Exoplanet Transit and Eclipse spectra with JWST:
potentials and limitations

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Exoplanet Spectroscopy Status

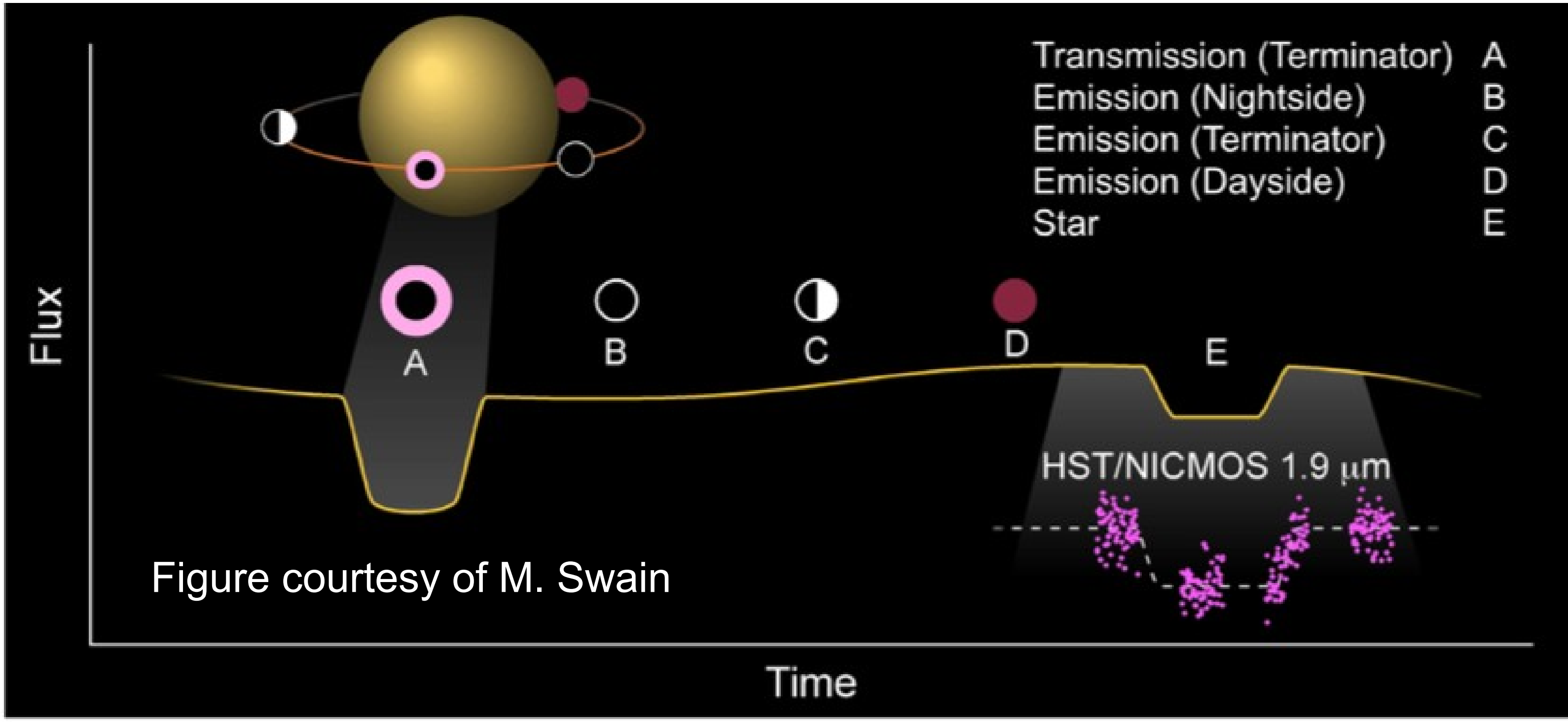
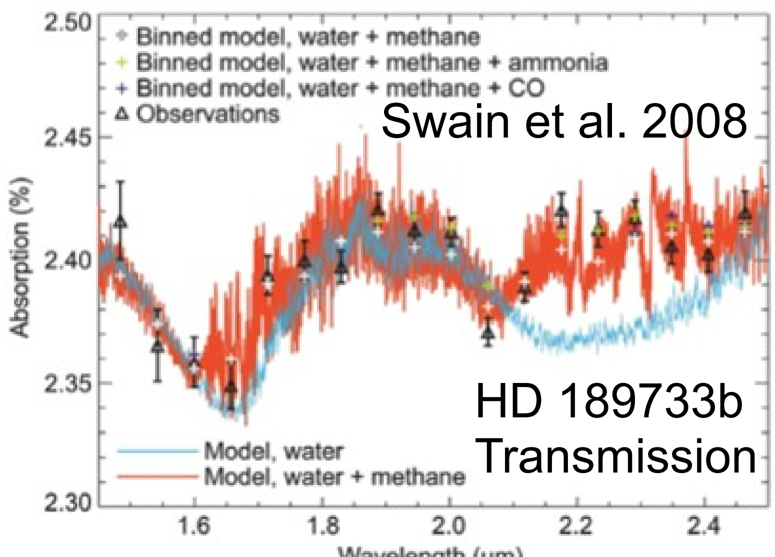
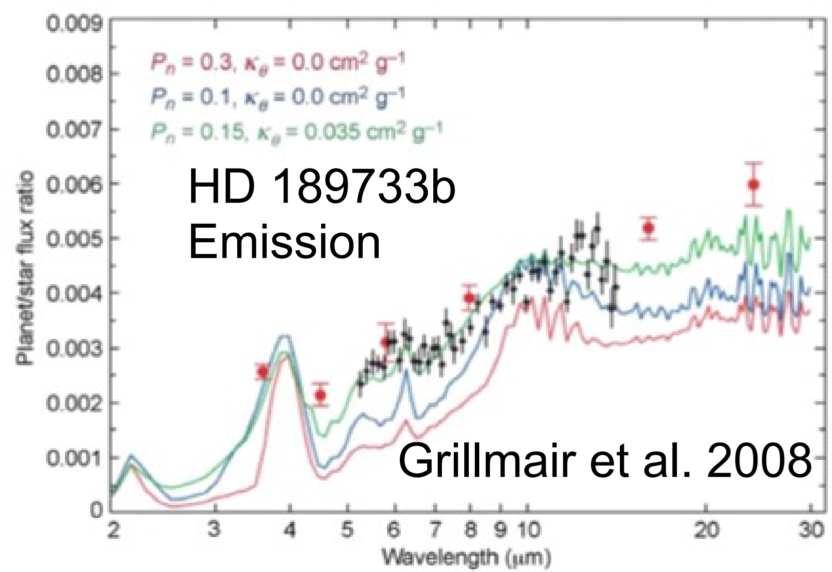


