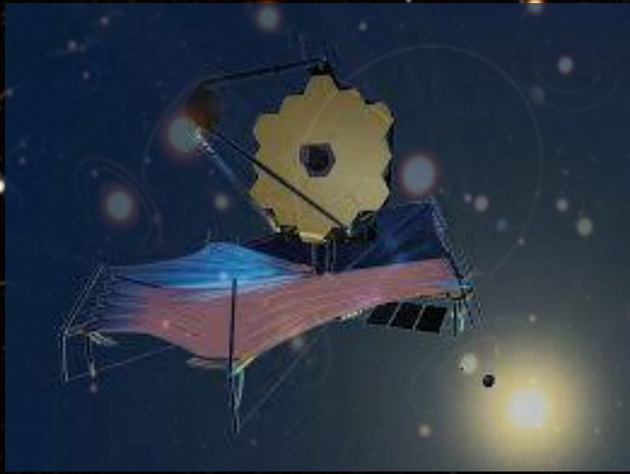
Characterizing exoplanet atmospheres with the James Webb Space Telescope



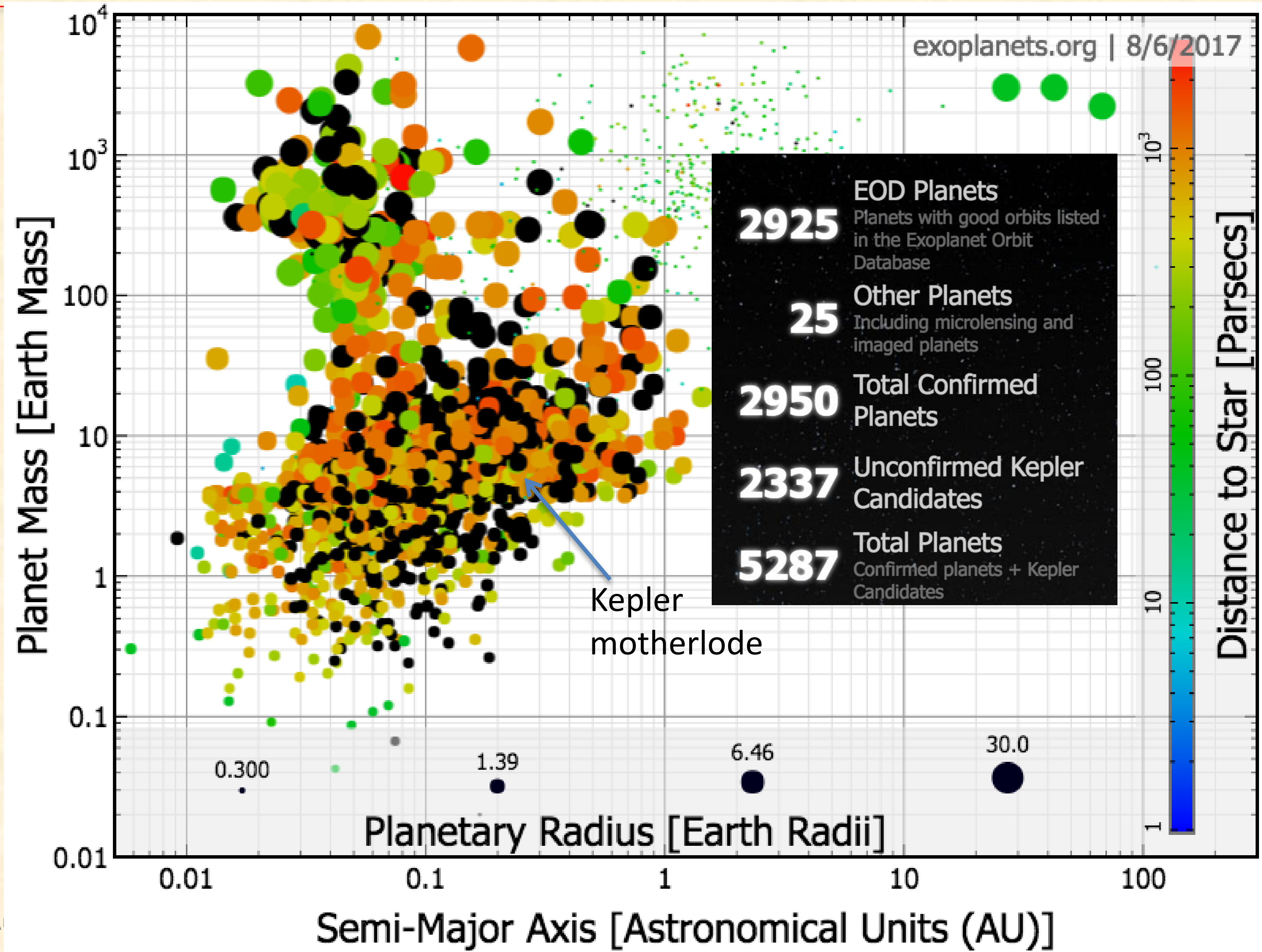
Tom Greene (NASA Ames)

