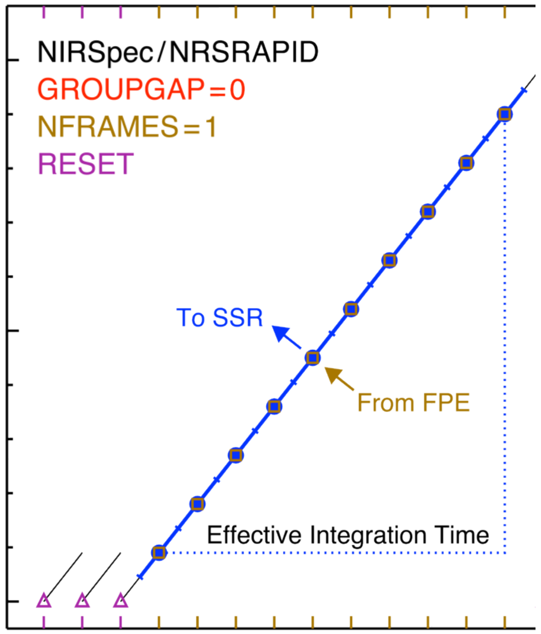
What about HD189733 again?

- Saturation only in small region
- Observability depends strongly on stellar spectrum



Effective exposure times

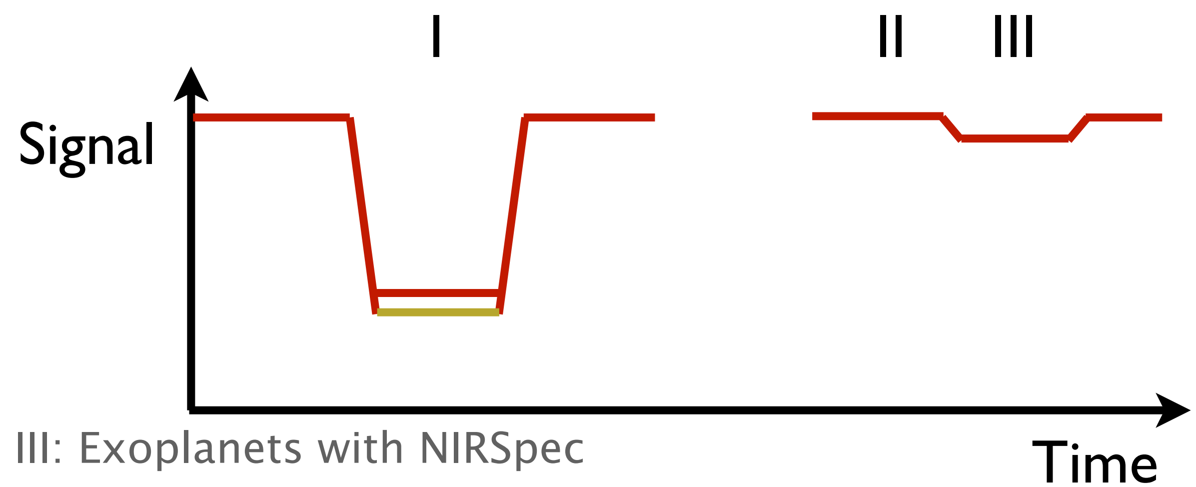
- Readout overhead: 2 groups per integration (reset, first read)
- Limited number of exposures: reduction of effective exposure time



Planet	NIRSpec mode	Maximum group number n_g	Duration T_{trans} / sec	Effective exposure time t_{eff} / sec
HD189733b (eclipse)	R2700 band III	2	3456 (Knutson et al. 2007)	1151
HD189733b (transit)	R2700 band III	2	3600 (Winn et al. 2007)	1200
GJ1214b	R1000 band I	6	2406 (Berta et al. 2010)	1717
GJ1214b	R1000 band II	6	2406	1717
GJ1214b	R1000 band III	12	2406	2033

Signals and SNR for transits

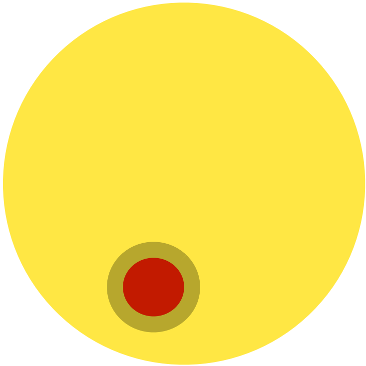
- Star count rate R, transit depth d
- Transit depths:
  - Primary transit: $d = \dfrac{R_{out} - R_{in}}{R_{out}}$
  - Eclipse: $d = \dfrac{R_{out} - R_{in}}{R_{in}}$



