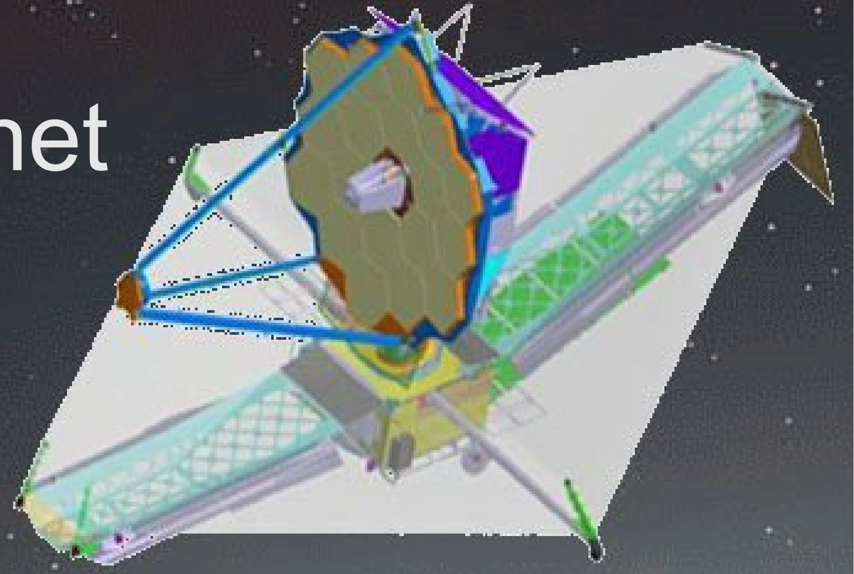
# Transit and Eclipse Exoplanet Spectroscopy with JWST