Figure courtesy of M. Swain





Some Outstanding Issues

- What spectral features are really present?
- Are observed strengths of spectral features due to intrinsic abundances or temperature profiles?
  - Distinguish temperatures, T profiles, compositions
  - Are ice giants overabundant in carbon / metals like Neptune?
- How is energy absorbed and transported in highly irradiated planets?
  - Measure & determine causes of temperature inversions
  - Study transport via day / night side differences
  - Is there non-equilibrium chemistry?
    - Hydrocarbons like C_2H_2 (acetylene), C_2H_6 (ethane) indicate photo-chemical production
- What is the composition of mini-Neptune atmospheres?
- Can Kepler Earth candidates (1 Me, 1AU) be confirmed?
- Can we detect any features in Super/Earth atmospheres?

How Can JWST Help?

- JWST has 6.5 m aperture vs. 2.4 m for HST and 0.85 m for Spitzer
  - Photon noise-limited SNR goes as aperture size, so JWST should be capable of SNR ~ 3 – 8 times present values
- JWST has great spectroscopic capabilities, particularly:
  - λ = 0.7 – 5 μm, R ~ 100 mode with NIRSpec prism
  - λ = 0.7 – 2.5 μm, R ~ 700 mode with NIRISS grism+prism (slitless)
  - λ = 2.5 – 5 μm, R ~ 1700 mode with NIRCam grisms (slitless)
  - λ = 5 – 12+ μm, R ~ 70 mode with MIRI LRS prisms (slitless)
- JWST is being designed and will be operated to maximize exoplanet spectroscopy SNR
  - Wide NIRSpec slit (1400 mas) and slitless mid-IR spectroscopy
  - Testing spectrophotometric precision and simulating operations
  - Systematic noise due to pixel size and observatory parameters are being modeled (P. Deroo PASP submitted), mitigation possible

What are the optimum JWST targets?

- Ideally we need planets transiting / eclipsing IR bright nearby but small stars
  - SNR ~ sqrt(star signal), planet emitting / absorbing area, & R_*^{-2}
  - M stars are ideal if stable
  - Kepler planets are too faint / distant for spectroscopy
- Large planet atmospheric scale heights $H = kT/(\mu g)$ will have relatively high SNR transit spectra: $A_{atm} \sim 2\pi R_{pl} 5H$
  - Gas giants, ice giants, mini-Neptunes will be good
- Do harder (smaller / cooler) planets with JWST
- Impossible to characterize true Earth / Sun analog via transit spectroscopy