Signals and SNR for transits

- Primary transit: detection of atmosphere with effective height h around planet with radius r_{Pl} :
  (Kaltenegger & Traub 2009)

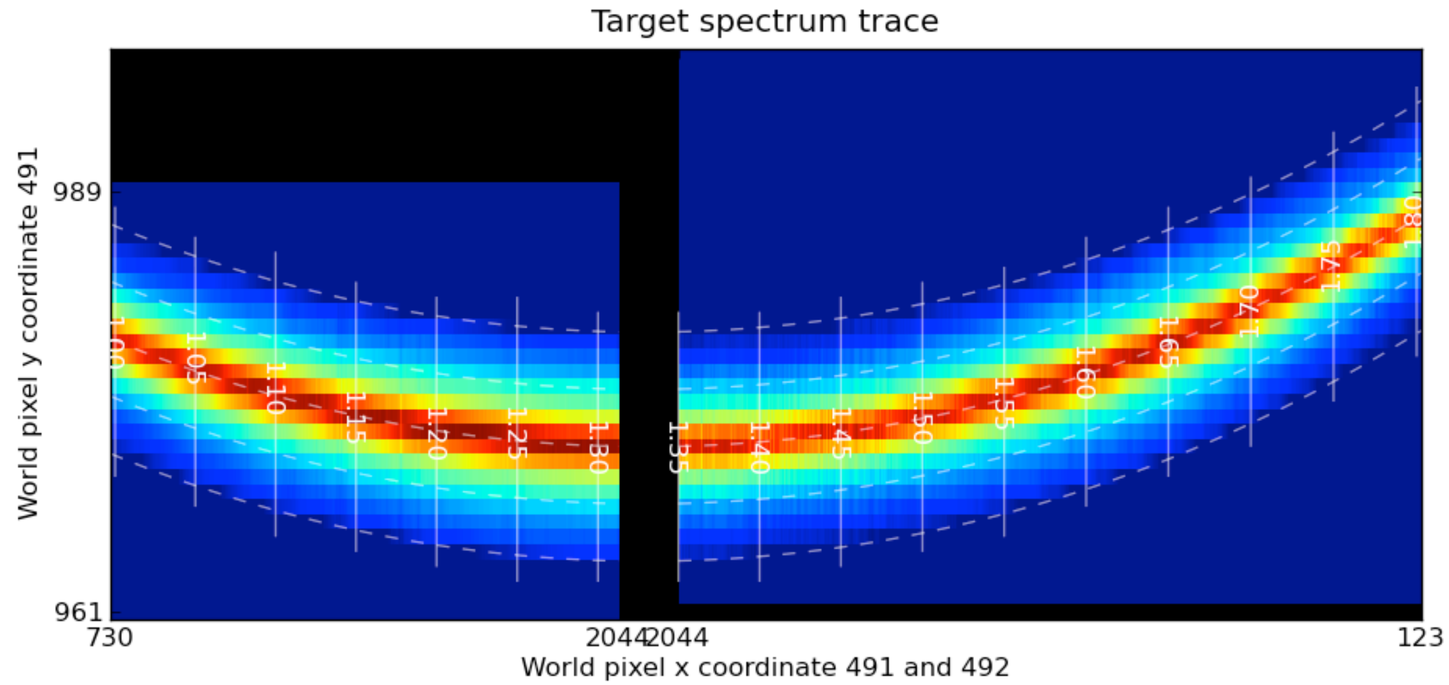
$$d = \frac{2 r_{Pl} h}{r_{Star}^2}$$



