# High-fidelity simulations of planetary transit spectroscopy with JWST/NIRSpec

Bernhard Dorner, CRAL – Observatoire de Lyon

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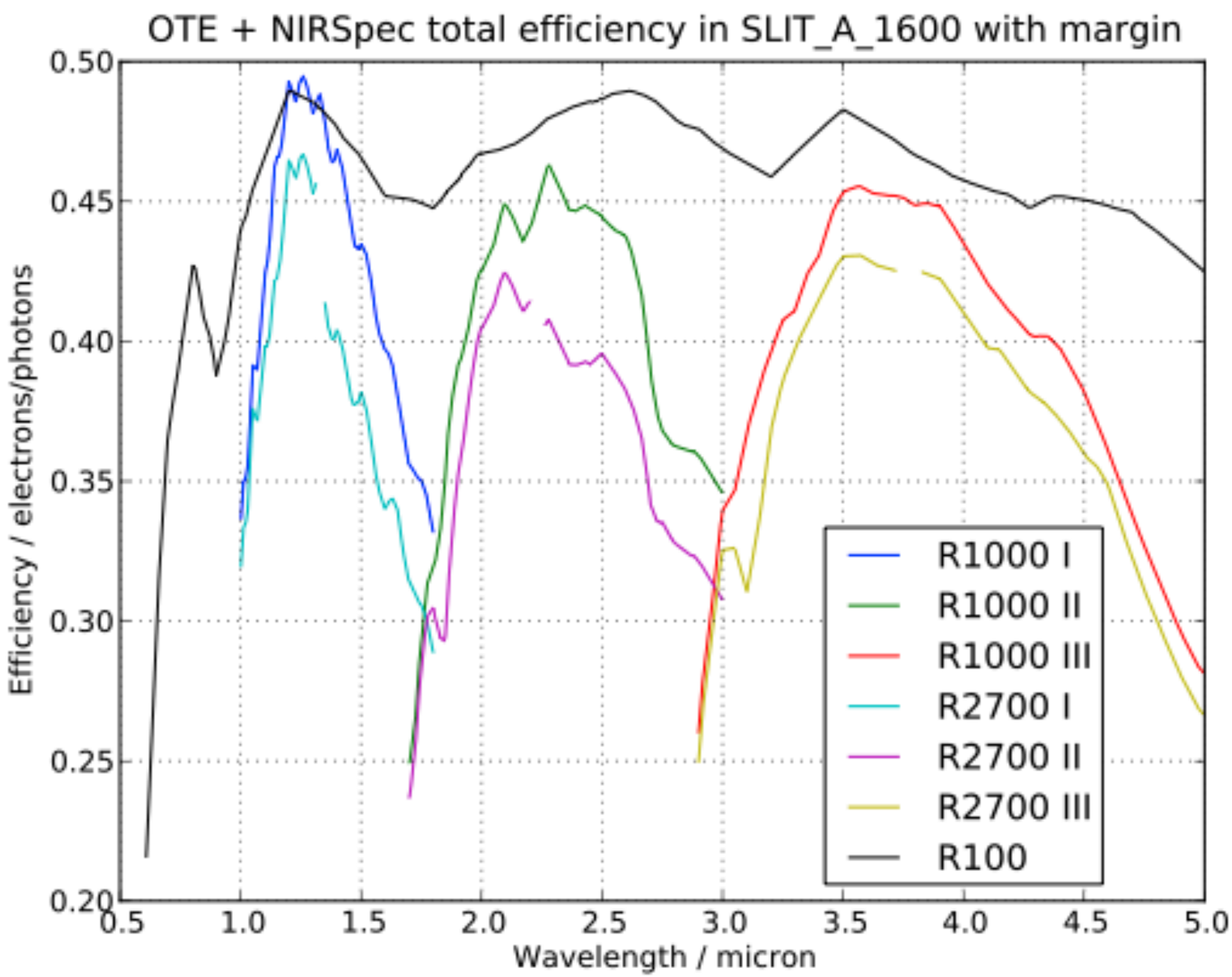
# The Instrument Performance Simulator (IPS)

- Developed by CRAL for EADS Astrium GmbH and ESA (Piqueras et al. 2008, 2010)
- End-to-end simulation for NIRSpec calibration and science exposures
- Includes Fourier optics, radiometry, and coordinate transforms
- Output:
  - Noiseless electron rates
  - NIRSpec raw data cube
- Additional tools:
  - Data handling framework
  - Science data input interface
  - Data reduction pipeline