Molecules in Space

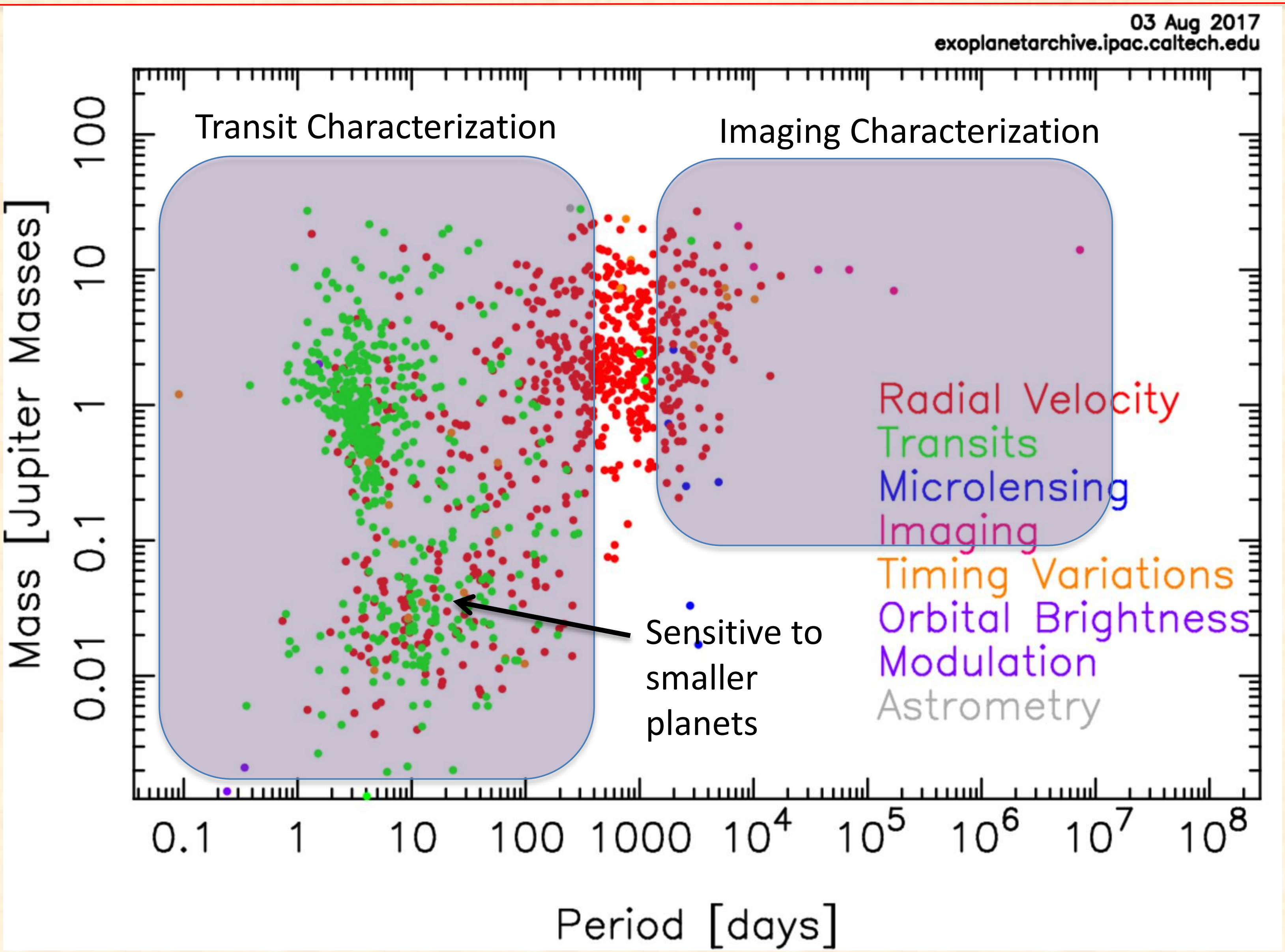
ACS Meeting

Aug 24, 2017

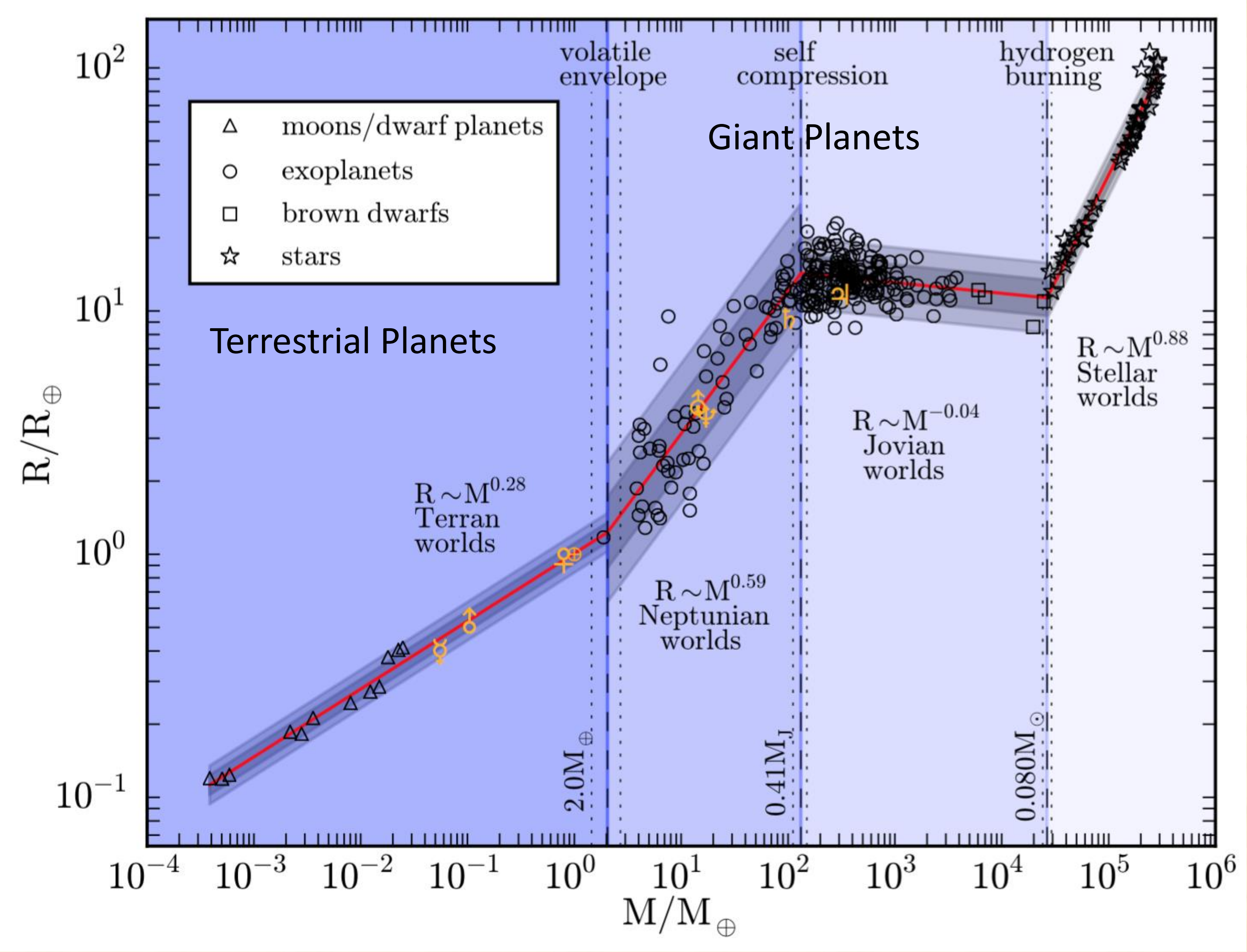
Known Exoplanets (August 2017)



Many known planets can be characterized



Planet-to-stellar mass-radius relation



Chen & Kipping (2016)

Planet Characterization: What is on the inside?

- ***We wish to know:***
  - How and where did the planets form?
  - How are they similar to and influenced by their host stars?
  - What are their temperature profiles and 3D heat distribution?
  - What are the compositions, locations, and impacts of clouds?

- ***How we can find out (or at least get clues):***
  - Observe spectra to probe compositions and temperatures
  - Compare compositions to host star to understand formation process (core accretion) and location in disk
  - Observe a large, diverse population to correlate results with bulk parameters (mass, density, insolation, host star)

Probe planet formation via C/O abundance

Öberg, Murray-Clay, & Bergin 2011

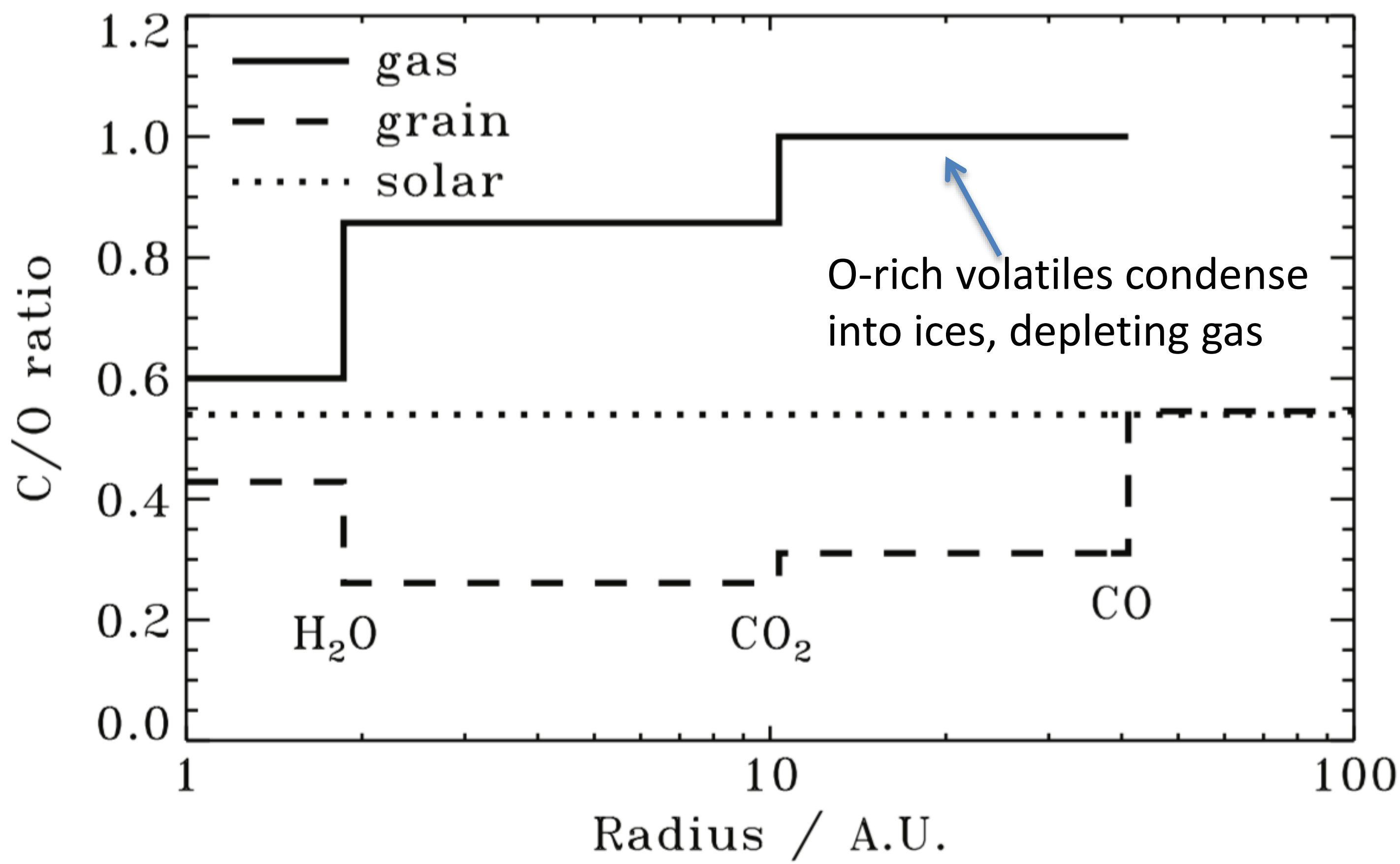
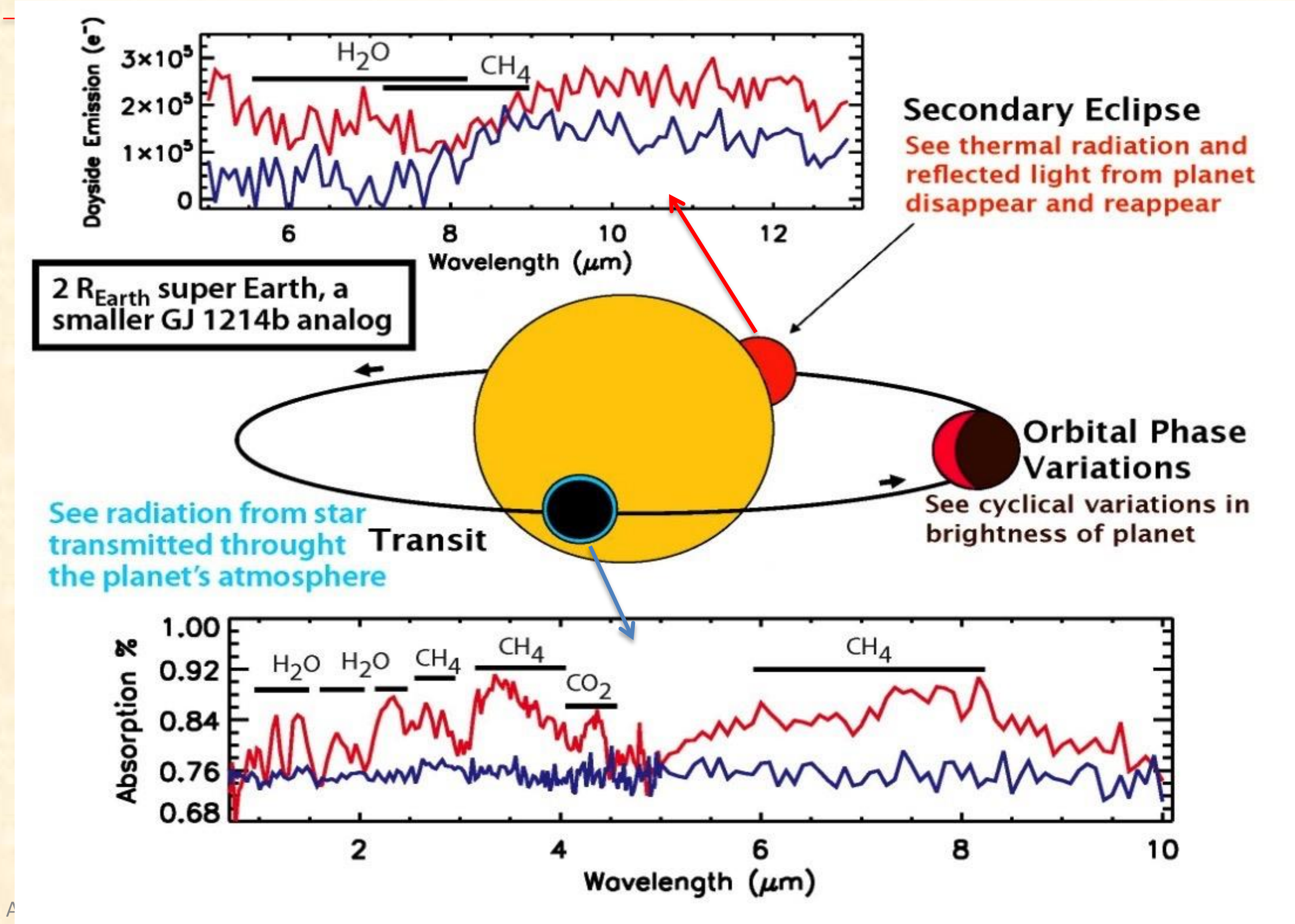


Figure 1. C/O ratio in the gas and in grains, assuming the temperature structure of a "typical" protoplanetary disk around a solar-type star (T_0 is 200 K and $q = 0.62$). The H_2O, CO_2, and CO snowline are marked for reference.