Strange New Worlds Meeting

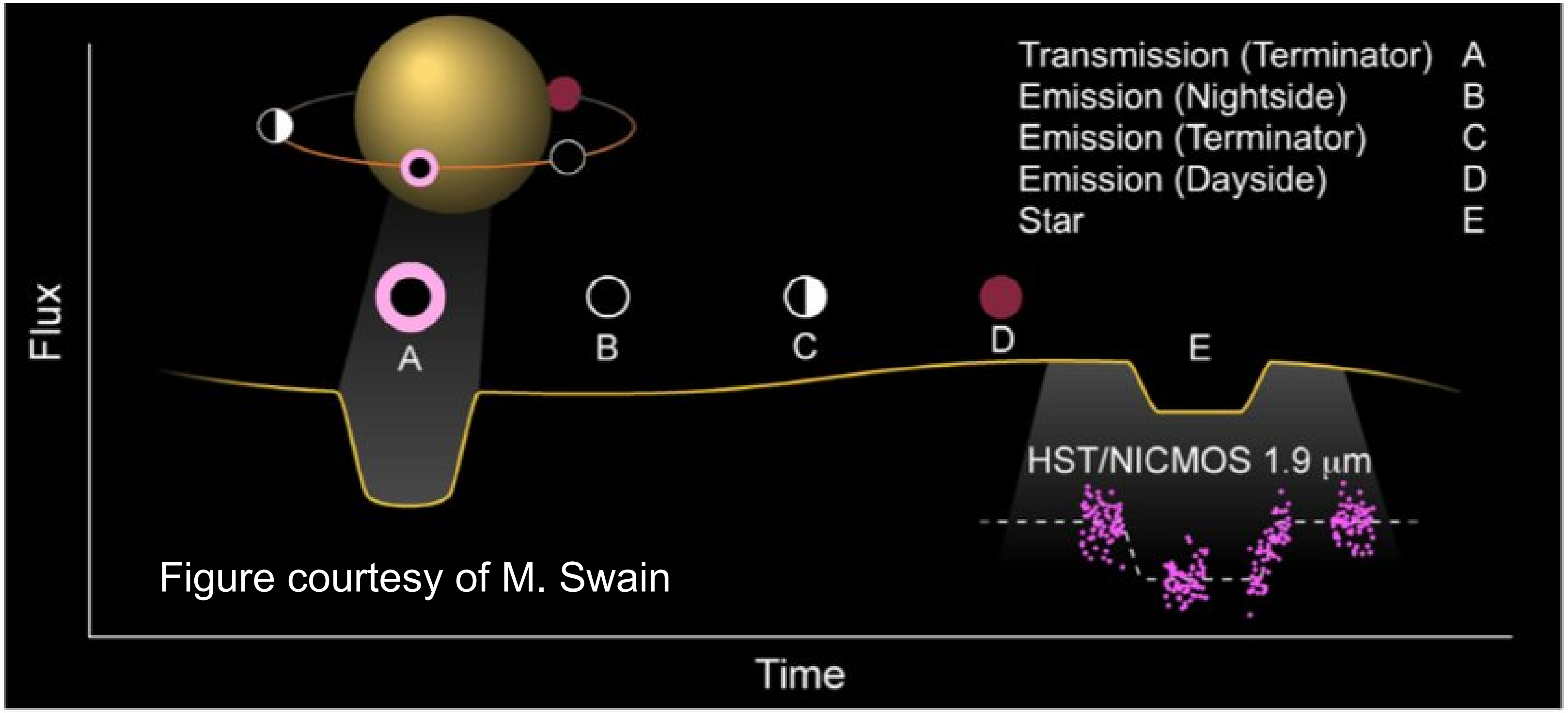
Tom Greene

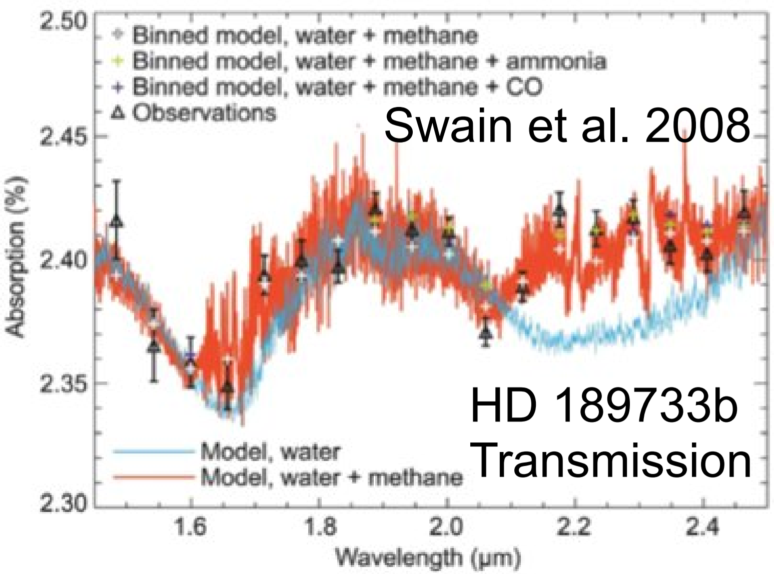
May 3, 2011

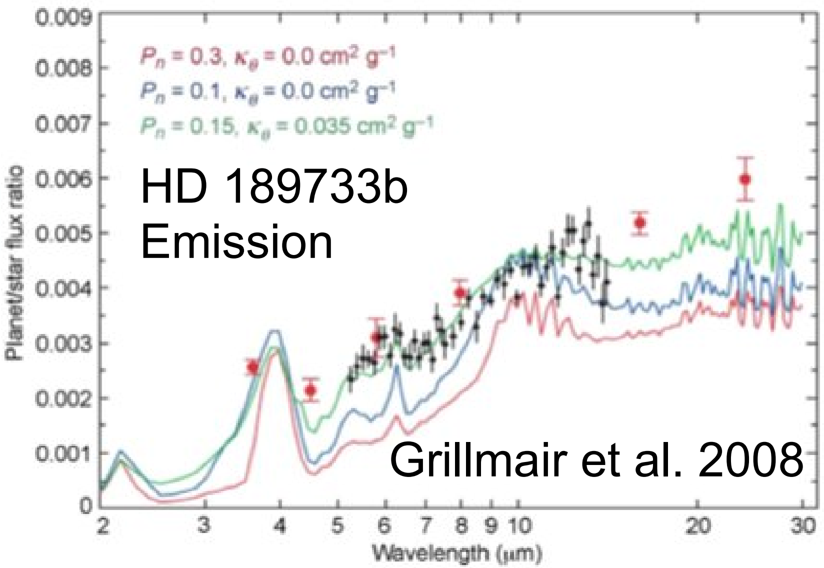
# Presentation Scope

- Exoplanet Time Domain Spectroscopy
- Outstanding Issues
- How Can JWST Help?
- Optimum Targets
- Planet Models
- Simulated Spectra and Potential Science
- Takeaways