# Instrument model status

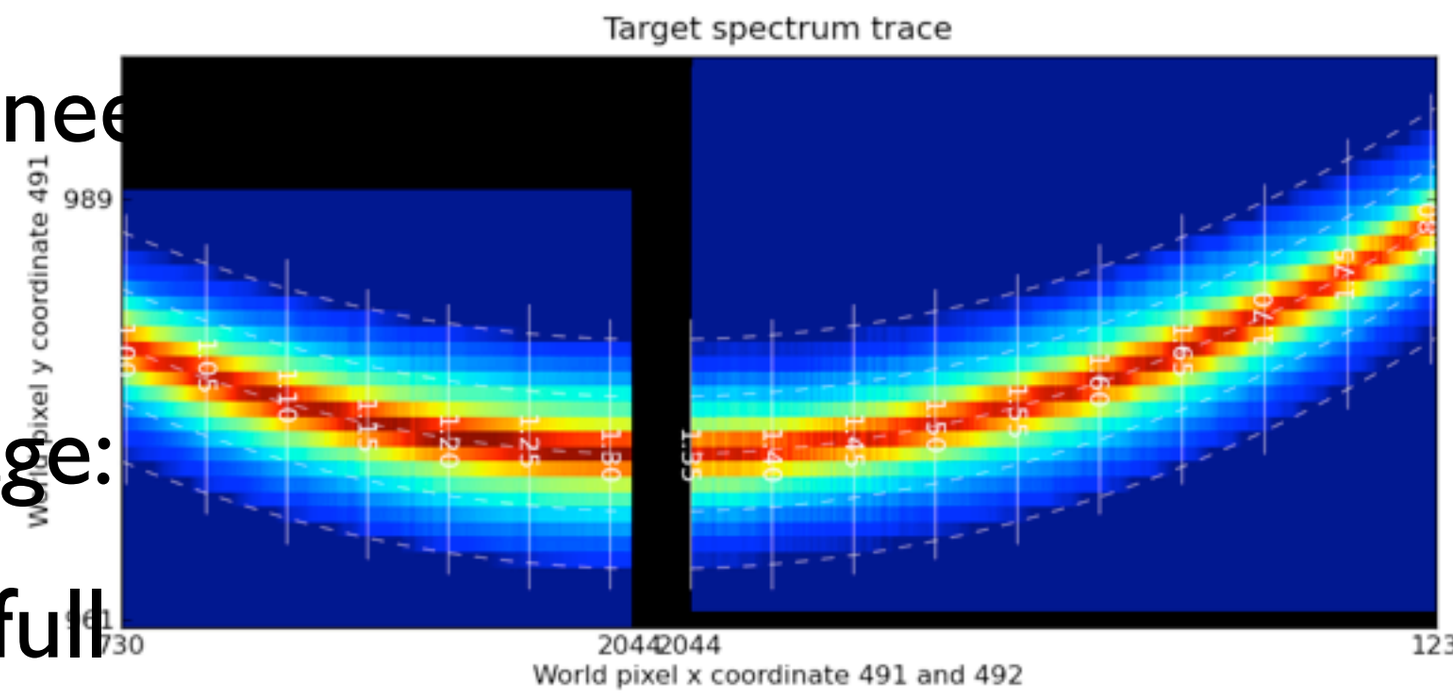
- As-built optical models almost complete
- Realistic geometries (accurate down to ±3 px)
- Measured subsystem efficiencies
- Field dependent wavefront errors
- Detector: Spatially uniform efficiency, optimistic model
- Full model not yet verified
- Telescope: data similar to specifications