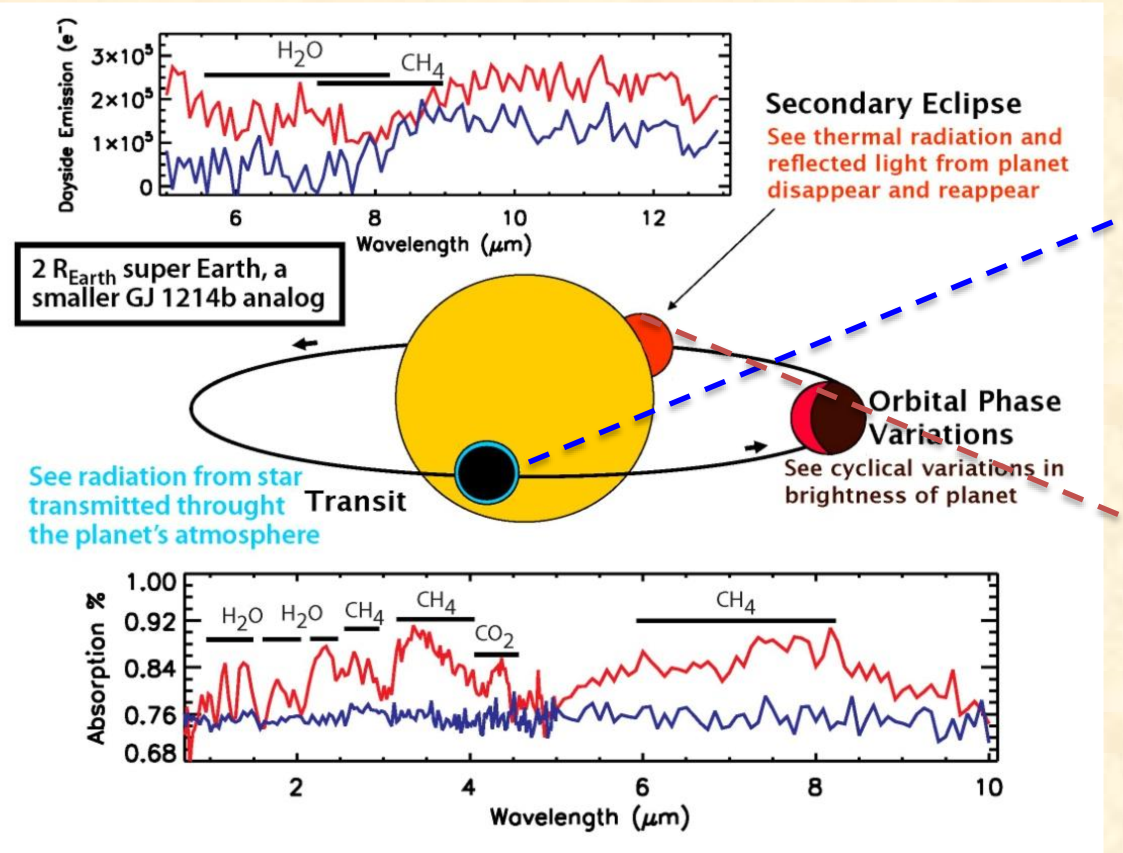
Specific questions about exoplanet atmospheres

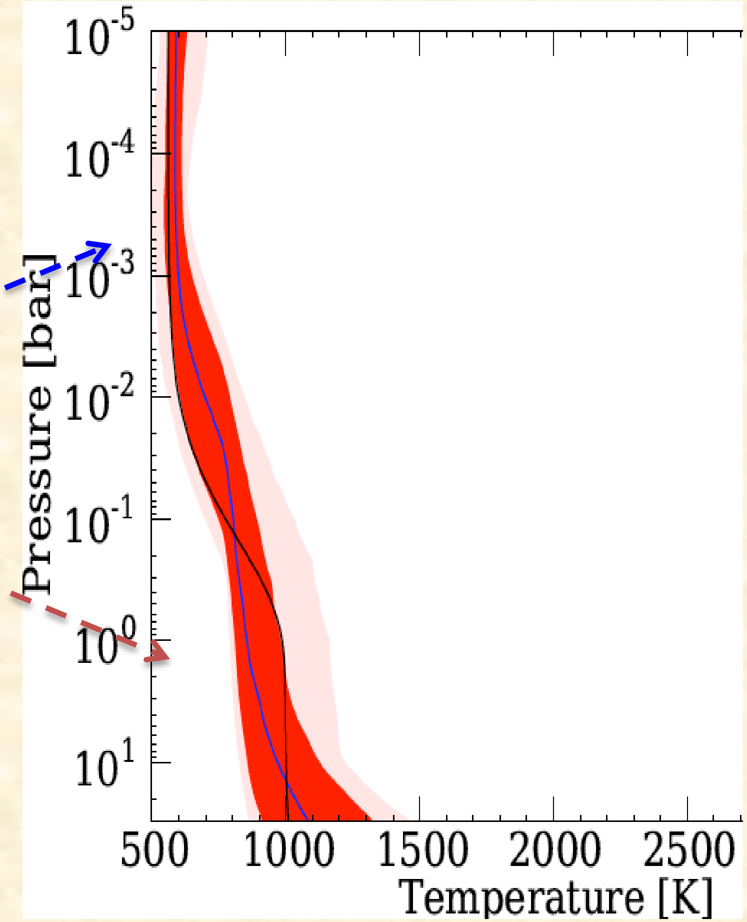
- ***What are their compositions?***
  - *Elemental abundances*
    - C/O and [Fe/H]: Both are formation diagnostics
  - *Molecular components and chemical processes*
    - Identify equilibrium & disequilibrium chemistry:
      - Vertical mixing, photochemistry, ion chemistry…
  - 3-D effects: spatial variations
- ***Energy budget and transport***
  - 1-D structure: measure profiles, inversions present?
  - Dynamical transport: day/night differences
- ***Clouds***
  - Cloud composition, particle sizes, vertical & spatial distribution
  - Remove cloud effects to determine bulk properties
- ***Anything about low mass / small r< ~2R_e planet atmospheres***
- ***Trends with bulk parameters*** *(mass, insolation, host stars, …)*
  - Requires a population of diverse planets

Transmission & Emission Spectroscopy



Transmission & Emission Spectroscopy

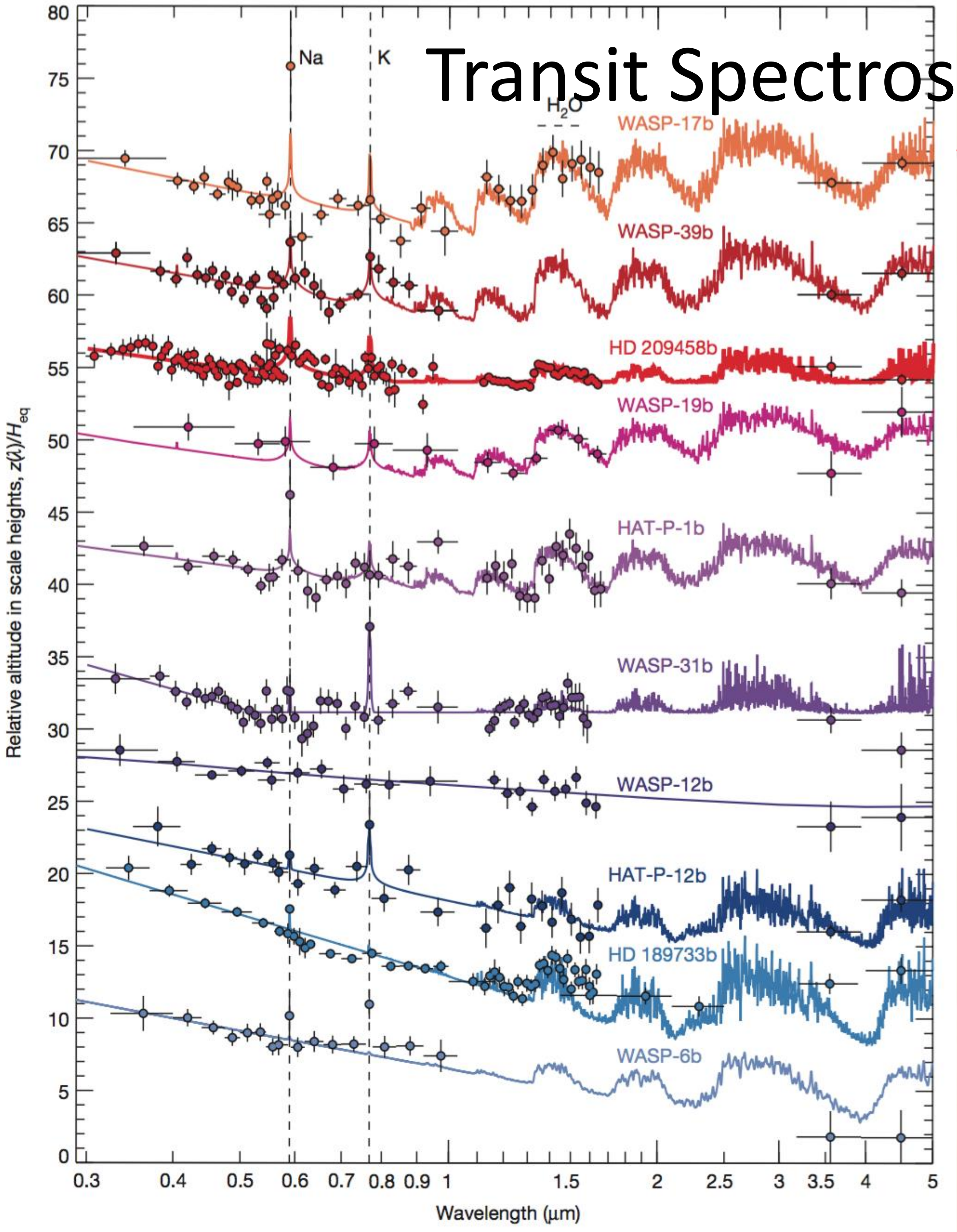




Some progress from transit spectroscopy

- ***Molecules & atoms identified*** in exoplanet atmospheres
  - H_2O, CO (CH_4, CO_2), Na, other alkali, HI, CII, OI,…
  - Most planets have been found to be partially clear to cloudy
- ***Measured temperature-pressure profiles*** from hot Jupiter emission spectra
  - Few with high confidence T inversions
- ***Some Neptune-sized planets have been studied***
  - HAT-P-11 (Fraine+ 2014) and GJ 436b (Knutson+, etc.)
- ***Sub-Neptunes and super-Earths have been difficult***
  - GJ 1214b: flat absorption, no sec. eclipse (many people…)
  - Promise of cooler planets like K2-3 (Crossfield+ 2015) and K2-18b (Montet+ 2015): T = 300 – 500K, different clouds?