# Exoplanet Spectroscopy Status

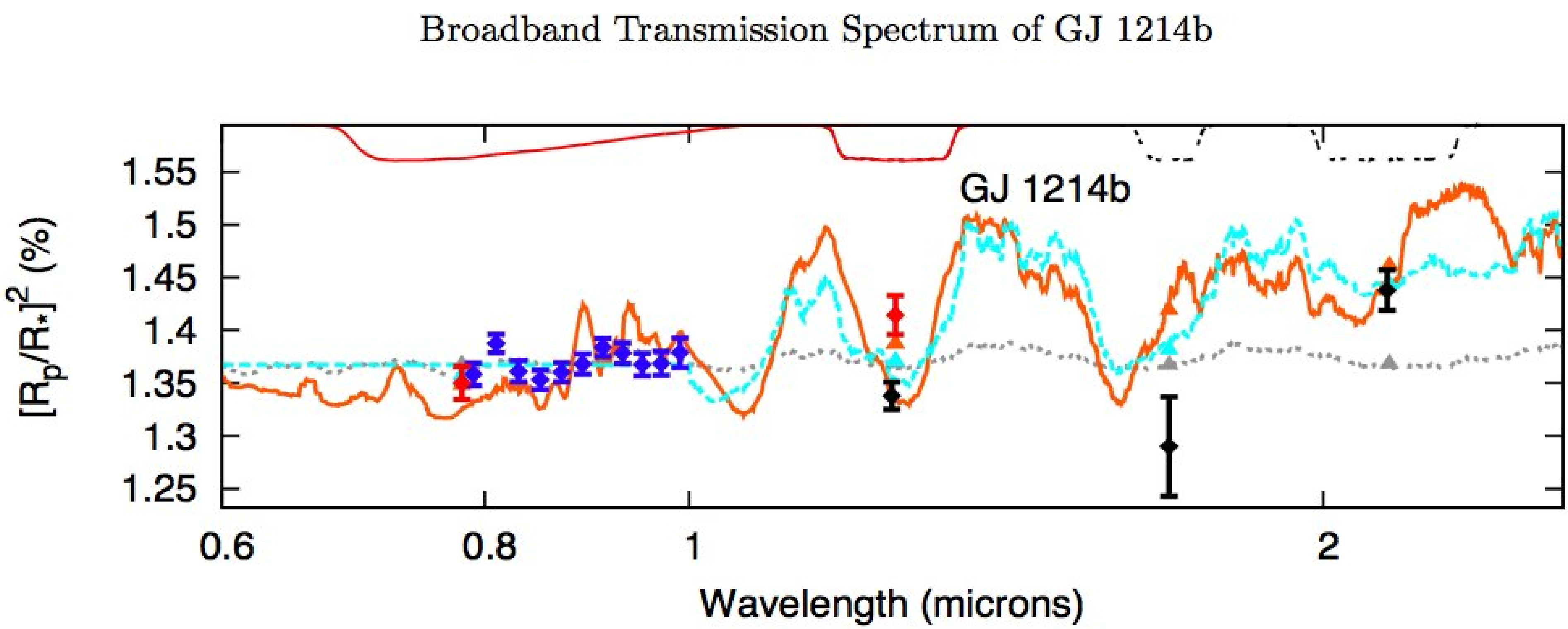


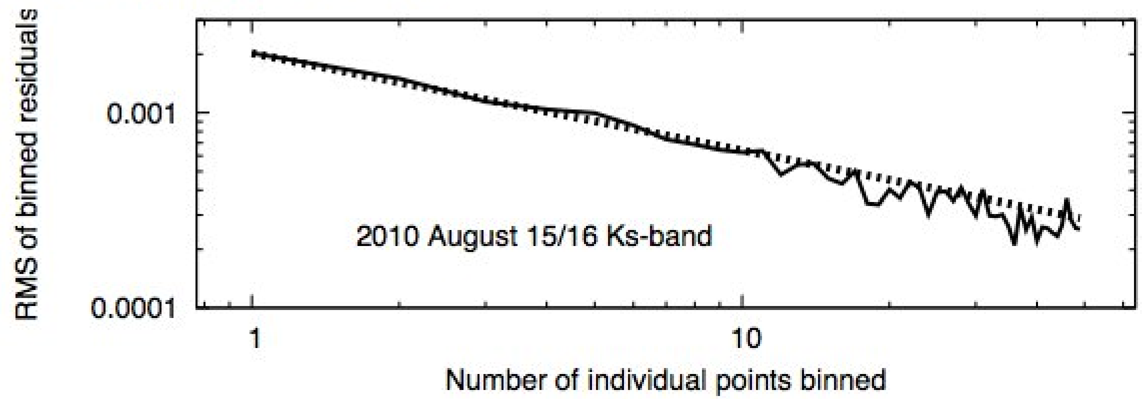



# Exoplanet Spectroscopy: The Ground

- The ground is trying. Enough aperture but control of systematic noise is difficult.




- Croll et al. 2011 photometry
- See also Ian Crossfield et al. Poster (Keck NIRSpec GJ 1214b)
- Swain and others doing spectroscopy