# Throughput: total efficiency



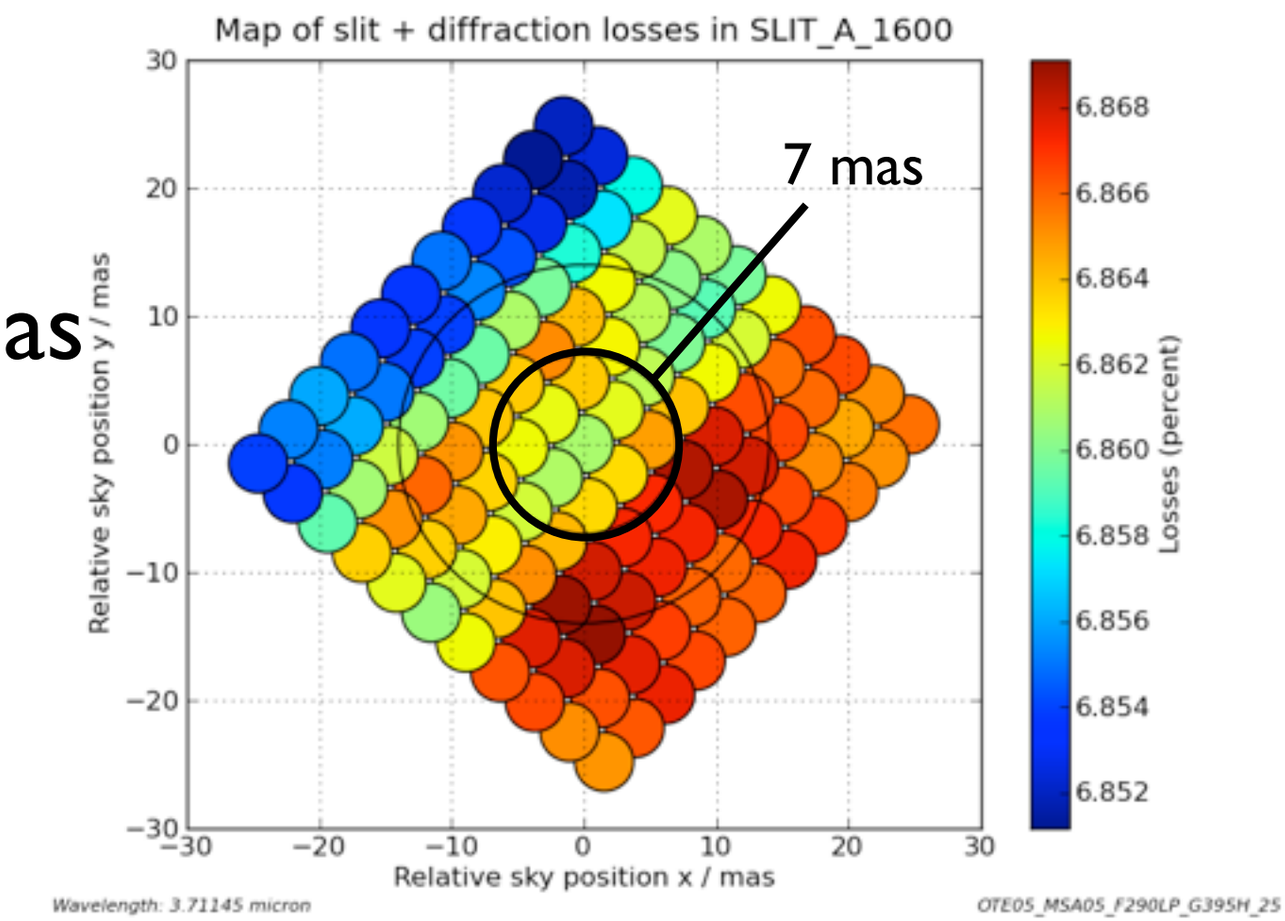
# Simulation scenery

- Single star (point source) in 1.6" square aperture
- Different NIRSpec modes (filters, dispersers)
- Subarray readout (2048 x 32 pixels)
  - Accommodate spectrum curvature
  - Reference pixels nee
- No dithering
- Wavelength coverage:
  - PRISM + R1000: full
  - R2700: detector gap