Transit Spectroscopy Status 2016



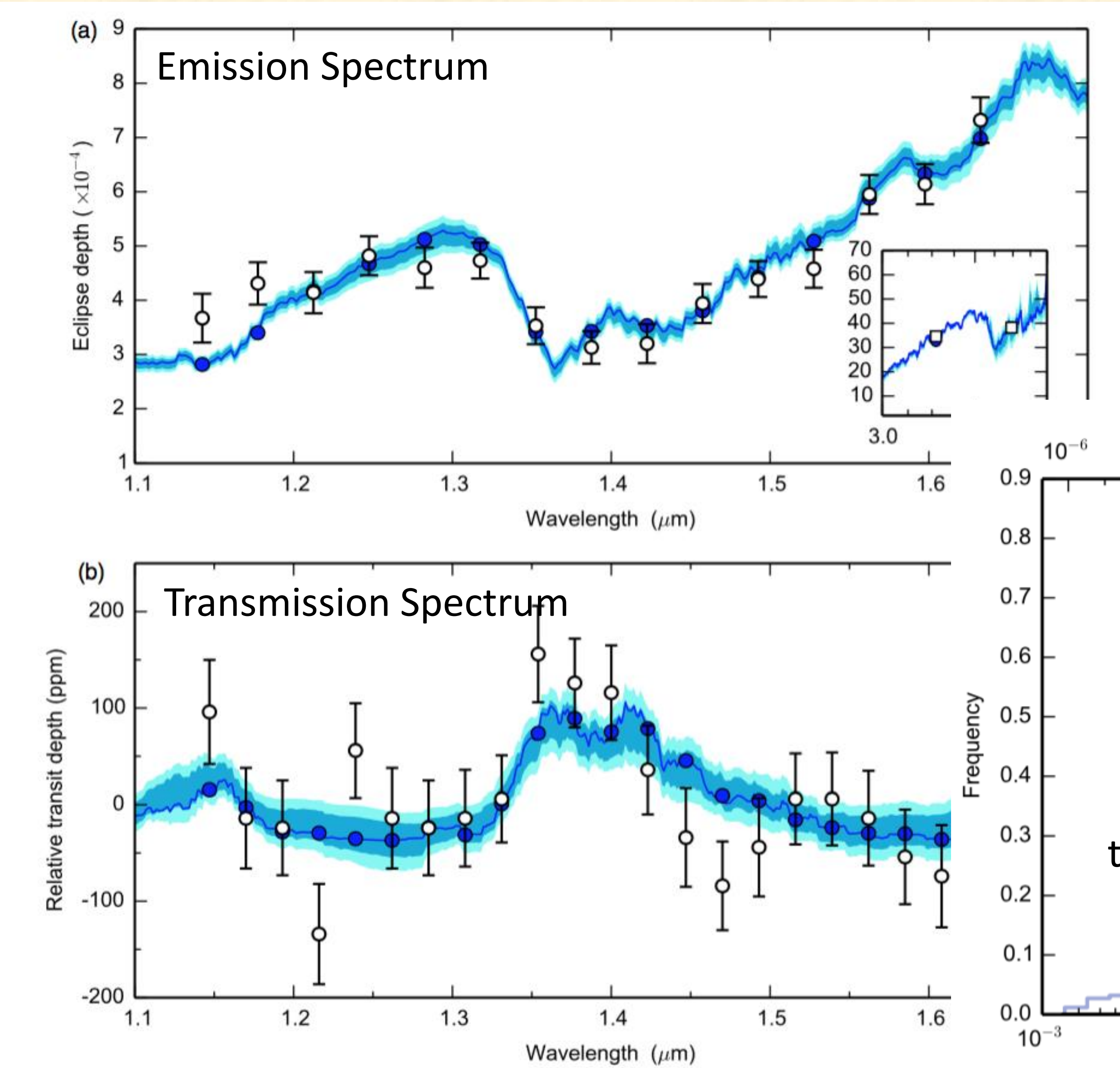
Clear atmospheres show spectral features

Clear-to-cloudy hot Jupiter transmission spectra from visible to mid-IR

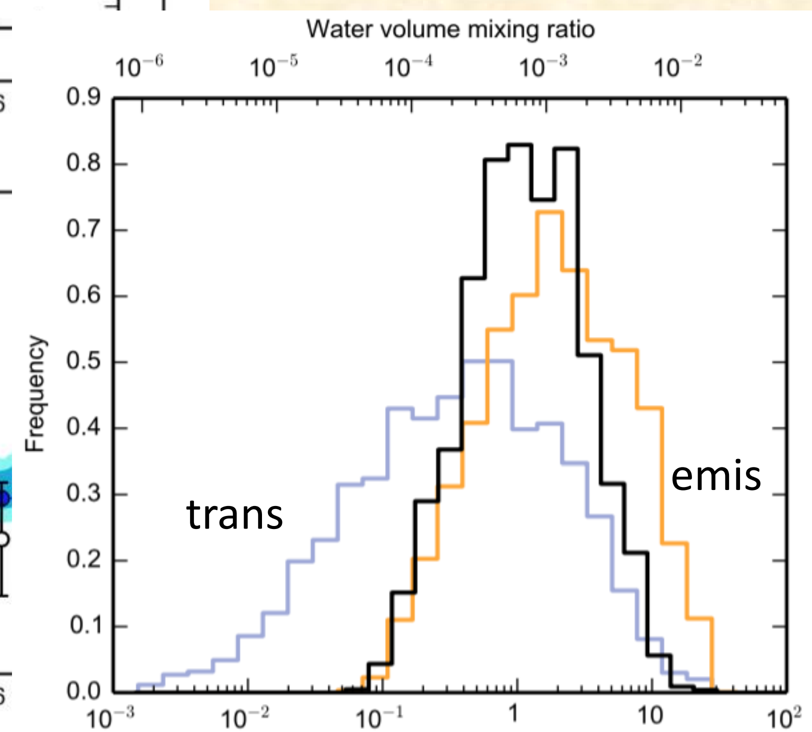
Cloudy or hazy have strong blue scattering slopes and weak spectral features

Sing+ (2015)

WASP-43b: HST Emission + transmission

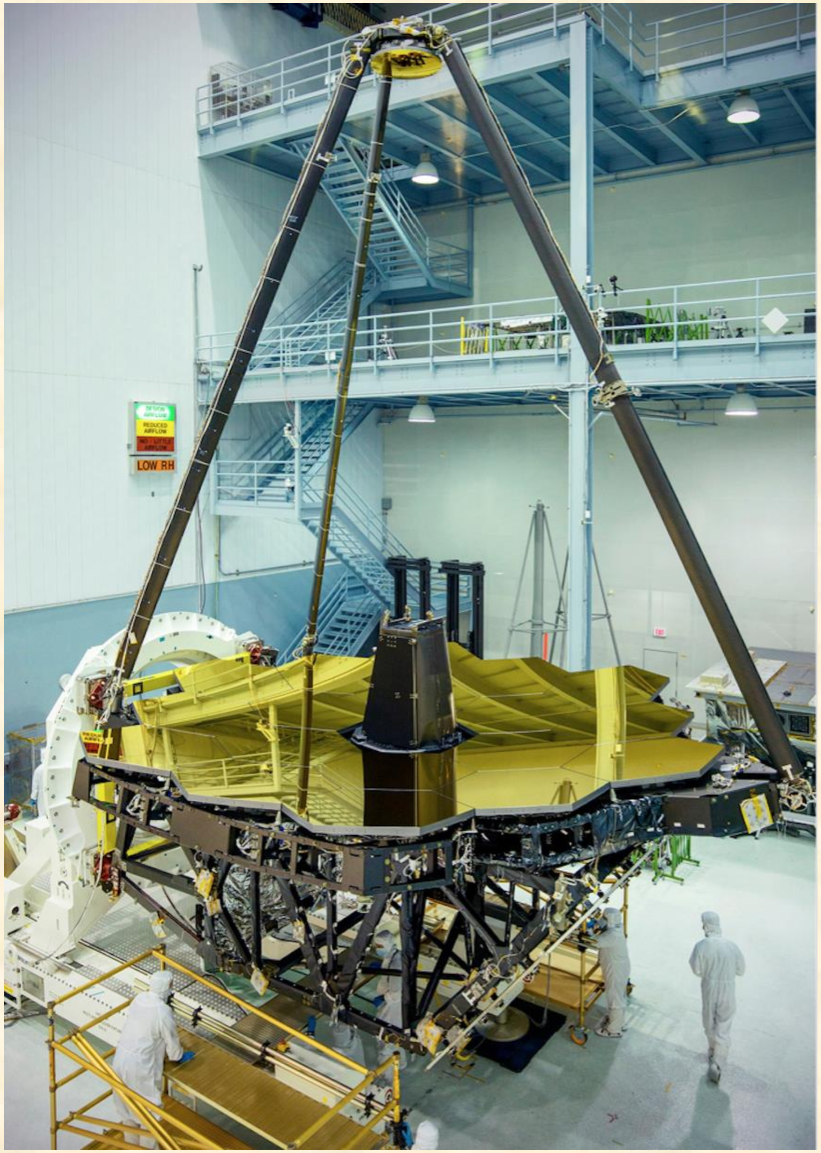


- Emission samples the bulk atmosphere (up to P ~ 1 bar) while transmission samples the stratosphere (P ~1 mbar)



Kreidberg+ (2014)