JWST Simulations

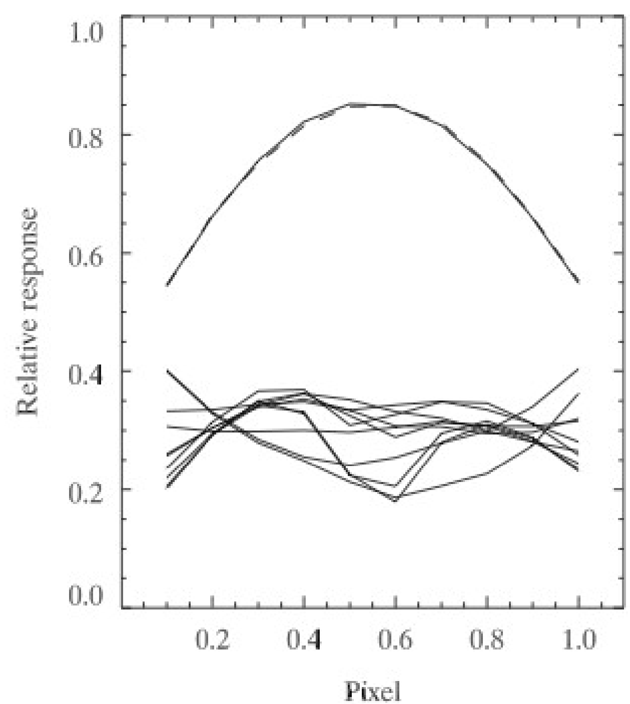
- Transmission and emission models from J. Fortney group
- Semi-realistic model of telescope and instrument wavelength-dependent resolution and throughput
  - Includes reflections, grating functions, filters
  - Use actual instrument models or guesstimates
- Photon noise and systematic noise added
- Systematic noise is difficult to predict but starting to model it
  - Different for each instrument and mode
  - May have large wavelength dependencies (Deroo sub. PASP)
- Compare simulations of model variants to determine what science issues can be addressed with JWST data

JWST Systematic Noise Estimates

- Variable PSF and image jitter will induce spectrophotometric errors due to non-uniform intra-pixel detector response and residual flat field errors
- These effects were noted in the Spitzer IRAC InSb detectors and calibrated out to about 1E-4 precision
- Use of slitless spectrographs and JWST NIRSpec wide slit (1600 mas) will eliminate any systematic noise due to jitter-induced slit losses