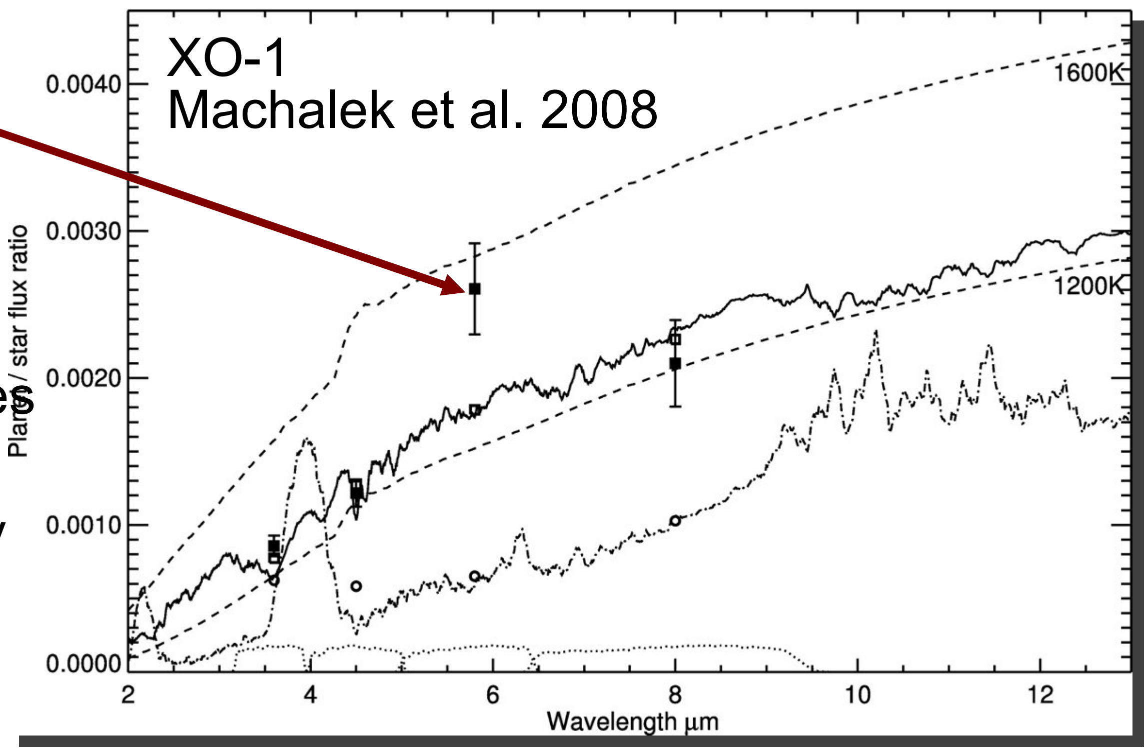


# Some Outstanding Issues

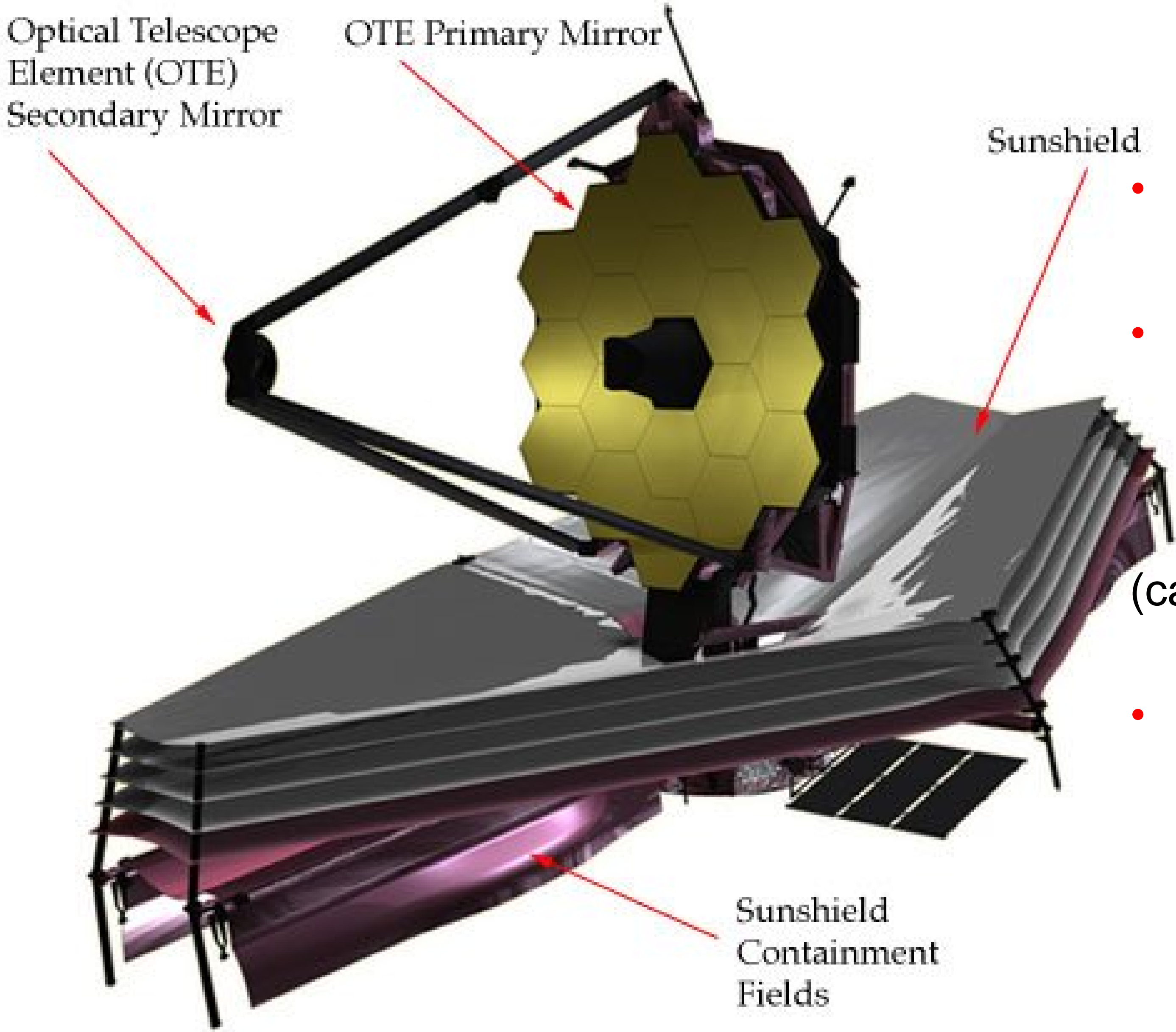
- Are observed strengths of spectral features due to abundances or temperature profiles?
  - Distinguish temperatures, T profiles, compositions
  - Are Ice giants overabundant in carbon like Neptune?
- How is energy absorbed and transported in highly irradiated planets?
  - Measure & determine causes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

# Unidentified features in high insolation

- Excess Spitzer IRAC Band 3 emission seen in exoplanets with hot stratospheres / high altitude inversions like HD 209458
- Common to many planets, most highly insolated
- Is it enhanced continuum or an unknown spectral feature
  - Current models can't fit it with continuum or a species (TiO / VO tried & non-equiib processes suggested)
  - Useful in understanding energy transport in atmosphere and compositions of planets