- number of exposures n_e , summation over $n_{pix} = 16$ pixels in column

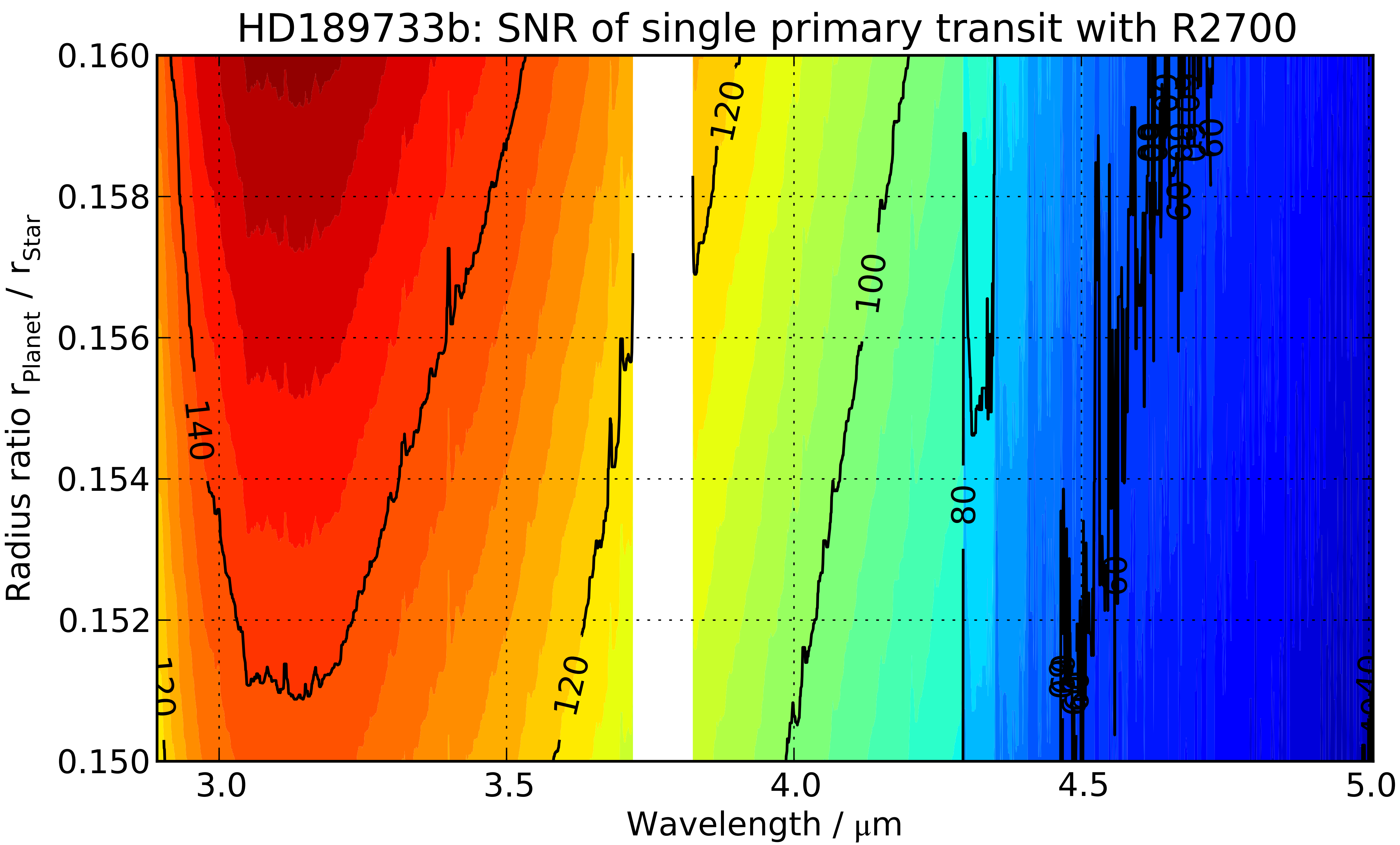
- SNR: $$\frac{d}{\sigma_d} = \frac{d\, R\, t_{eff}}{\sqrt{2(R\, t_{eff} + 2\, n_{pix}\, n_e\, \sigma_{read}^2)}}$$