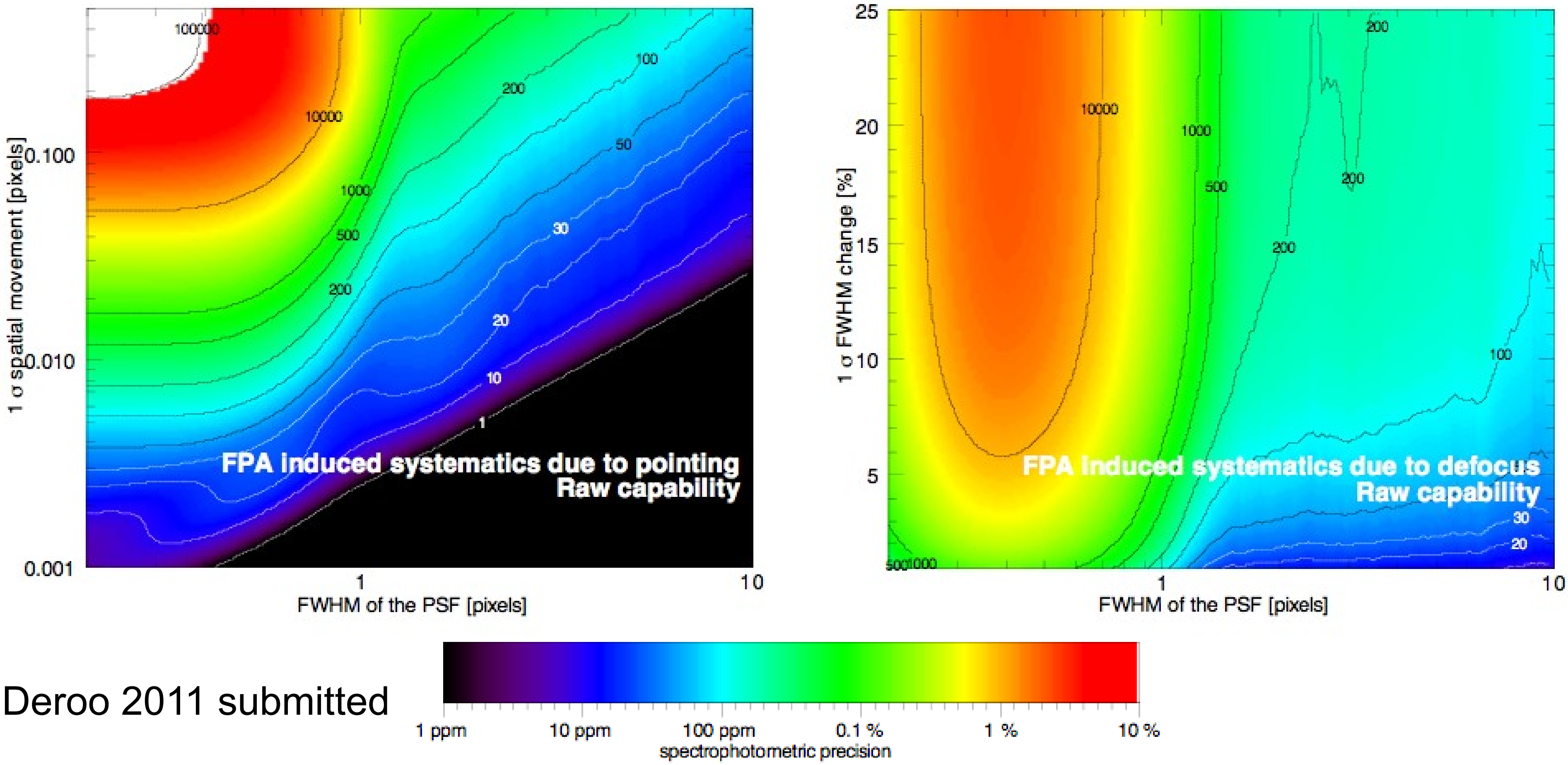
Deming et al. 2009 PASP

FIG. 8.—Intrapixel sensitivity variation for a representative NIRSpec detector pixel, from engineering measurements of the flight detector. The upper traces show the average variation in the dispersion direction (*solid line*), and the spatial direction (*dashed line*). The lower traces divide the pixel into 10 strips parallel to the spectral dispersion, and they show the difference from a parabolic fit of response vs. distance from pixel center. The differences have been amplified by a factor of 4, and offset by 0.3, for clarity of presentation.