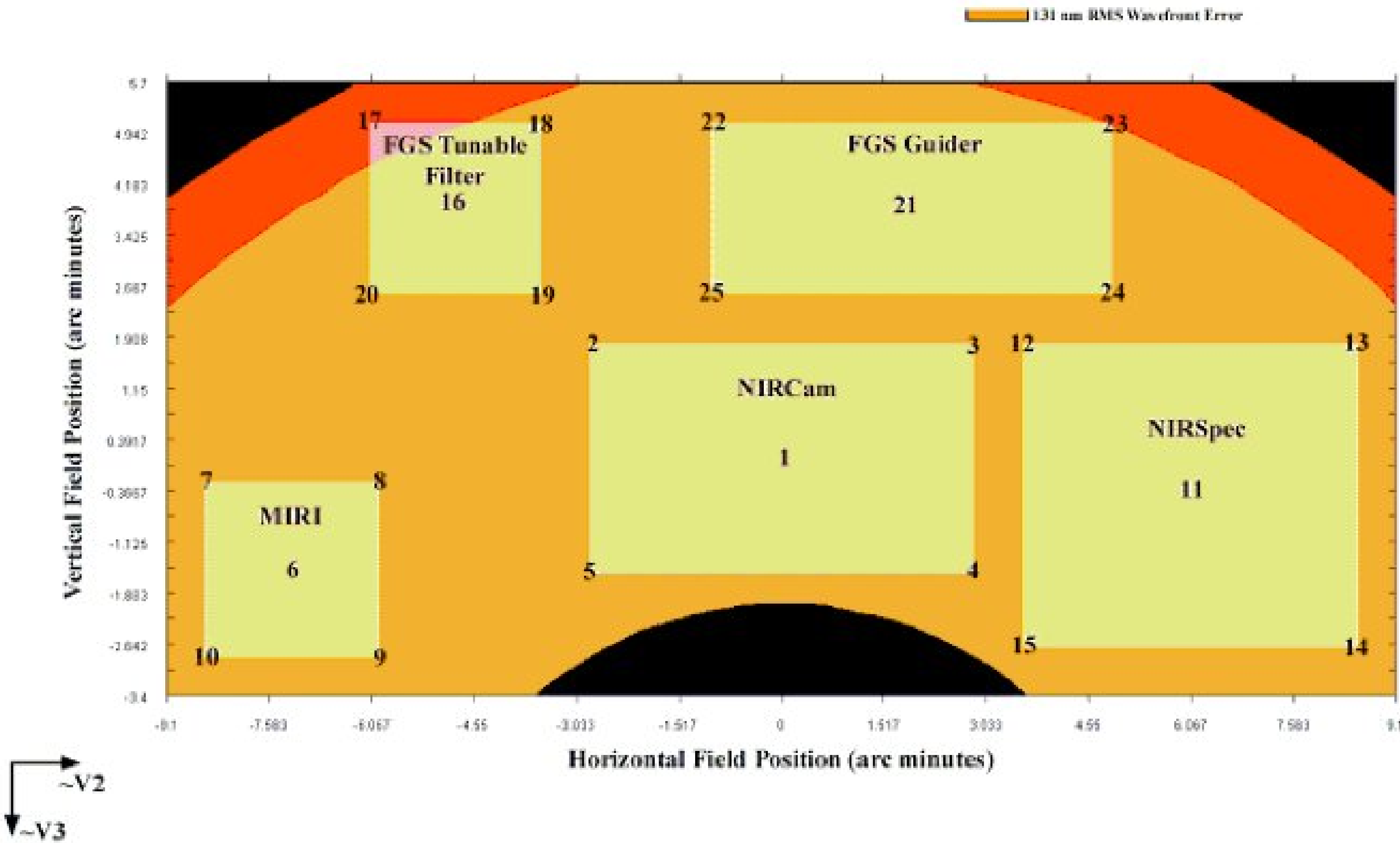


# JWST in a nutshell




- 6.5-m primary mirror; 18 segments.
  - T~40K, bkg. limited
- λ <1 - 28 μm
  - zodi-limited to 10μm
- Instruments:
  - NIRCam 1 – 5 μm
  - NIRSpec 1 – 5 um
  - MIRI 5 – 28 um (cam + spec)
  - FGS w/TF 1 – 5 um
- 201X launch
  - Arianne V to L2
  - 5 yr req life
  - 10 yr goal
  - No cryogens

# Focal Plane Layout




- Instruments view different parts of JWST focal plane
- Little parallel operation currently planned

# 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:
  - $\lambda$ = 1 – 5 $\mu$m, R ~ 100 mode with NIRSpec prism
  - $\lambda$ = 5 – 12+ $\mu$m, 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
  - Large NIRSpec pixels may reduce precision (see P. Deroo poster); mitigation possible?

# JWST Observational Constraints

- JWST instantaneous field of regard is limited
  - Sun angles between 85 and 135 degrees (35% of sky)
  - Two 50-day visibility windows per year near ecliptic
- JWST is optimized for long exposures of faint objects but subarrays do provide reasonable bright limits:
  - K ~ 5 mag for R=1700 NIRCam grism (2.4 – 5 μm)
  - K ~ 7 mag for NIRSpec R ~ 33 – 315 prism (0.7 – 5 μm)
  - Low overhead for long sequence of identical integrations if not too bright
- Ground bright limits are similar for R ~ 20,000 Keck NIRSpec & IRTF CSHELL / iSHELL
  - Narrow-band imaging could have similar limits if subarrays used

# What are the optimum JWST targets?

- Ideally we need planets transiting / eclipsing IR bright nearby but small stars
  - Star SNR ~ sqrt(Signal) and transit depth ~ $(R_{pl} / R_*)^2$
  - M stars are ideal if stable
  - Kepler planets are too faint / distant for spectroscopy
- Planets with large atmospheric scale heights $kT/(\mu g)$ will have relatively high SNR spectra
  - Gas giants, ice giants, mini-Neptunes will be good
- Impossible to detect atmospheric features in true Earth / Sun analog
- ***We need an all-sky transit survey mission to find good planets:*** ELEKTRA (or TESS) Explorer