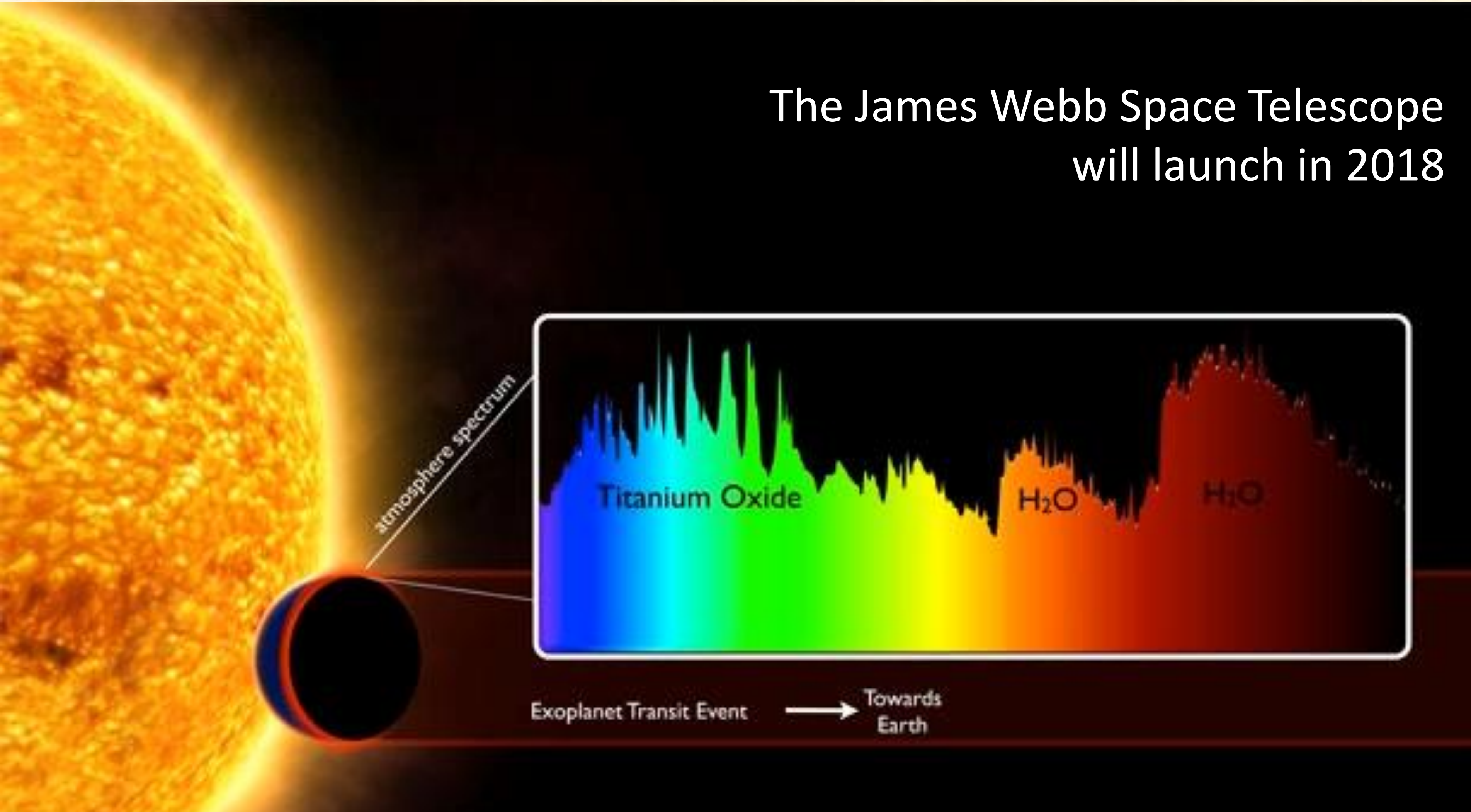
James Webb Space Telescope (JWST)



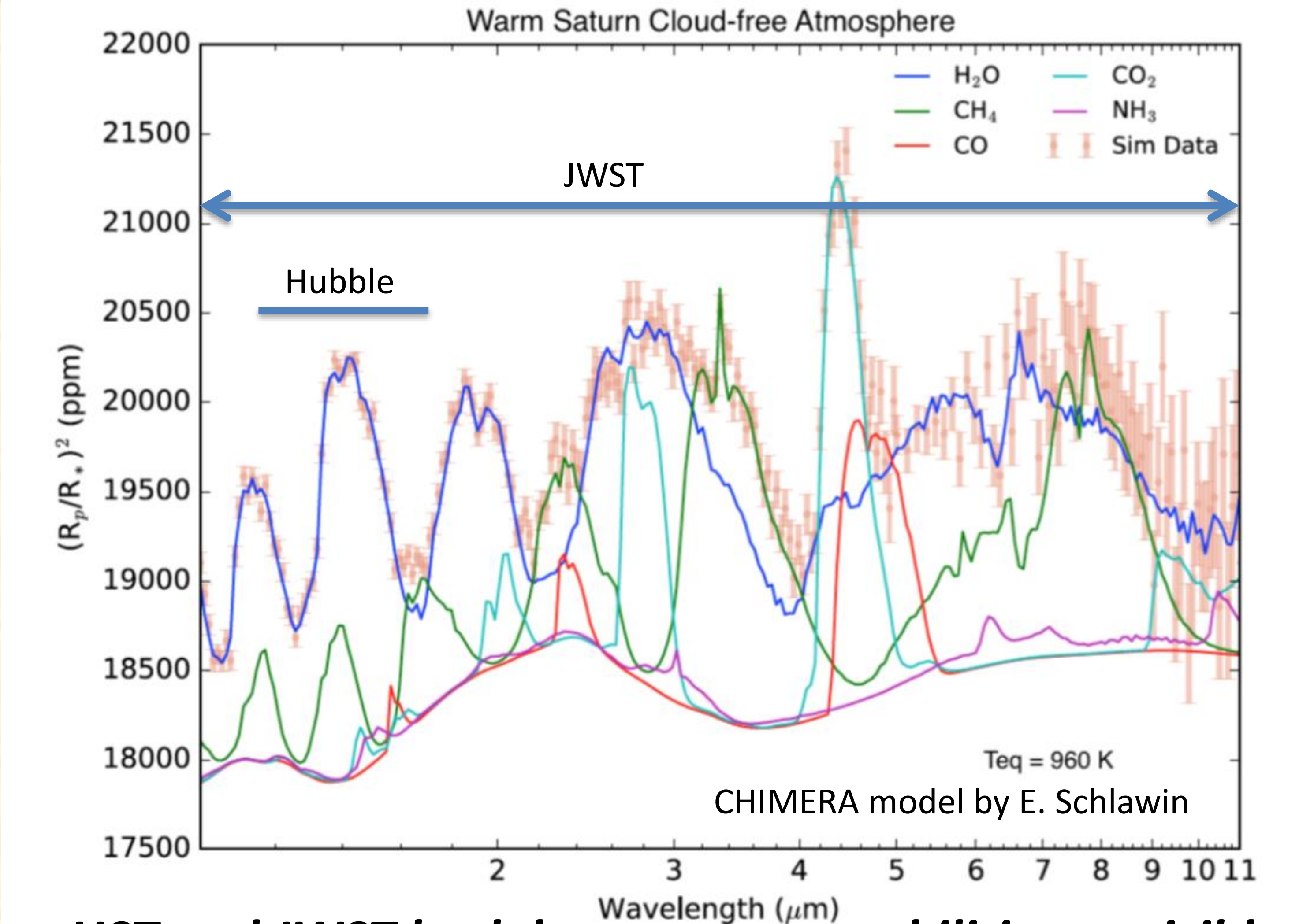
- 6.5-m primary mirror; 25 m^2
- 18 segments
  - T~40K, bkg. limited
- λ <1 - 28 μm
  - zodiacal-limited to 10 μm
- Instruments:
  - NIRCam: 0.7 – 5 μm
  - NIRSpec: 0.6 – 5 μm
  - MIRI: 5 – 28 μm
  - NIRISS/FGS: .7–5 μm
- 2018 October launch
  - Arianne V to L2
  - Science starts April 2019
  - 5 yr req life, >10 yr goal
- ERS proposals due Aug 18
  - only 500 hours
- GO Cycle 1 due Mar 2018

JWST Transit + Secondary Eclipse Spectroscopy

The James Webb Space Telescope
will launch in 2018

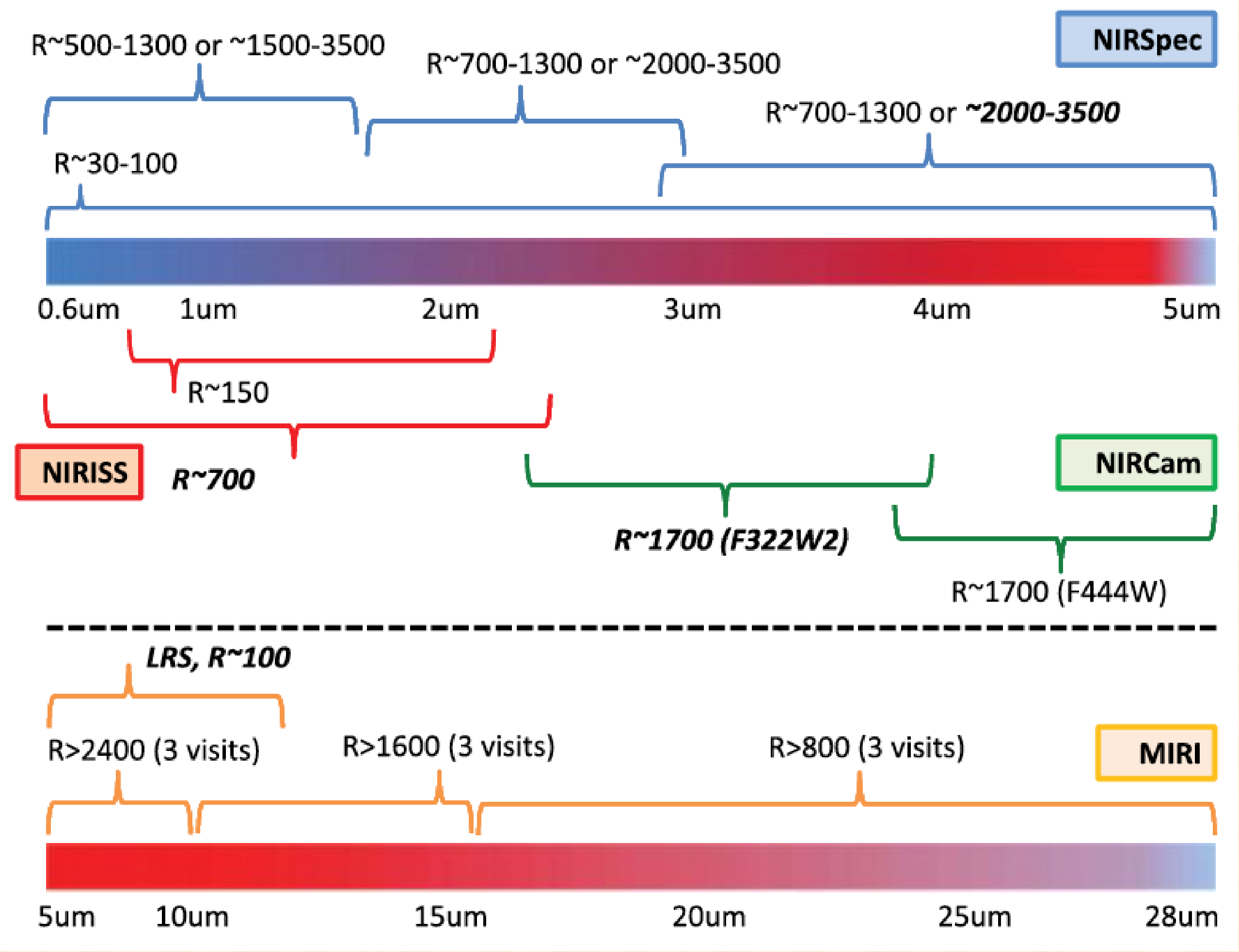


JWST vs. HST IR transit spectroscopy



- ***HST and JWST both have some capabilities at visible wavelengths and HST can also work in the UV***

Almost too many JWST spectroscopic modes!