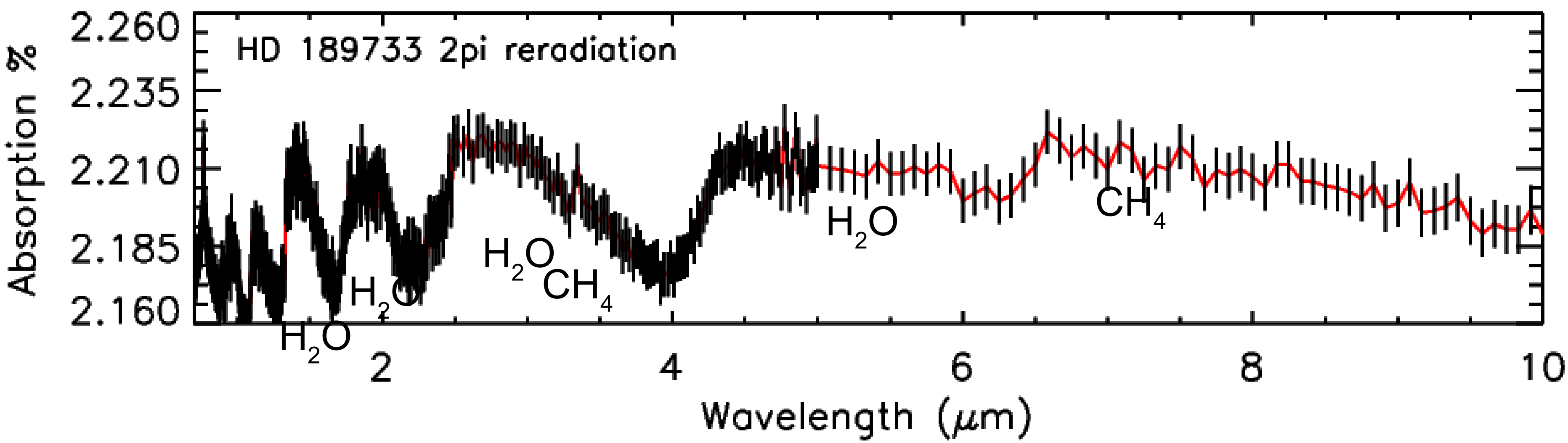
Systematic Noise Estimate Models

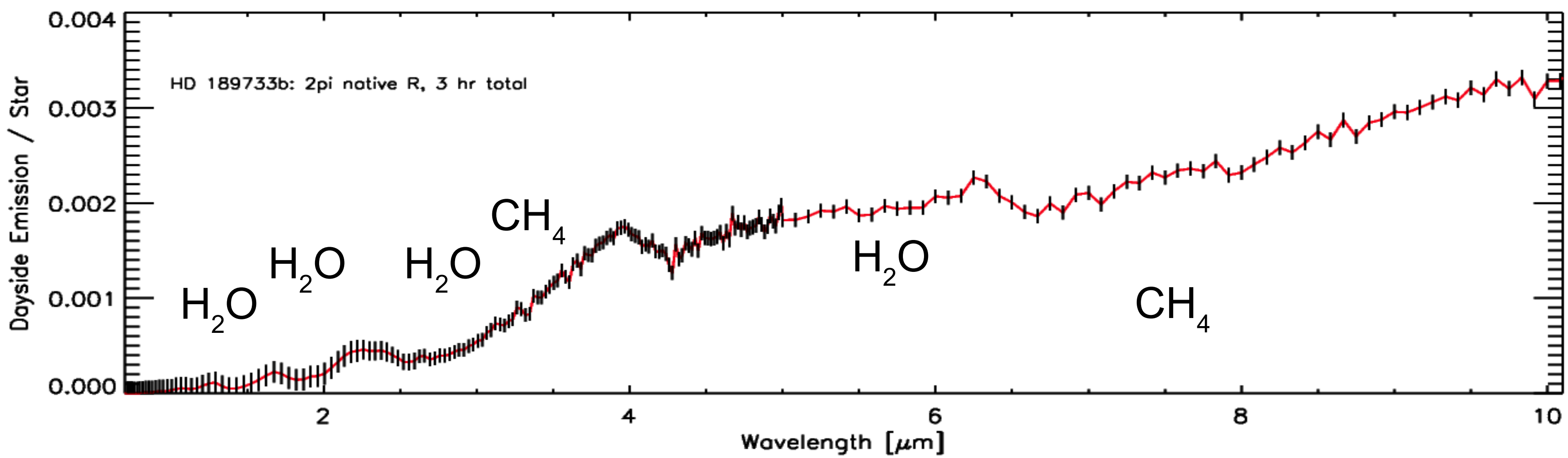
- Focus and pointing drifts are likely the biggest impact for JWST NIRSpec due to its undersampled PSF. Most critical below 2.5 or 3 microns.
- NIRISS GR700XD, NIRCam grism, and MIRI LWS all minimal impact