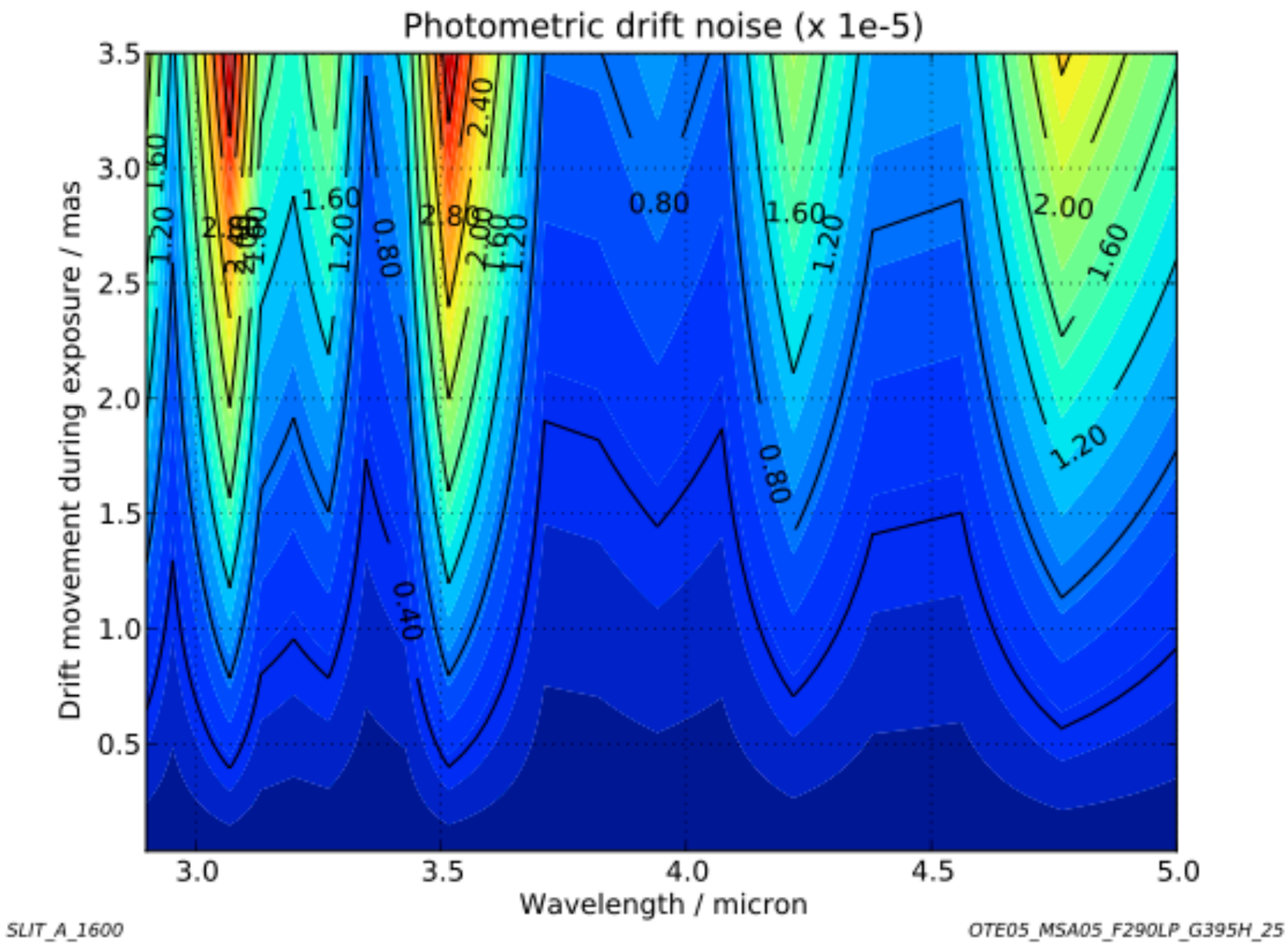
# Poiting and photometric stability

- Truncation of PSF in slit and pupil at disperser
- Position dependent
- Random jitter in slit: <7 mas (1 $\sigma$) during 10,000 sec (requirement)
- Simple drift on very short timescales
- Characterize with RMS in radial distance



# Impact of drift

- Relative error of throughput should be $<10^{-5}$
- Maximal drift during one exposure: 1 mas