# Planet Models (J. Fortney & Collaborators)

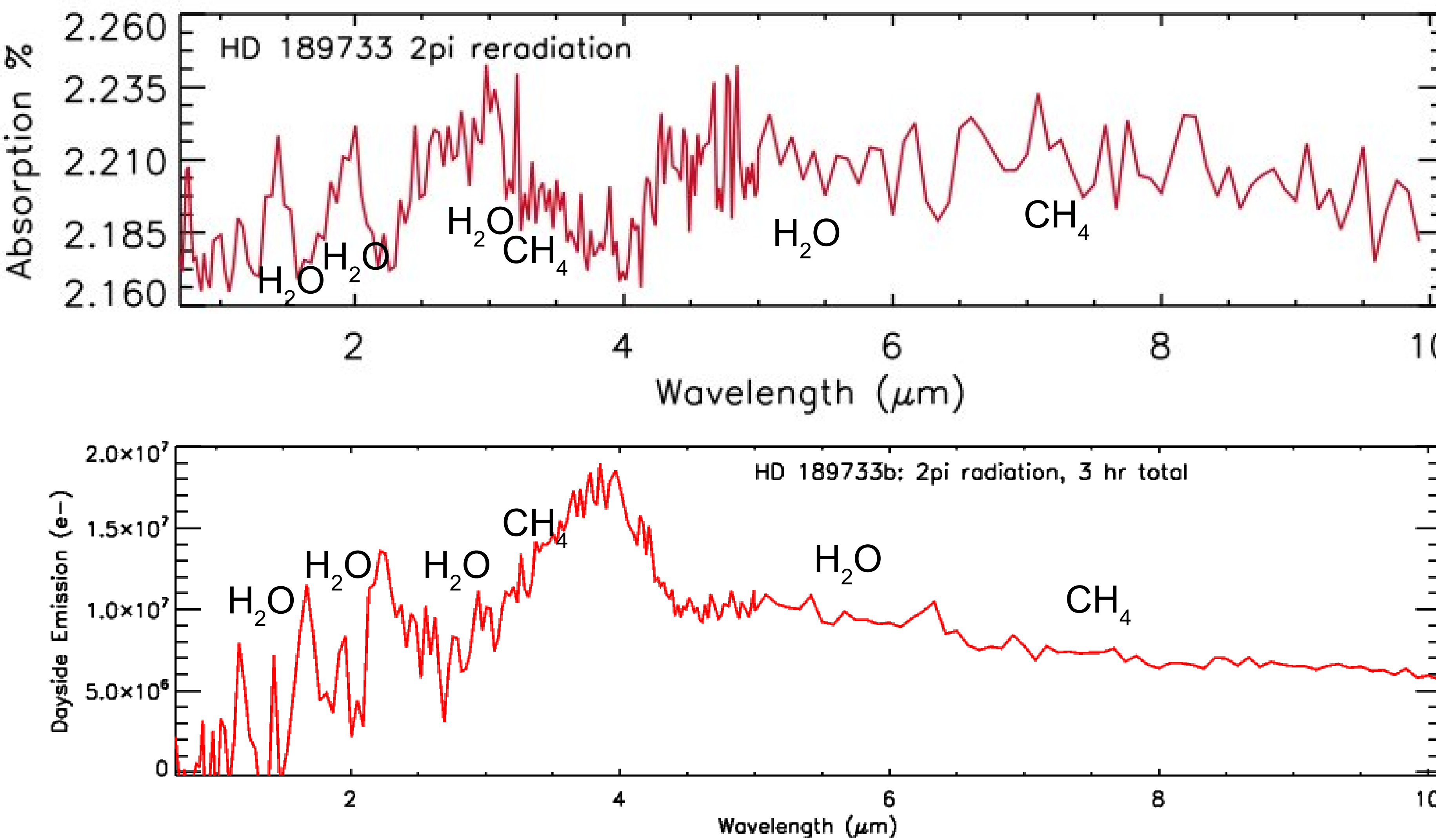
- “Hot Jupiters”, “Neptunes”, “mini-Neptunes”
- Absorption and Emission models
- Variations for re-radiation geometry (2 pi / 4 pi), abundances, chemistry

| Planet | Star SpT | V* (mag) | R* (Rsun) | R_pl (Rj) | t_trans (m) | t_ecl(m) |
|---|---|---|---|---|---|---|
| HD 189733b | K1.5 | 7.7 | 0.79 | 1.15 | 110 | 110 |
| HD 209458b | G0V | 7.7 | 1.15 | 1.38 | 144 | 144 |
| HD8606b | G5 | 8.9 | 0.98 | 0.92 | 728 | 101 |
| TrES-3 | G | 12.4 | 0.81 | 1.31 | 78 | 78 |
| WASP-12b | G0V | 11.7 | 1.57 | 1.79 | 162 | 162 |
| WASP-17b | F6 | 11.6 | 1.38 | 1.74 | 262 | 262 |
| WASP-18b | F9 | 9.3 | 1.23 | 1.17 | 135 | 135 |
| GJ 436b | M2.5V | 10.7 | 0.46 | 0.37 | 60 | 60 |
| GJ1214b | M4.5V | 14.7 | 0.21 | 0.24 | 50 | 50 |