P. Deroo 2011 submitted

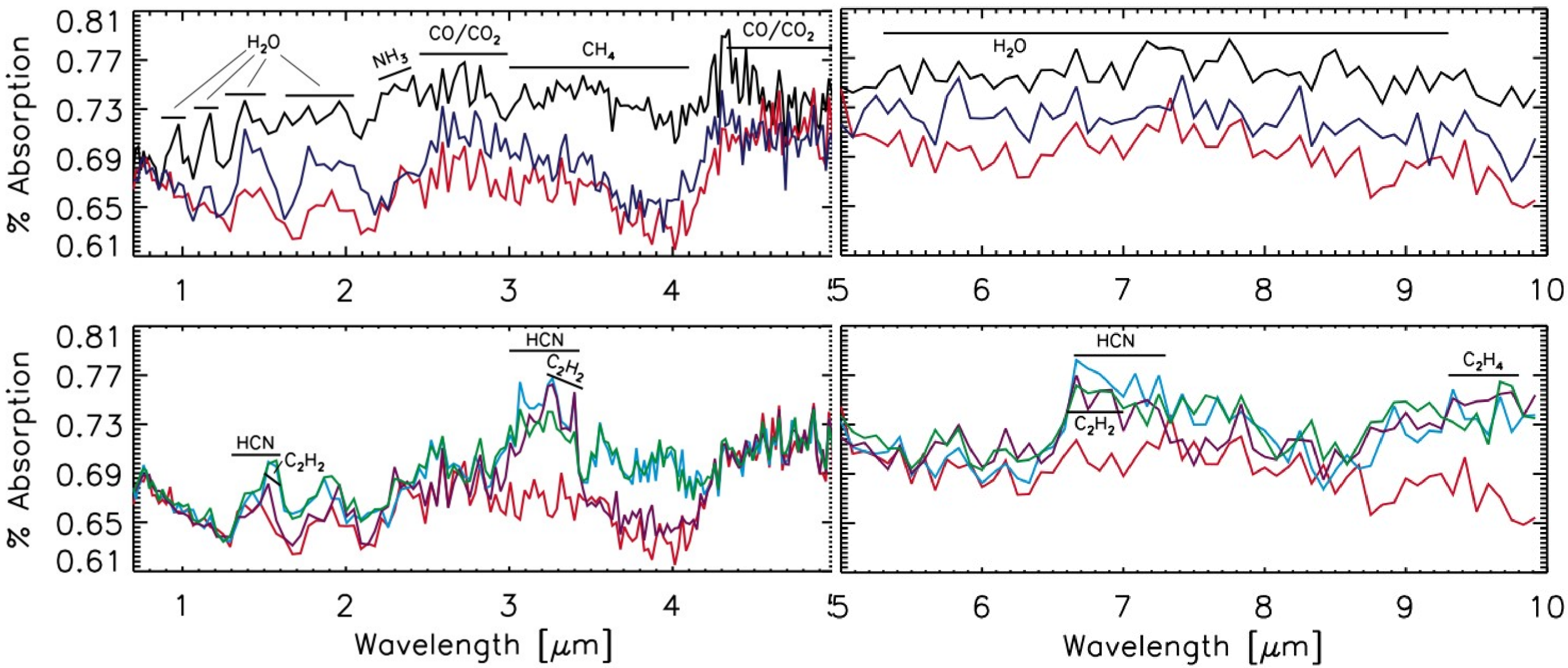
HD 189733b Gas Giant



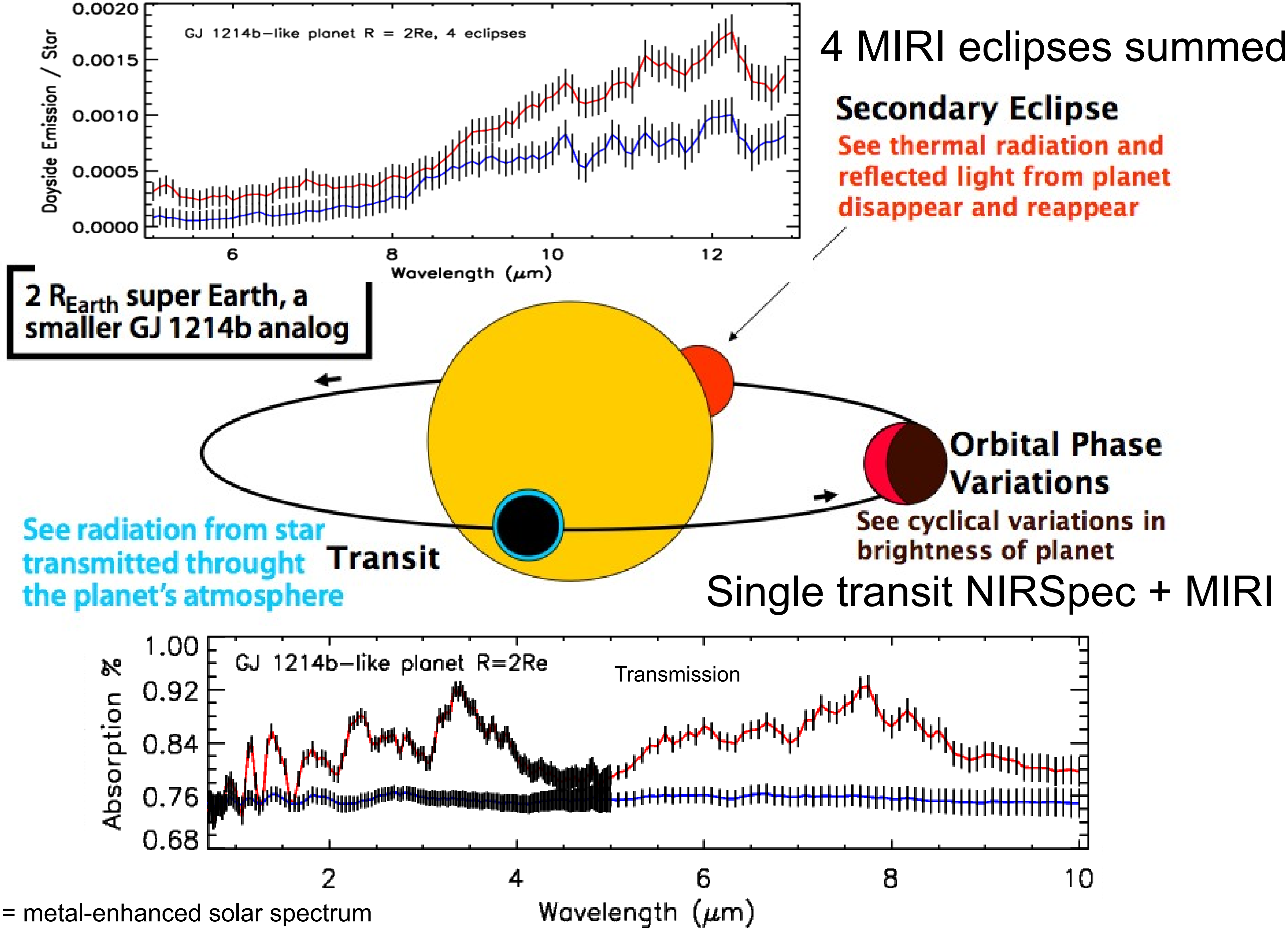


- Only 1 transit (top) or eclipse (bottom) plus time on star for each (1 NIRSpec + 1 MIRI)
- Multiple features of several molecules separate compositions, temperature, and distributions (J. Fortney group models + JWST simulation code)

GJ 436b (warm Neptune) transmission spectra simulations



- Simulated single transit model absorption spectra distinguish between equilibrium 30X solar (black), reduced CH4 & H2O (blue, red) or non-equilibrium chemistries where H_2O and CH_4 are absent in favor of higher order hydrocarbons HCN, C_2H_2, and other molecules (purple, cyan and green curves). 1 transit each: 30 min star + 30 min in-transit integration time. Noise has been added (*Shabram et al. 2011)*.