J. Christiansen / Beichman+ 2014

Some modes may deliver better precision than others; *will not know until after launch*

- Numerous modes for transits and direct (IFU) exoplanet spectroscopy
- ***Covering 0.6 – 12 μm requires 2 – 4 separate transits or eclipses***

Best JWST modes for transit spectra

Instrument	Mode	λ (μm)	R $\lambda/\delta\lambda$	PSF (pixels)	Saturation (K mag)	Comment
NIRISS	SOSS	0.6 – 2.8	$\sim$700	$\sim$25	6.2 – 7.5	Slitless
NIRSpec	Prism	0.6 – 5.3	$\sim$100	< 2	10.2	Wide Slit BOTS
NIRSpec	G140M/H+F100LP	1.0 – 1.9	$\sim$1000 / 2700	< 2	8.0 / 6.8	Wide Slit BOTS
NIRSpec	G235M/H+F170LP	1.7 – 3.2	$\sim$1000 / 2700	< 2	7.5 / 6.3	Wide Slit BOTS
NIRSpec	G395M/H+F290LP	2.9 – 5.3	$\sim$1000 / 2700	< 2	6.5 / 5.5	Wide Slit BOTS
NIRCam	Grism+F322W2	2.4 – 4.0	$\sim$1500	≤ 2	4.4	Slitless
NIRCam	Grism+F444W	3.9 – 5.0	$\sim$1500	≥ 2	3.7	Slitless
MIRI	LRS	$\sim$5 – $\sim$12	$\sim$100	$<$2 – 3	5.7	SLITLESSPRISM

JWST Simulation / Retrieval Assessment

Model some known planet types, simulate spectra, assess information & constraints

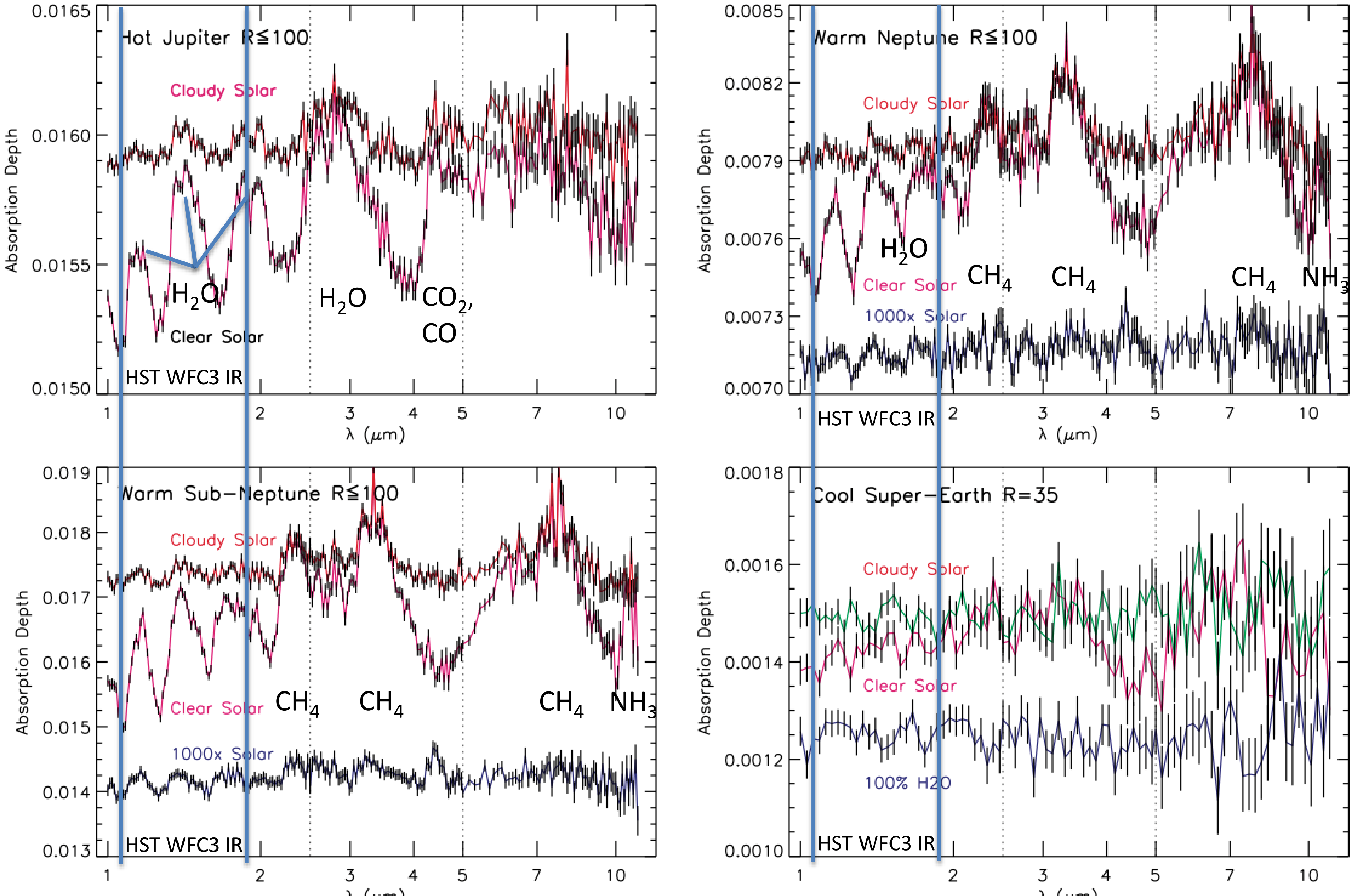
1. Select archetypal planets from known system parameters
2. Create model transmission and emission spectra (M. Line)
3. Simulate JWST spectra using performance models (TG)
   - Simulate slitless modes with large bandpasses & good bright limits: NIRISS SOSS, NIRCam grisms, MIRI LRS slitless 1 – 11 μm
   - 1 transit or eclipse per spectrum
4. Perform atmospheric retrievals (M. Line) to assess uncertainties in molecules, abundances, T-P profiles
   - Focus on uncertainties, not absolute parameters

- ***Identify what wavelengths give most useful information for what planets***

Forward models & retrievals

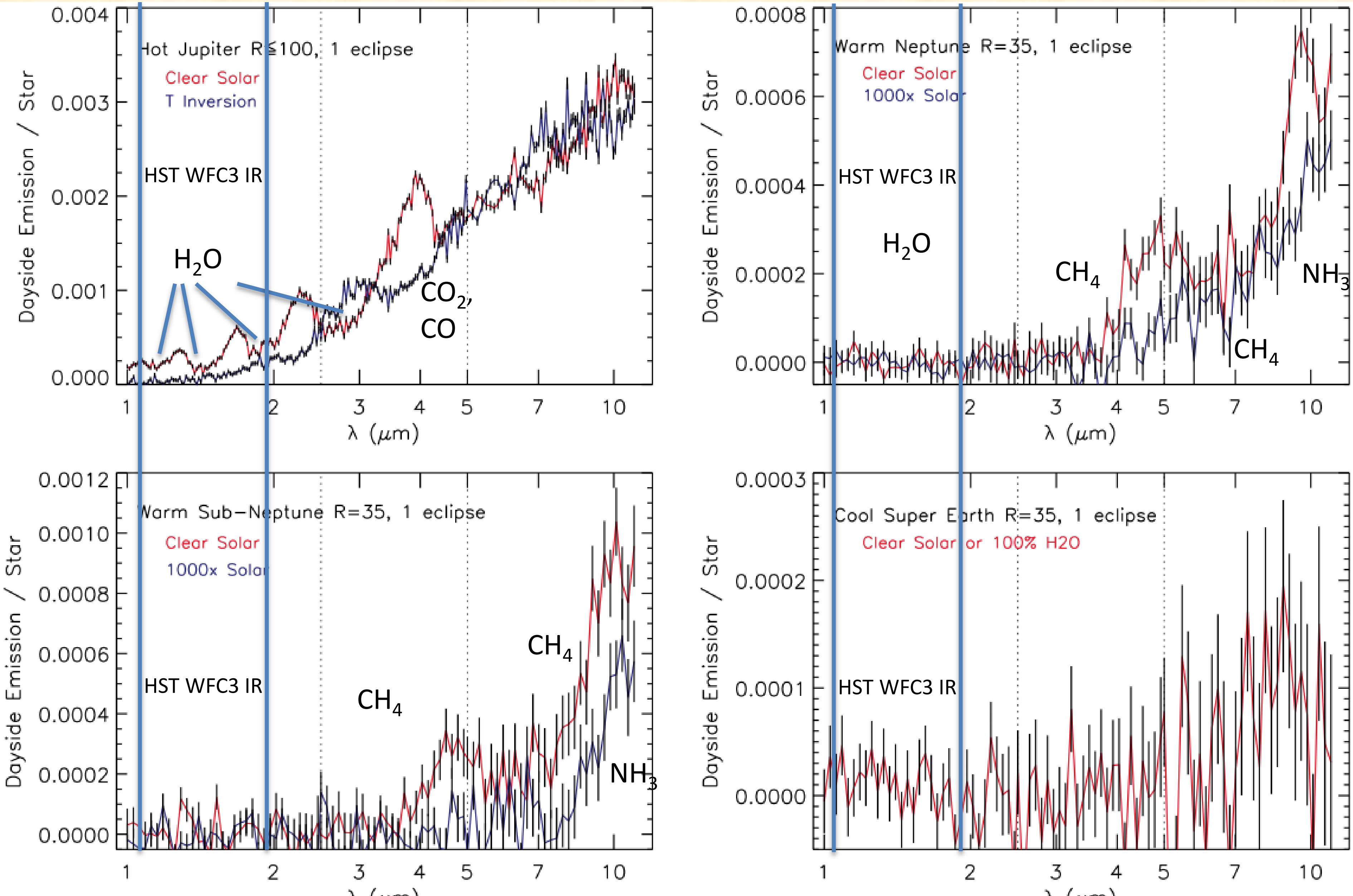
- **Use 1-D forward models**
  - Emission: Line+(2013a), Diamond-Lowe+(2014), Stevenson+(2014)
  - Transmission: Line+(2013b) Swain+(2014), Kreidberg+(2014, 2015)
- **Transmission model has 11 free parameters**
  - T(SH), R(P=10b),hard clouds (Pc, σ_0, β), H_2O, CH_4, CO, CO_2, NH_3, N_2 absorbers, constant with altitude
- **Emission model has 1D T-P profile & 10 free params**
  - H_2O, CH_4, CO, CO_2, NH_3, 5 gray atm parameters for T-P (Line+ 2013a)
- **CHIMERA Bayesian retrieval suite (Line+ 2013a,b)**
  - Updated with emcee MCMC
  - Uniform & Jeffreys priors