Simulation setup



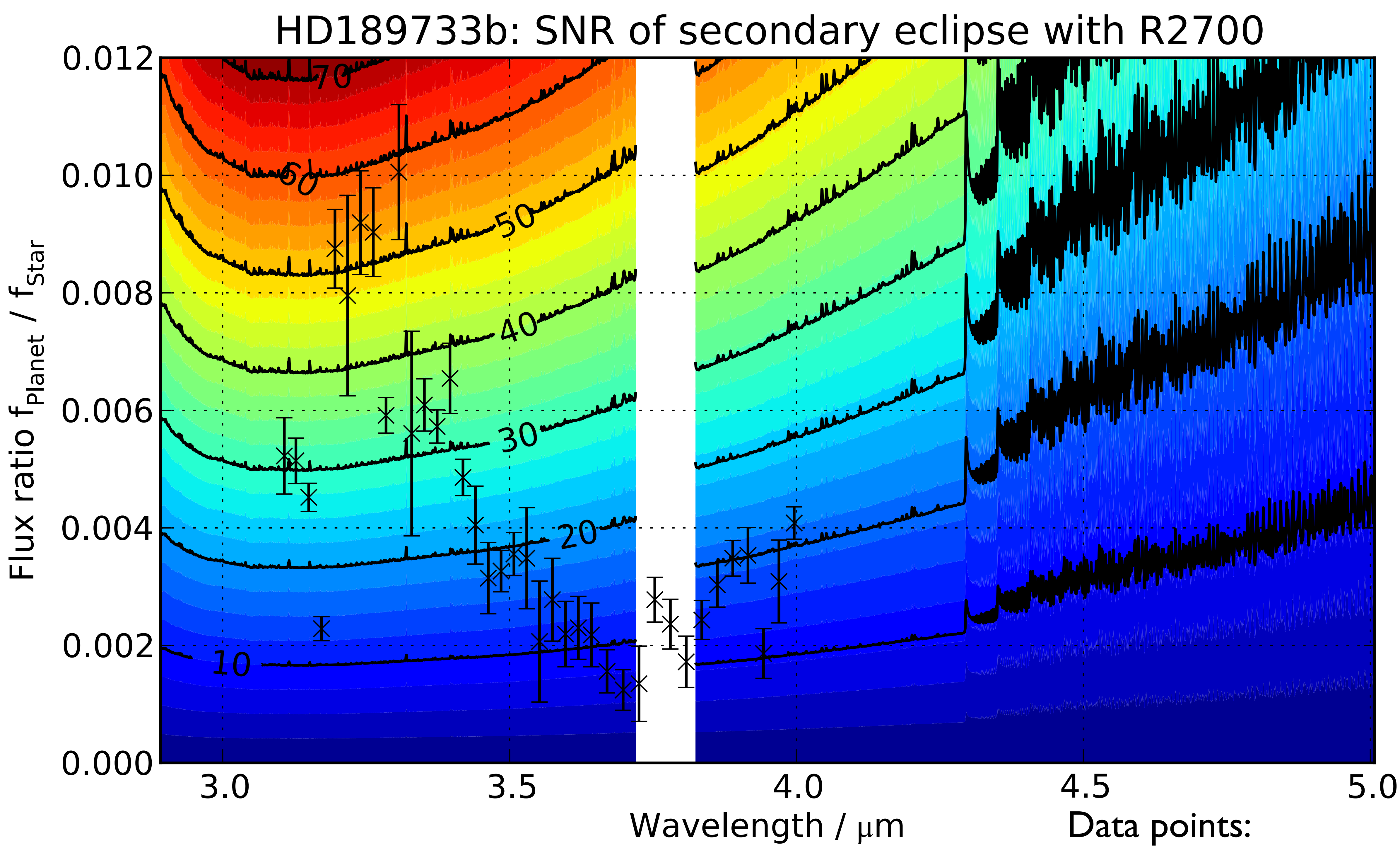
- Star in S1600A1
- As-built instrument model, but uniform QE
- No readout, only electron rates
- Exploration of performances: Noise used in analysis
- Extraction: Sum of 16 pixels in each column