# JWST Simulations

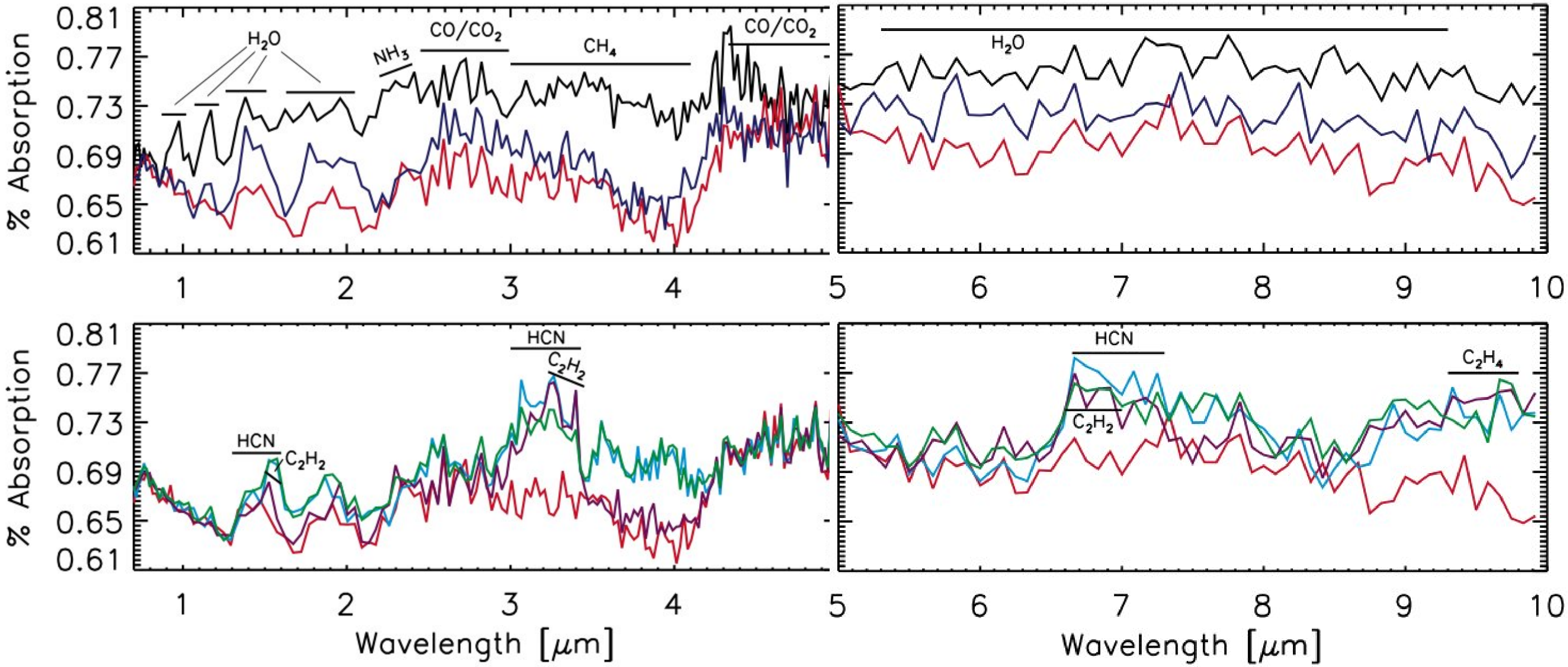
- Semi-realistic model of telescope and instrument wavelength-dependent resolution and throughput
- Photon noise and systematic noise added
- Systematic noise is difficult to predict
  - May have large wavelength dependencies (See P. Deroo poster)
  - Currently assumed to be 50 ppm (max SNR = 20,000)
- Compare simulations of model variants to determine what science issues can be addressed with JWST data