Simulated JWST Transmission (1 transit per λ)



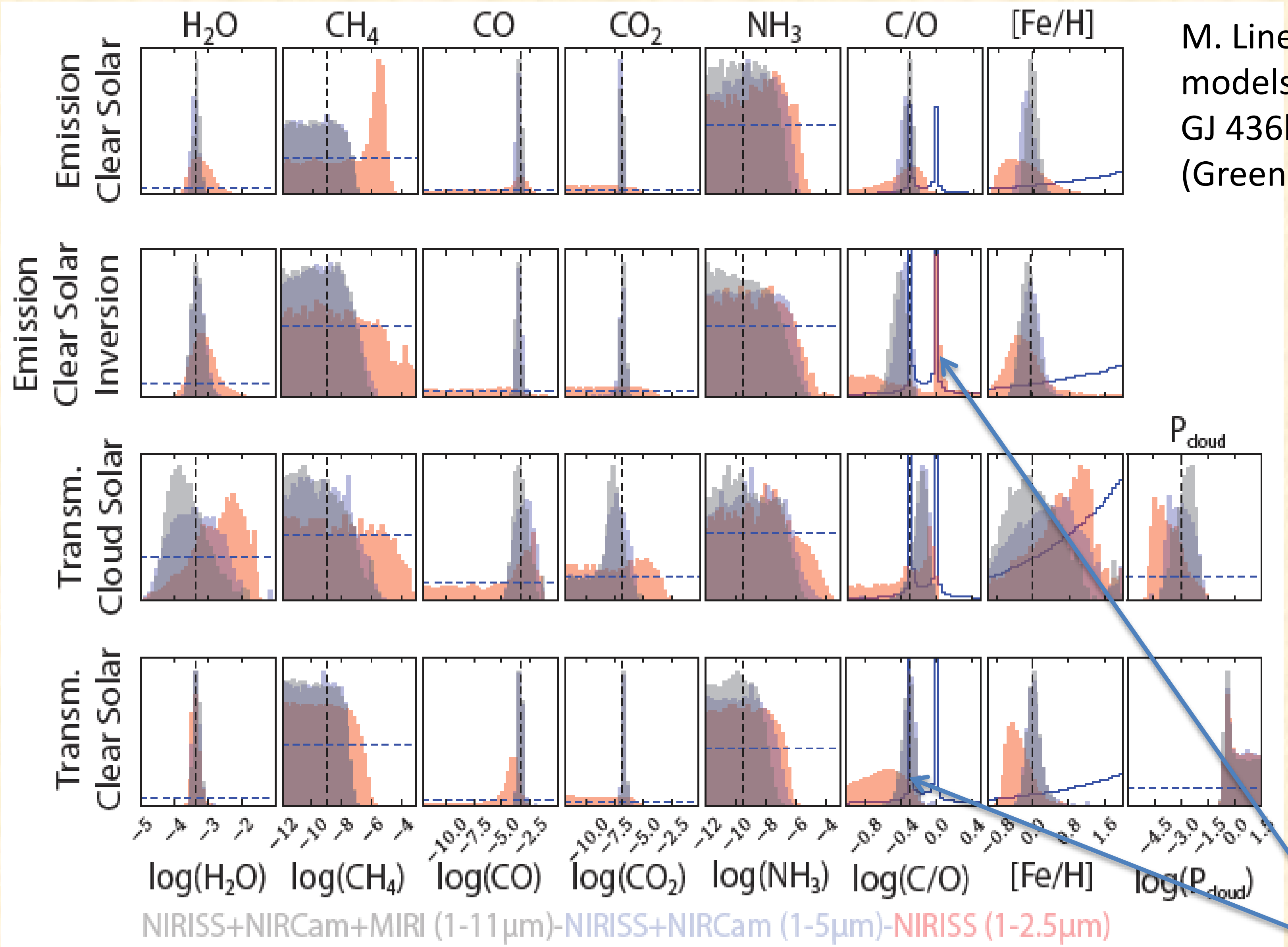
Greene+ (2016)

Simulated JWST Emission (1 eclipse / λ)



Greene+ (2016)

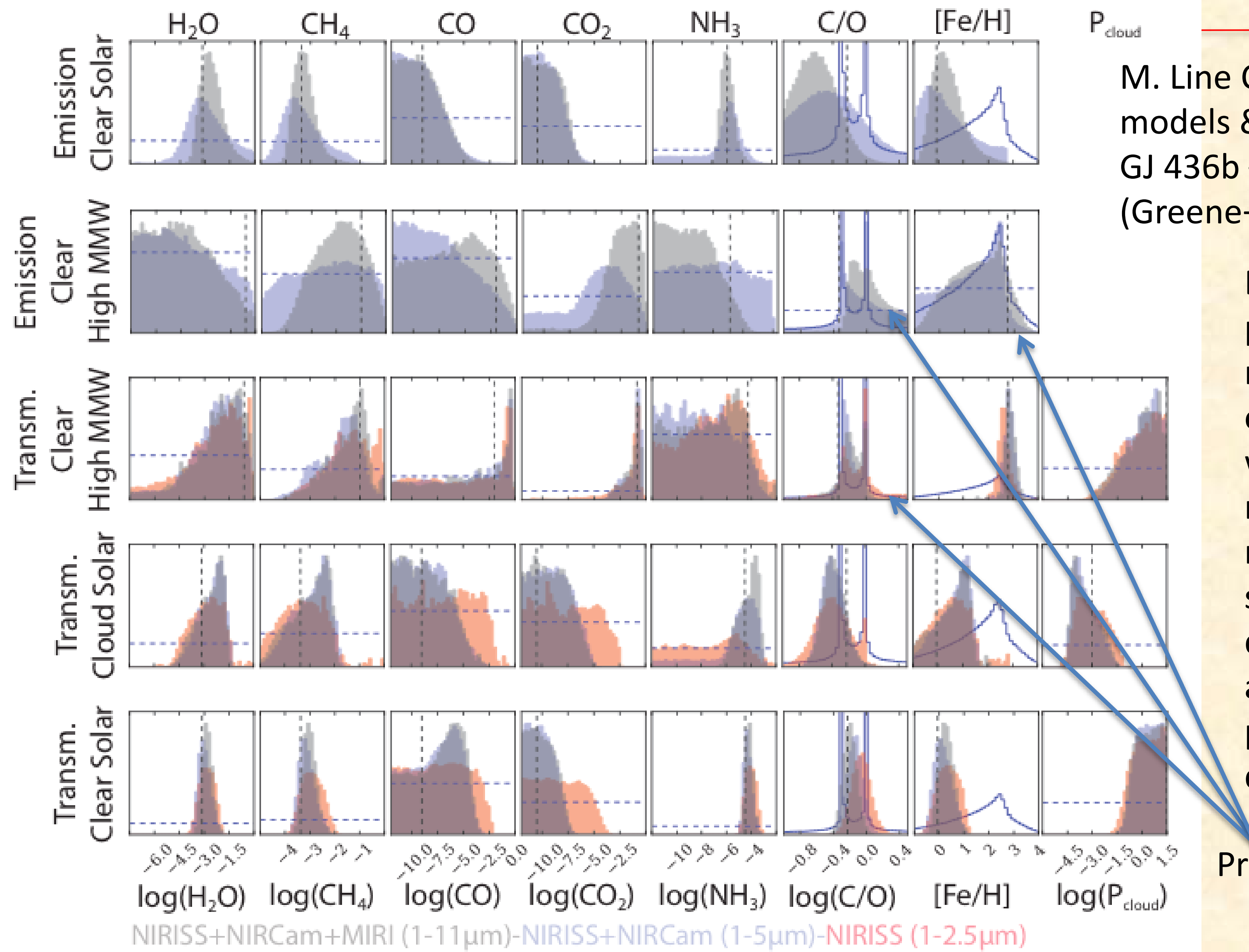
Retrieval Results: Hot Jupiter Gasses



M. Line CHIMERA models & retrievals, GJ 436b – like system (Greene+ 2016)

Different planets will require observations with different modes to measure specific quantities & address particular questions