HD189733b: Primary transit



$\Delta\lambda = 0.67\,\mathrm{nm}$

HD189733b: Eclipse



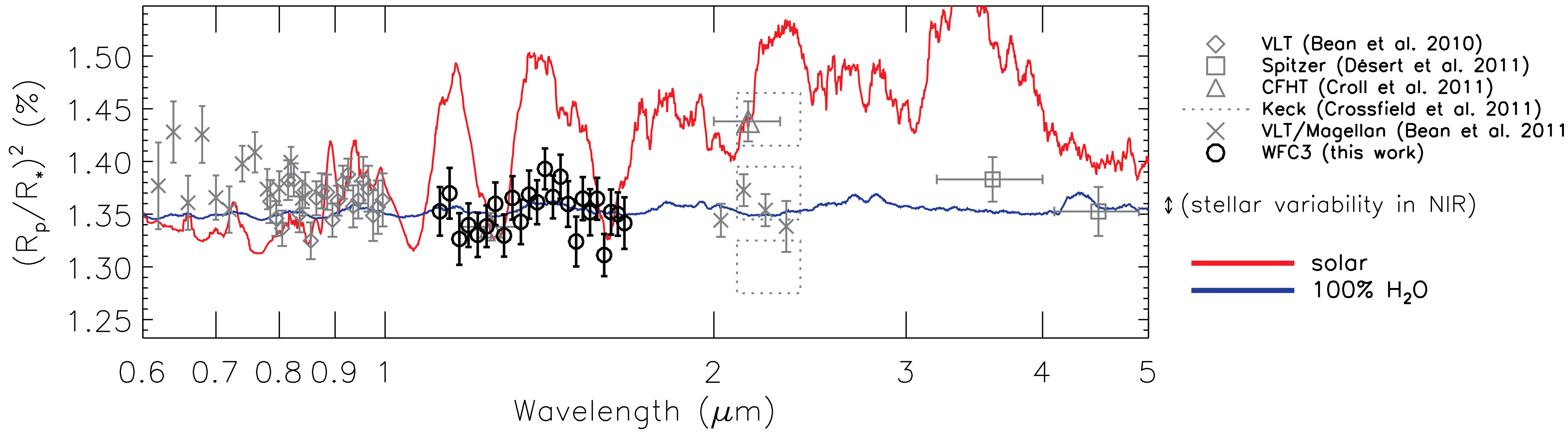
$\Delta\lambda = 0.67\,\mathrm{nm}$

Data points:
Waldmann et al., 2012
(4 transits, R=175)

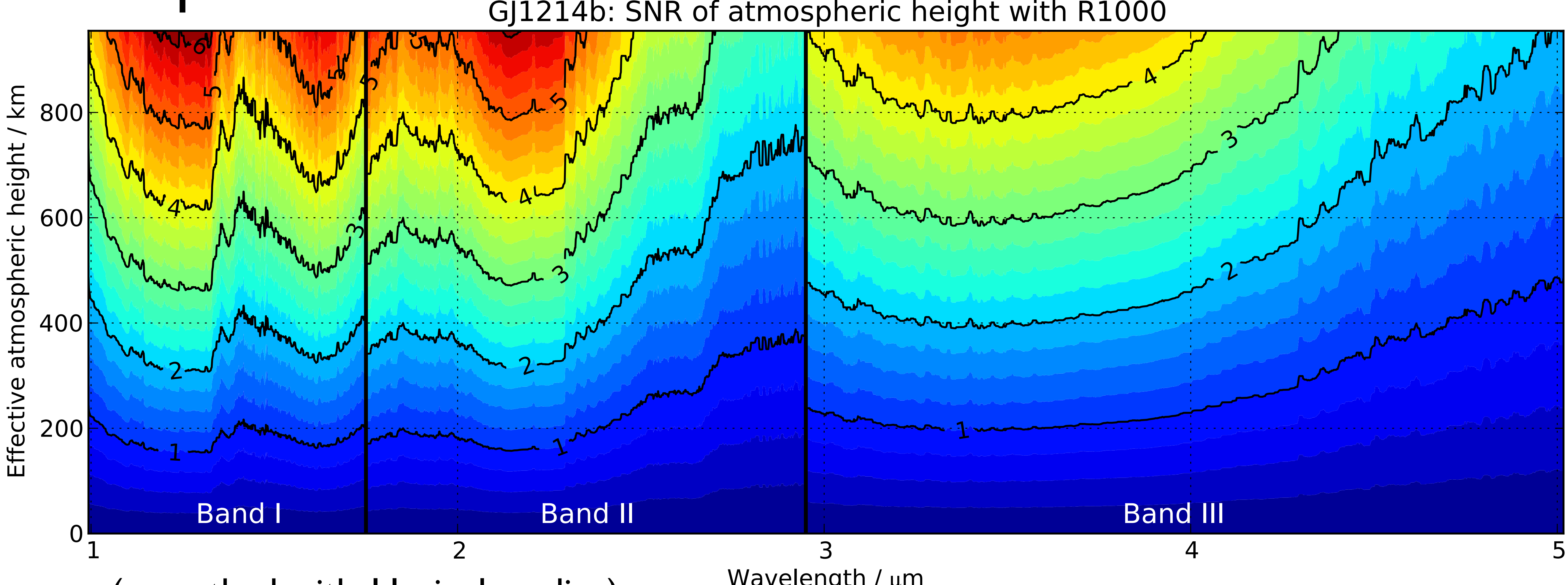
GJ1214b: Atmospheric features

Today:

(Berta et al. 2011)



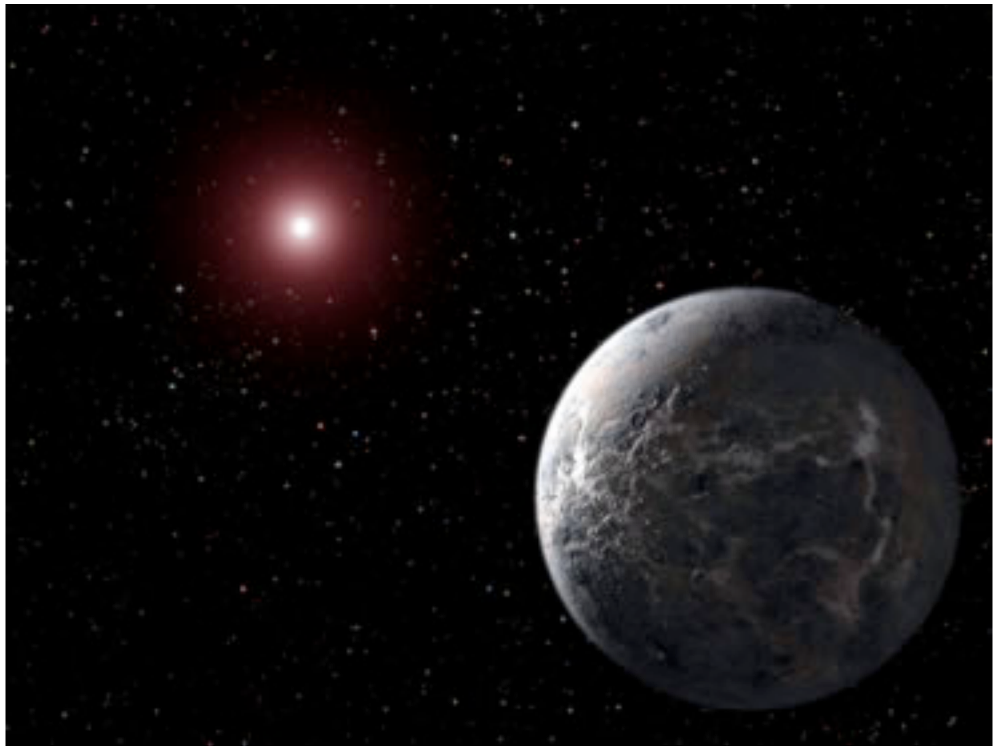
NIRSpec:



(smoothed with 11 pixel median)

Earth-sized planet around M4.5V star

- Put GJ1214 at 10 pc distance
- Earth-sized planet in habitable zone
  - Semimajor axis: 0.0558 AU
  - Orbital period: 12.18 days
  - Transit duration: 1.60 h



Earth-sized planet around M4.5V star

- Atmospheric feature detection:
  - SNR in single transit
  - N_5: number of transits for SNR=5
  - T_5: Time needed for N_5

Molecule	Center wavelength λ / µm	Feature width $\Delta\lambda$ / µm	Effective height *h* / km	single SNR	N_5	T_5 / years
H_2O	1.9	0.2	5	0.3	278.7	9.3
CO_2	2.8	0.1	20	0.44	130.3	4.37
H_2O	3.3	0.25	20	0.94	28.3	0.97
CO_2	4.3	0.4	20	0.84	35.8	1.2

→ Large features within reach during mission

Conclusions: Simulation and targets

- Simple simulation: only 1 point source
- Data exploitation directly from electron rates
- Restriction of observable stars: (almost) too sensitive!
- Only few Neptune/Earth-sized targets known

Conclusions: Analysis

- Photon and readout noise dominant
- Observation examples:
  - Hot Jupiters characterized in one observation
  - Super-Earths: On the edge with one transit
  - Earth-sized planets: Multiple visits required
- Massive improvement over current and near-future facilities