# HD 189733b Gas Giant

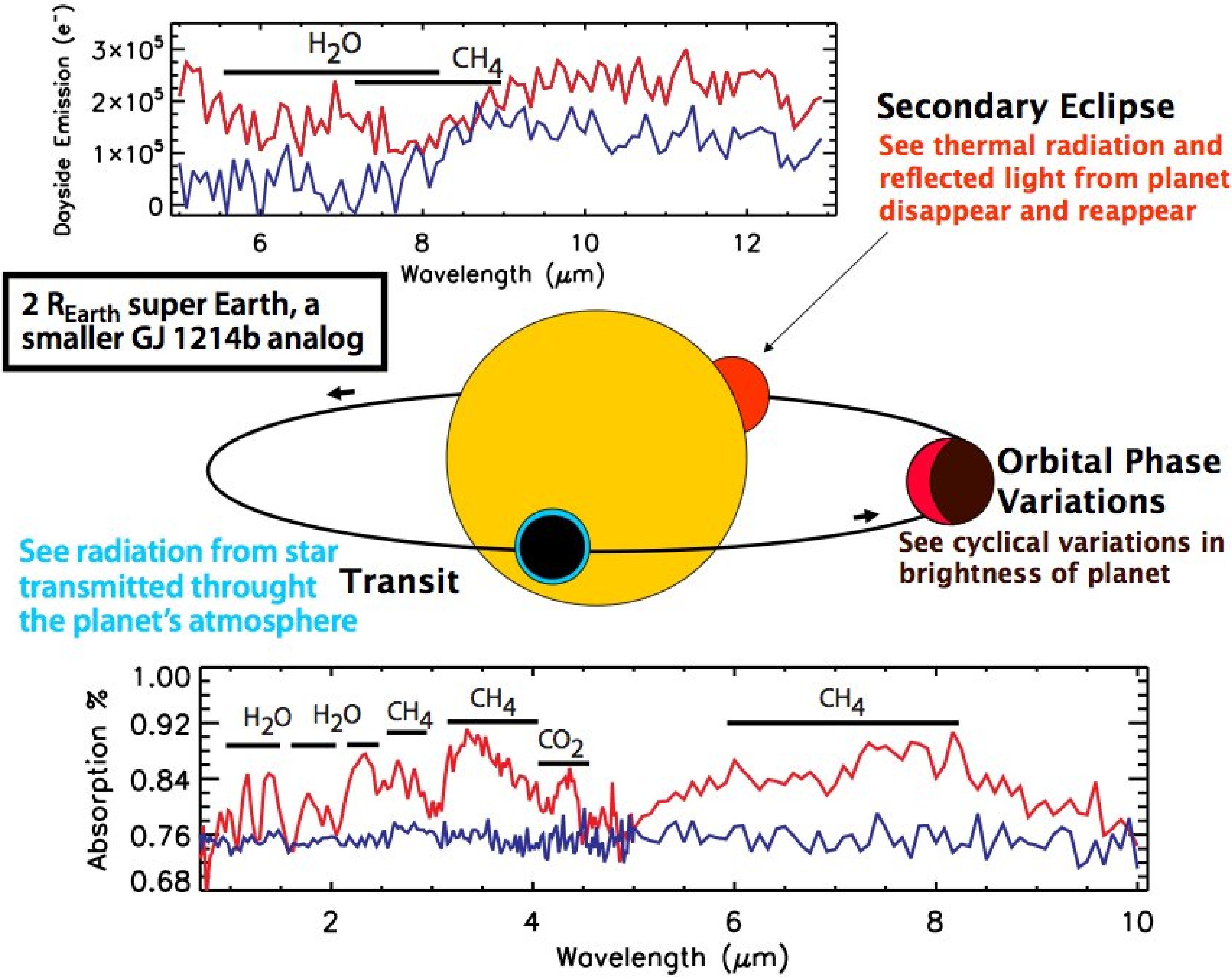



- Only 1 transit (top) or eclipse (bottom) plus time on star for each (1 NIRSPec + 1 MIRI)
- Multiple features of several molecules separate compositions, temperature, and distributions

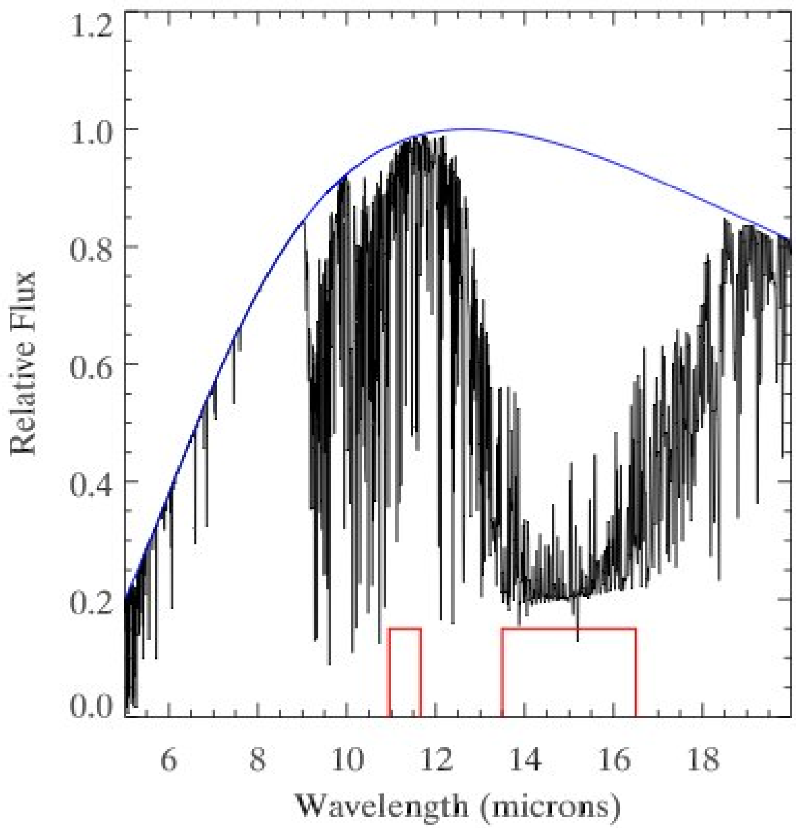
# GJ 436b (warm Neptune) transmission spectra simulations




- Simulated single transit model absorption spectra distinguish between equilibrium (black, 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). See *Shabram et al. (2011)*.


Dayside Emission (e⁻)
3×10⁵
2×10⁵
1×10⁵
0
H2O
CH4
6
8
10
12
Wavelength (μm)
Secondary Eclipse
See thermal radiation and reflected light from planet disappear and reappear
2 REarth super Earth, a smaller GJ 1214b analog
Orbital Phase Variations
See cyclical variations in brightness of planet
See radiation from star transmitted throught the planet's atmosphere
Transit
Absorption %
1.00
0.92
0.84
0.76
0.68
H2O
H2O
CH4
CH4
CO2
CH4
2
4
6
8
10
Wavelength (μm)

# MIRI detection of $CO_2$ in Super-Earths?




Deming et al. (2009) showing Miller-Ricci Super-Earth (2009) and MIRI filters

- JWST MIRI filters (red boxes, left) can be used to detect deep CO2 absorption in Super-Earth atmospheres in emission observations (Miller-Ricci 2009 model, left)
- Modelling shows that modest S/N detections possible on super-Earth planets around M stars (Deming et al. 2009).

# Some Takeaways

- Expect exquisite JWST spectra of gas giants
  - Determine abundances, temperature profiles, and energy transport in hot Jupiters with little degeneracy using transit and eclipse spectra over 0.8 – 10+ microns.
- Mid-IR spectra can identify unknown emission in Spitzer IRAC 5.8 μm band of planets with suspected hot stratospheres
- Easily constrain compositions of mini-Neptunes like GJ 1214b (down to 2 R_E and smaller)
- Possibly detect $CO_2$ absorption in Super-Earths
- ***We need an all-sky transit survey mission to find good planets:*** ELEKTRA (or TESS) Explorer