RED = metal-enhanced solar spectrum
BLUE = H_2O dominated (small H)

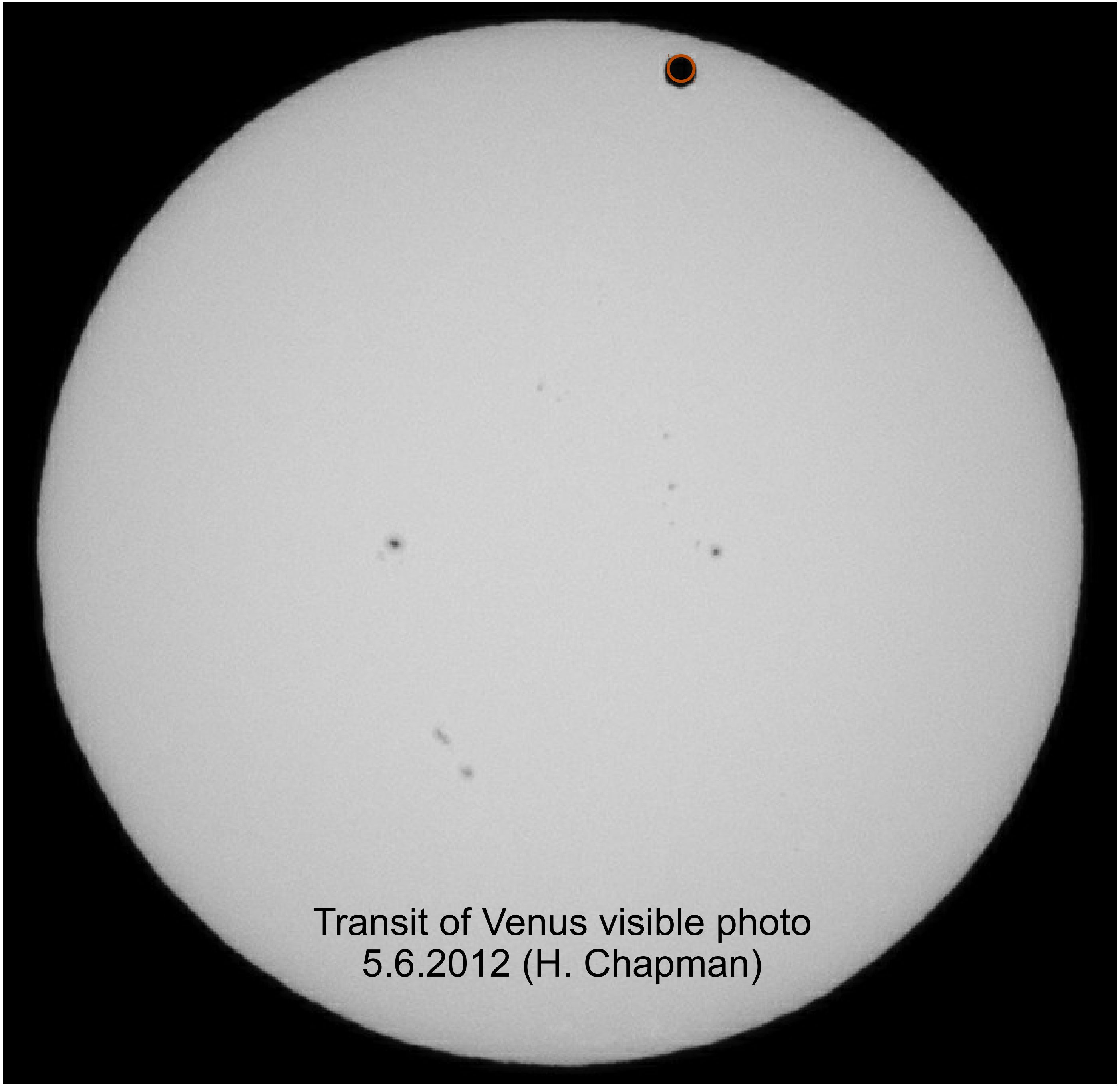
Next Steps: Better noise models & retrieval

- Will update systematic noise estimates with info from instrument tests

- Need to assess what information can be extracted from simulated spectra:
  - What features are present at what strengths and significance?
  - What is uncertainty in derived atmospheric parameters?
- I'll probably start with simple χ^2 retrieval methods