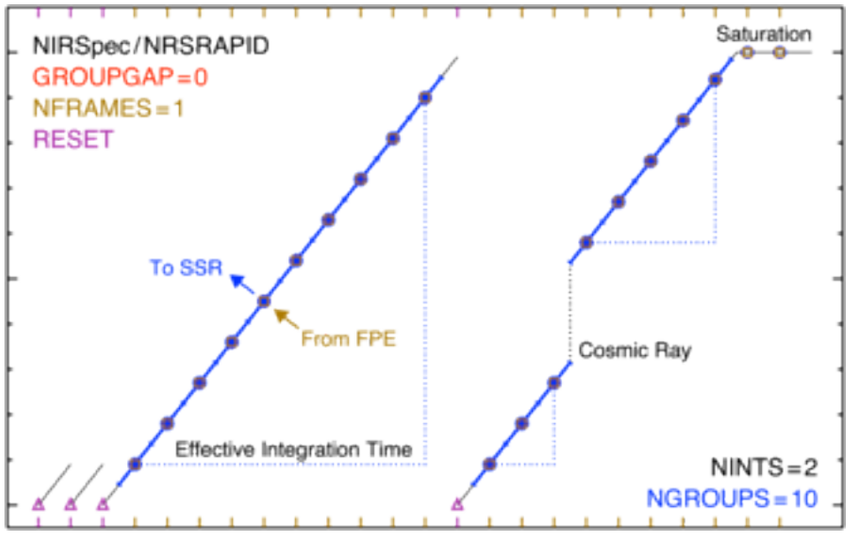


# Observability and exposure times

HD189733

G5, 19.45 pcGJ1214

- M4.5V, 12.95 pc




| Planet | NIRSpec mode | Maximum frame number $n_f$ | Duration $T_{trans}$ / sec | Effective exposure time $t_{eff}$ / sec |
|---|---|---|---|---|
| HD189733b (eclipse) | R2700 band III | 2 | 3456 (Knutson et al. 2007) | 1145 |
| HD189733b (transit) | R2700 band III | 2 | 3600 (Winn et al. 2007) | 1199 |
| GJ1214b | R2700 band I | 20 | 2406 (Berta et al. 2010) | 2056 |
| GJ1214b | R2700 band II | 20 | 2406 | 2056 |
| GJ1214b | R2700 band III | 38 | 2406 | 2001 |
| GJ1214b | R1000 band I | 7 | 2406 | 1785 |
| GJ1214b | R1000 band II | 7 | 2406 | 1785 |
| GJ1214b | R1000 band III | 14 | 2406 | 1992 |

# Signal and SNR for transits

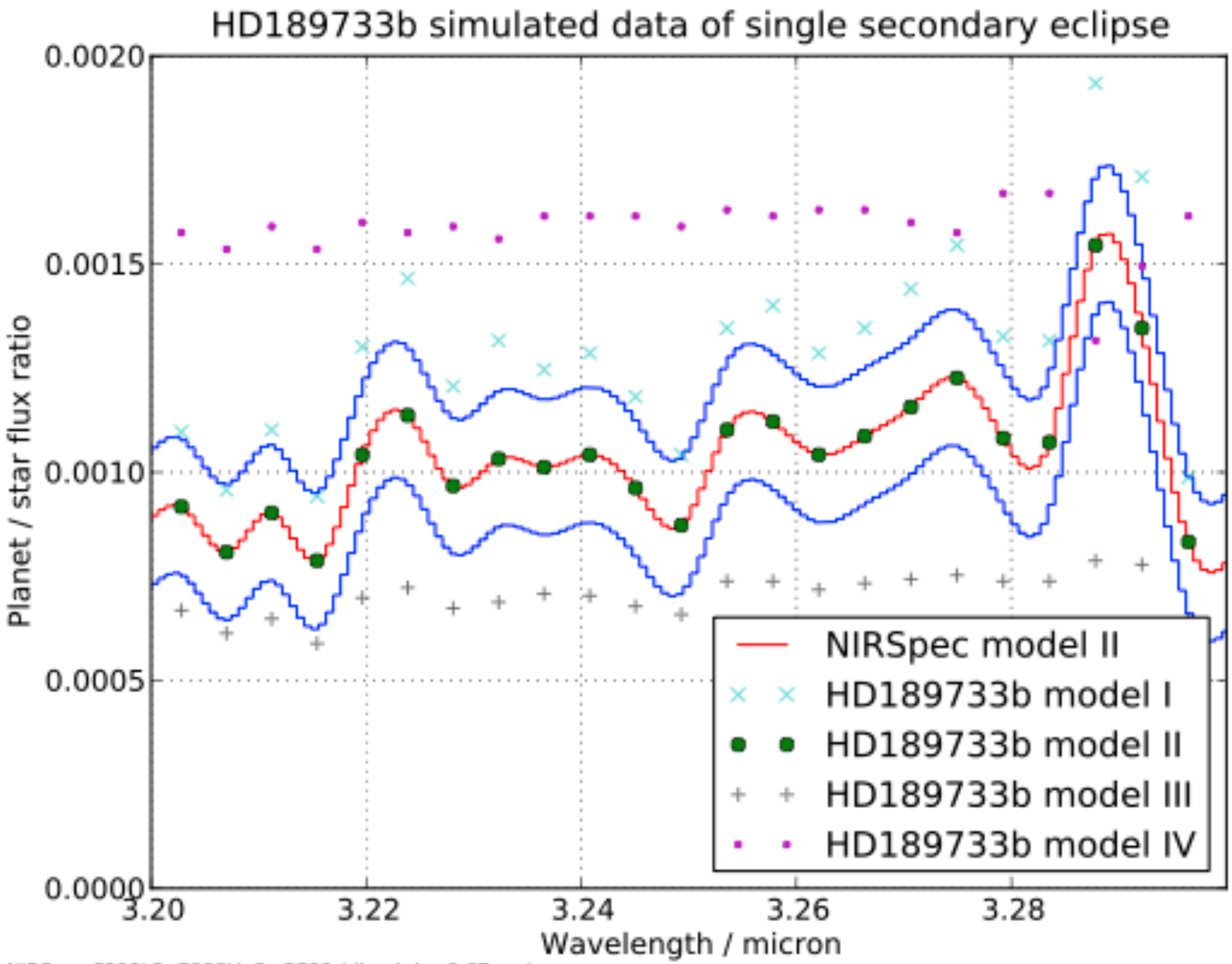
- Only photon noise considered
- Primary transit:
  - signal: transit depth $d = \frac{R_{out} - R_{in}}{R_{out}}$
  - SNR: $\frac{d}{\sigma_d} = \sqrt{R_{out} t_{eff}} \sqrt{\frac{d^2}{d^2 - d + 2}}$
- Eclipse:

$$d = \frac{R_{out} - R_{in}}{R_{in}} \qquad \frac{d}{\sigma_d} = \sqrt{R_{out} t_{eff}} \sqrt{\frac{d^2}{d^2 + d + 2}}$$

# Signal and SNR for transits

- Primary transit: detection of atmosphere with effective height $h$ around planet with radius $r_{Pl}$
  (Kaltenegger & Traub 2009)
  - signal: $d_A = \frac{2 r_{Pl} h}{r_{Star}^2}$
  - SNR: $\frac{d_A}{\sigma_{d_A}} = \frac{2 r_{Pl}}{r_{Star}^2} \sqrt{R_{out} t_{eff}} \cdot h$

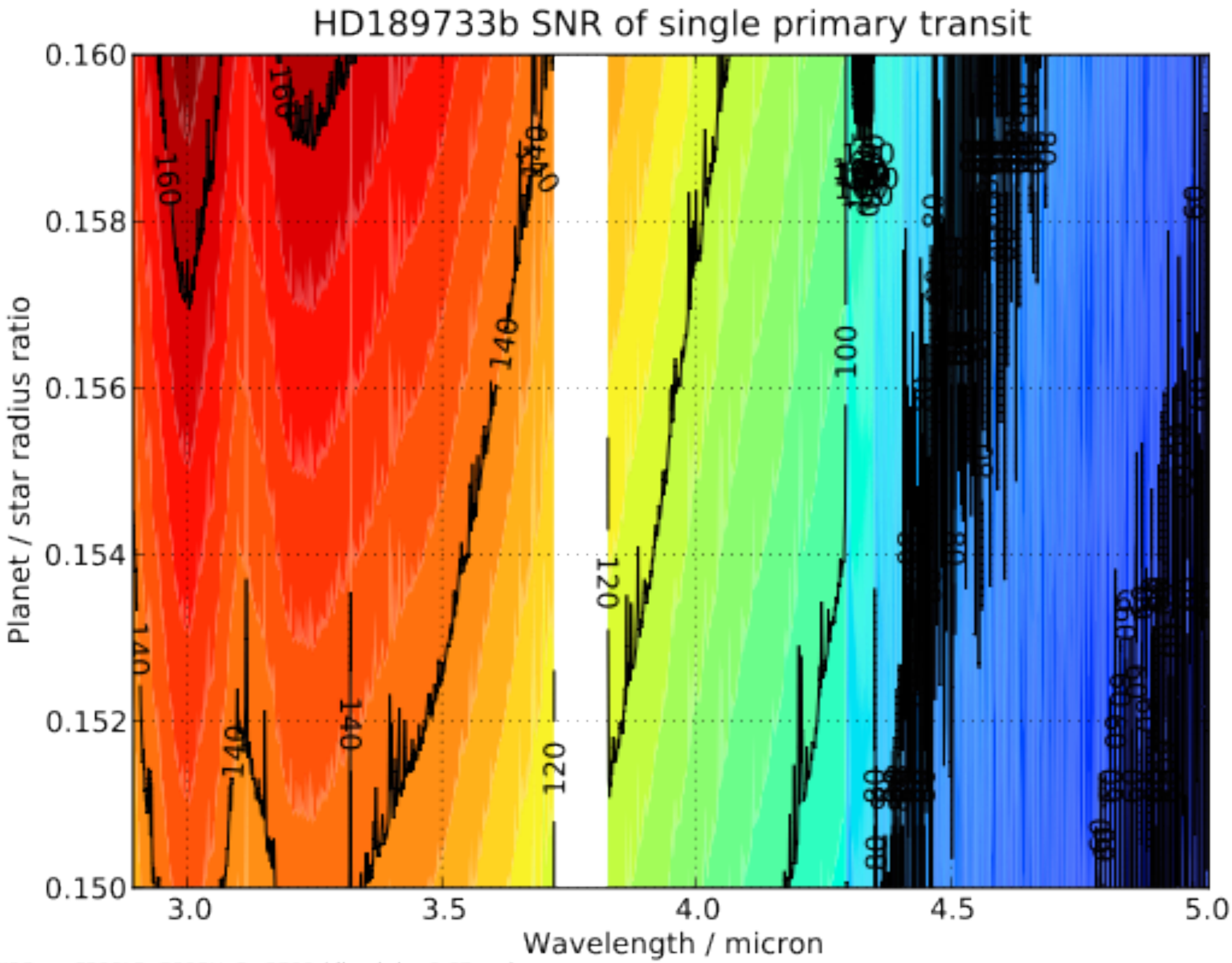
# HD189733b: eclipse




*NIRSpec F290LP, G395H, R=2700 (dlambda=0.67 nm)*

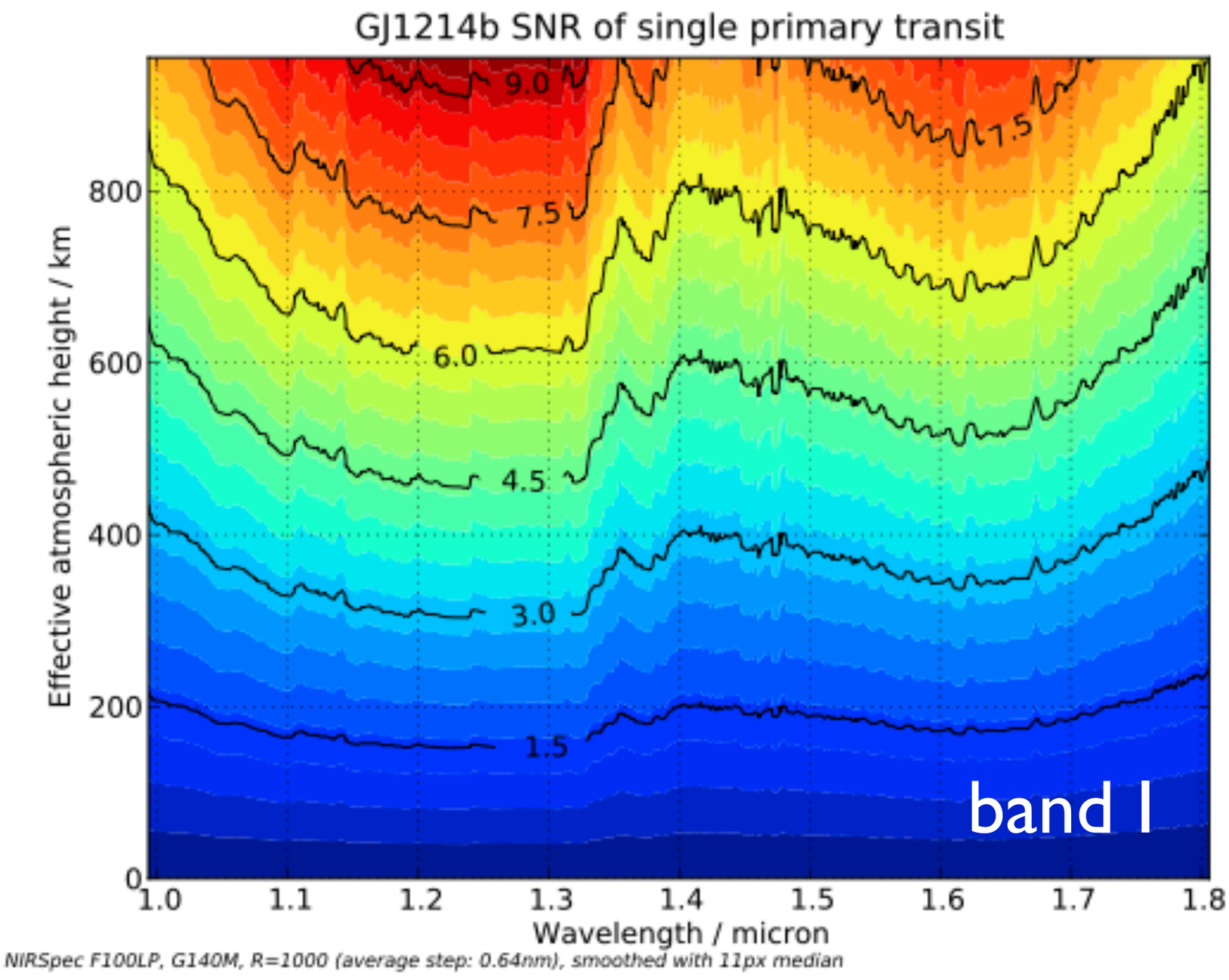
*Model data: Burrows et al. 2008*

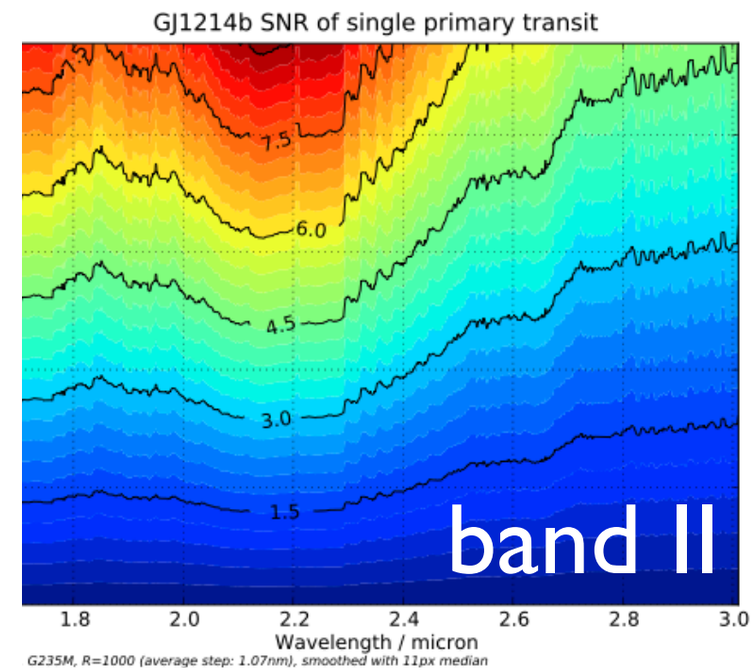
# HD189733b: primary transit depth

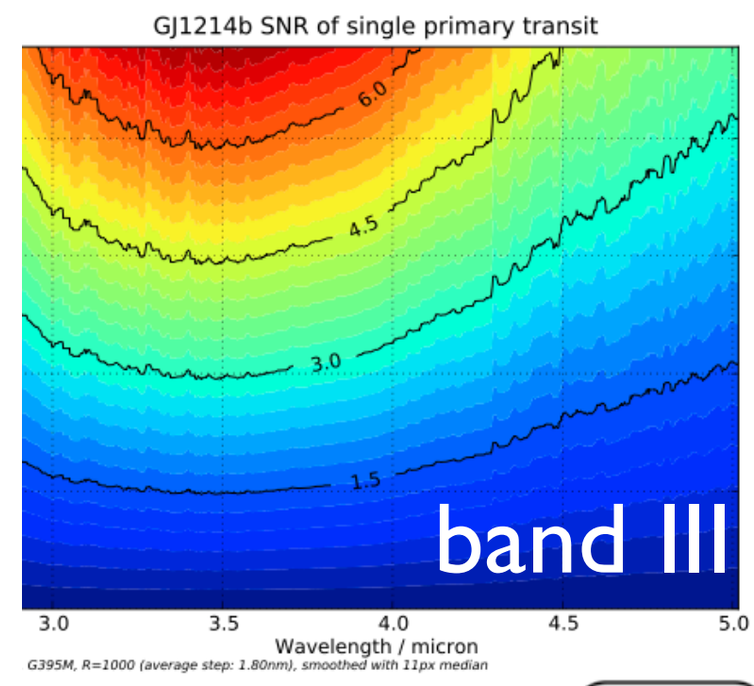