- I welcome your comments / advice / participation

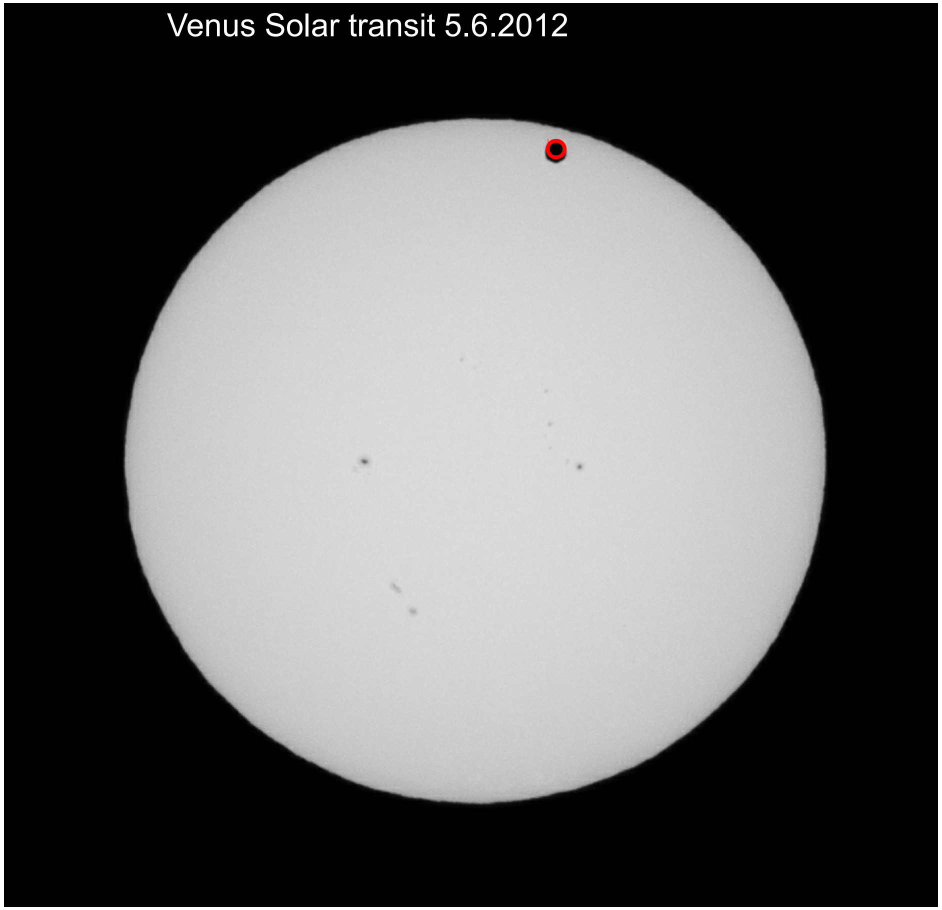
Are Earth transmission spectra possible?



Transit of Venus visible photo
5.6.2012 (H. Chapman)

Earth transit facts of life

- Earth disk area is ~ 1E-4 of a G2V star or 1E-3 of M3V (GJ 581)
- Absorbing area of Earth atmosphere is $A \sim 2\pi R_e 5H$, $H = kT_e/\mu g \sim 8$ km, so $A \propto T_e/\mu\rho$ and A/Ae ~ 0.01
- Therefore a completely absorbing spectral line would have a signal (Area) of ~1E-5 relative to M3V star
- Detecting this signal at SNR=3 requires precision of 3E-6 (3 ppm)
- Would require co-addition of ~100 transits to get 1E11 photons per spectral element, but systematic noise must be > 20x lower than HST
- Super-Earths? Remember $A \propto T_e/\mu\rho$ Area is independent of radius R



The disk of Venus against the Sun is about the size of Earth transiting an M3-5 dwarf. The red annulus is much larger than the absorbing limb of the Earth atmosphere. Notice the star spots. Photo by H. Chapman.

How to progress beyond individual planets?

- Need a dedicated, smaller mission to conduct a statistical survey to advance exoplanet atmosphere science:
  - How are exoplanet atmosphere compositions related to host stars, and what does this tell us about their formation?
  - What equilibrium and non-equilibrium chemistry is present, and what internal / external processes drive this?
  - How is stellar energy absorbed and transported in planets; what causes inflated radii?
    - Measure & determine causes of temperature inversions
    - Study transport via day / night side differences
  - How does the solar system and its formation compare with nearby planetary systems?
- Transit spectrocopy performance is not a strong function of aperture (SNR goes as D, not D^2) and is improved by simultaneous wavelength coverage and low systematic noise

Some Conclusions

- Expect exquisite JWST spectra of gas and ice giants
  - Determine abundances, temperature profiles, and energy transport in hot Jupiters with little degeneracy using transit & eclipse spectra over 0.7 – 10+ microns.
- Easily constrain compositions of mini-Neptunes like GJ 1214b (down to 2 R_E and smaller)
- Possibly detect CO_2 absorption in Super-Earths, but Earth-like planets are difficult otherwise
- There is plenty of exoplanet spectroscopy to do:
  - Cool, dense planets with JWST
  - Statistical survey of giant planet atmospheres with FINESSE or EChO
  - Stability and low systematics are as important as aperture