*NIRSpec F290LP, G395H, R=2700 (dlambda=0.67 nm)*

# GJ1214b: atmospheric height



# Earth-like planet around M4.5V star

- Put GJ1214 at 10 pc distance
- Earth-size planet in habitable zone
  - Semimajor axis: $a_{HZ}$ = 0.0558 AU
  - Orbital period: $P_{HZ}$ = 12.18 days
  - Transit duration: $T_{trans}$ = 1.60 h

# Earth-like 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 $\lambda$ / μm | Feature width $\Delta\lambda$ / μm | Effective height $h$ / km | NIRSpec mode | single SNR | $N_5$ | $T_5$ / years |
|---|---|---|---|---|---|---|---|
| $H_2O$ | 1.9 | 0.2 | 5 | R1000 band II | 0.420 | 141.4 | 4.74 |
| $CO_2$ | 2.8 | 0.1 | 20 | R1000 band II | 0.757 | 43.7 | 1.47 |
| $H_2O$ | 3.3 | 0.25 | 20 | R1000 band III | 1.34 | 13.9 | 0.47 |
| $CO_2$ | 4.3 | 0.4 | 20 | R1000 band III | 1.26 | 15.8 | 0.53 |

Large features within reach during mission

# Conclusion and outlook

- IPS allows generation of accurate mock NIRSpec observations
- As-built instrument models almost complete and partially verified
- In-depth evaluation of NIRSpec performance and operational constraints has begun (see also poster by Jeff Valenti, Missions 31)
- First results are very encouraging

**Stay tuned!**