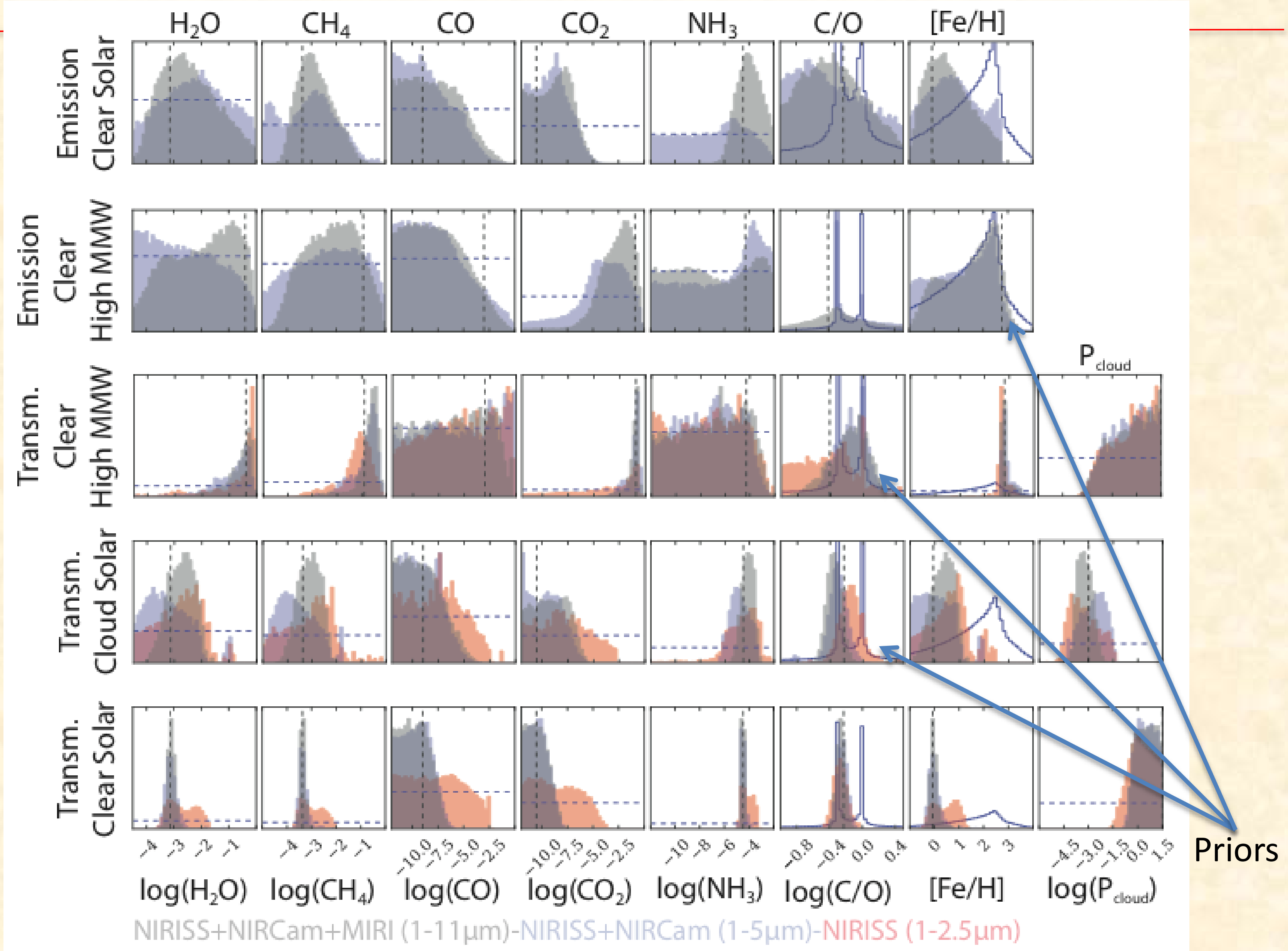
Retrieval Results: Warm Neptune Gasses



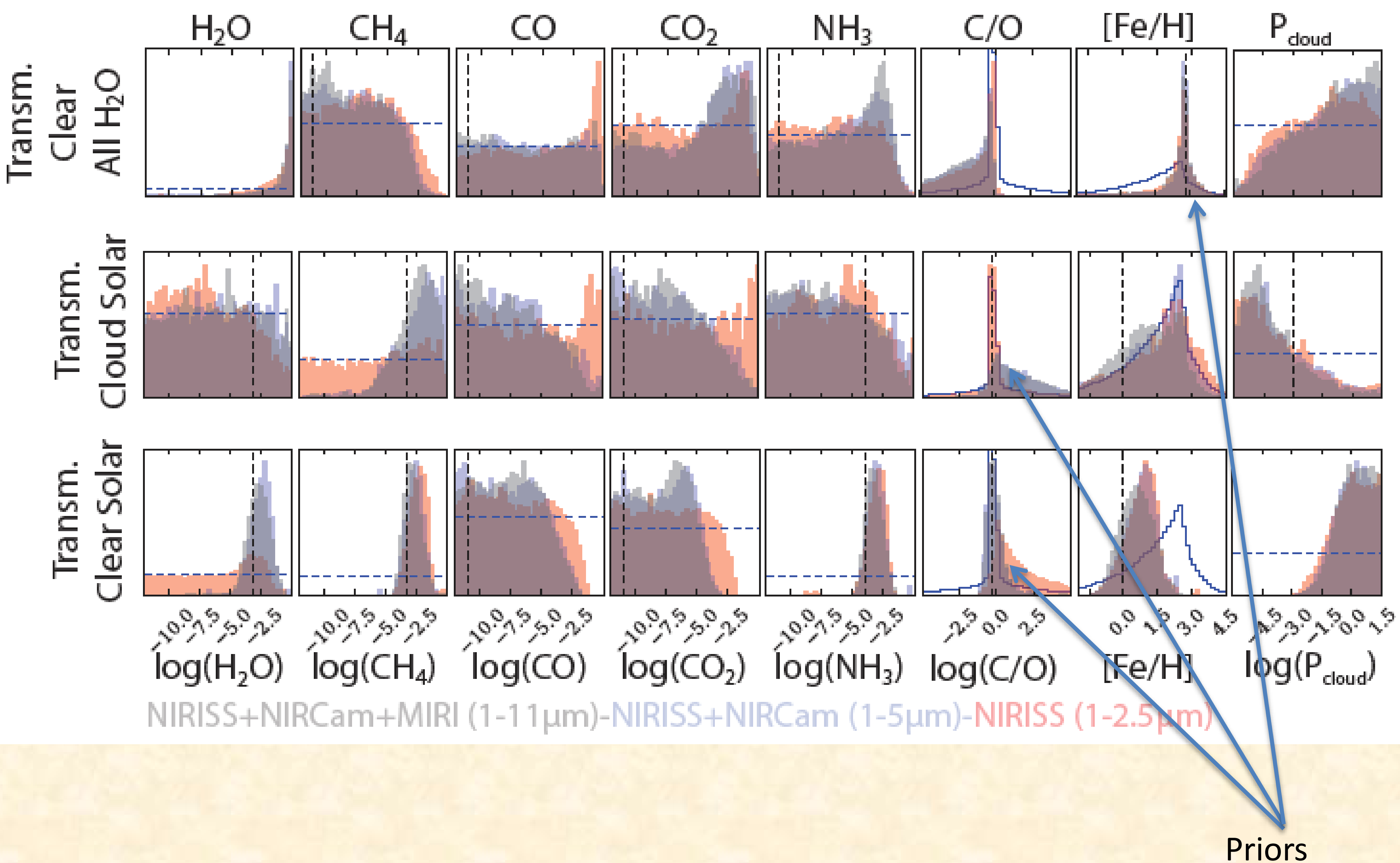
M. Line CHIMERA models & retrievals, GJ 436b – like system (Greene+ 2016)

Different planets will require observations with different modes to measure specific quantities & address particular questions

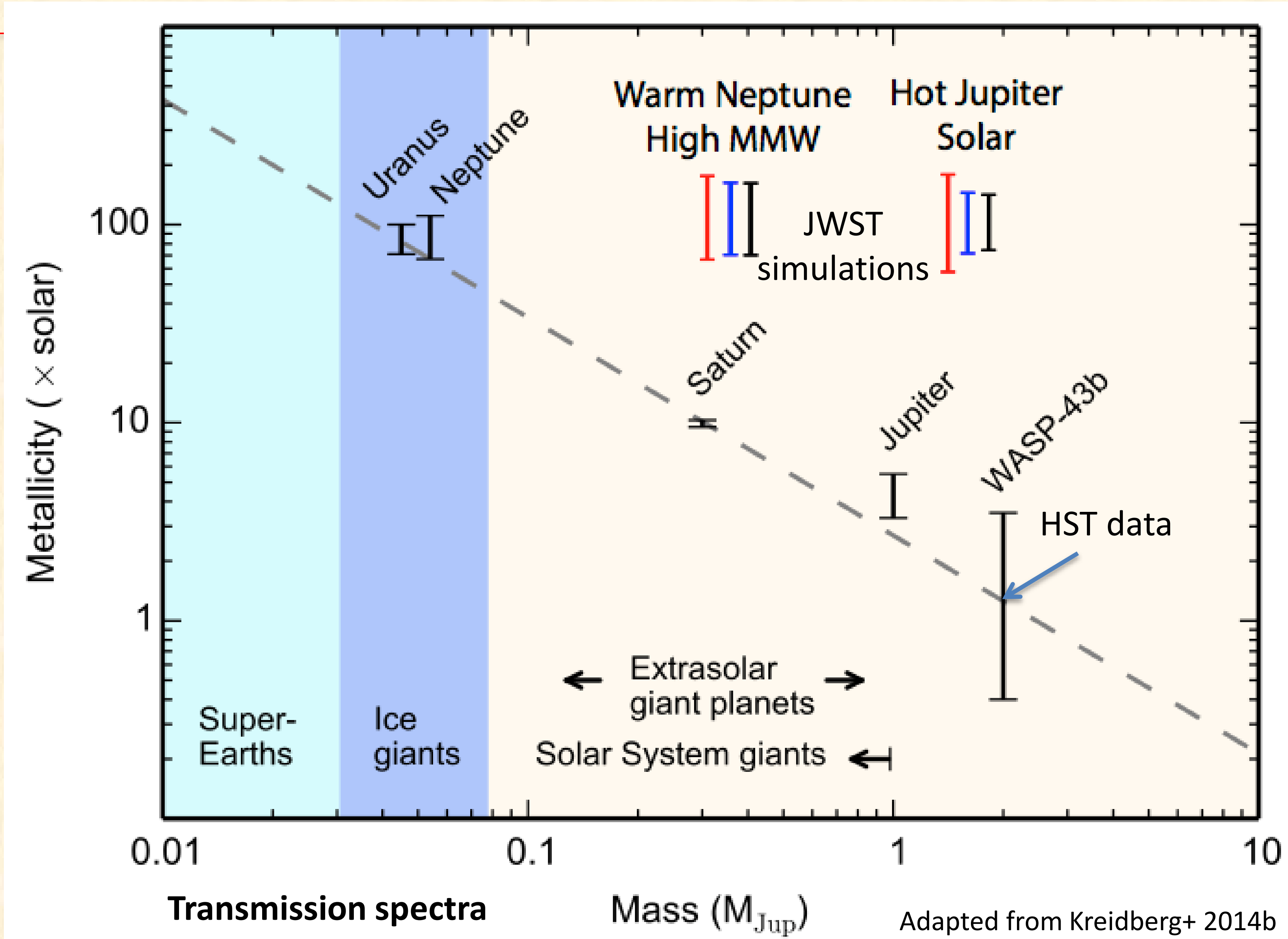
Retrieval: Warm Sub-Neptune Gasses



Retrieval Result: Cool Super-Earth Gasses

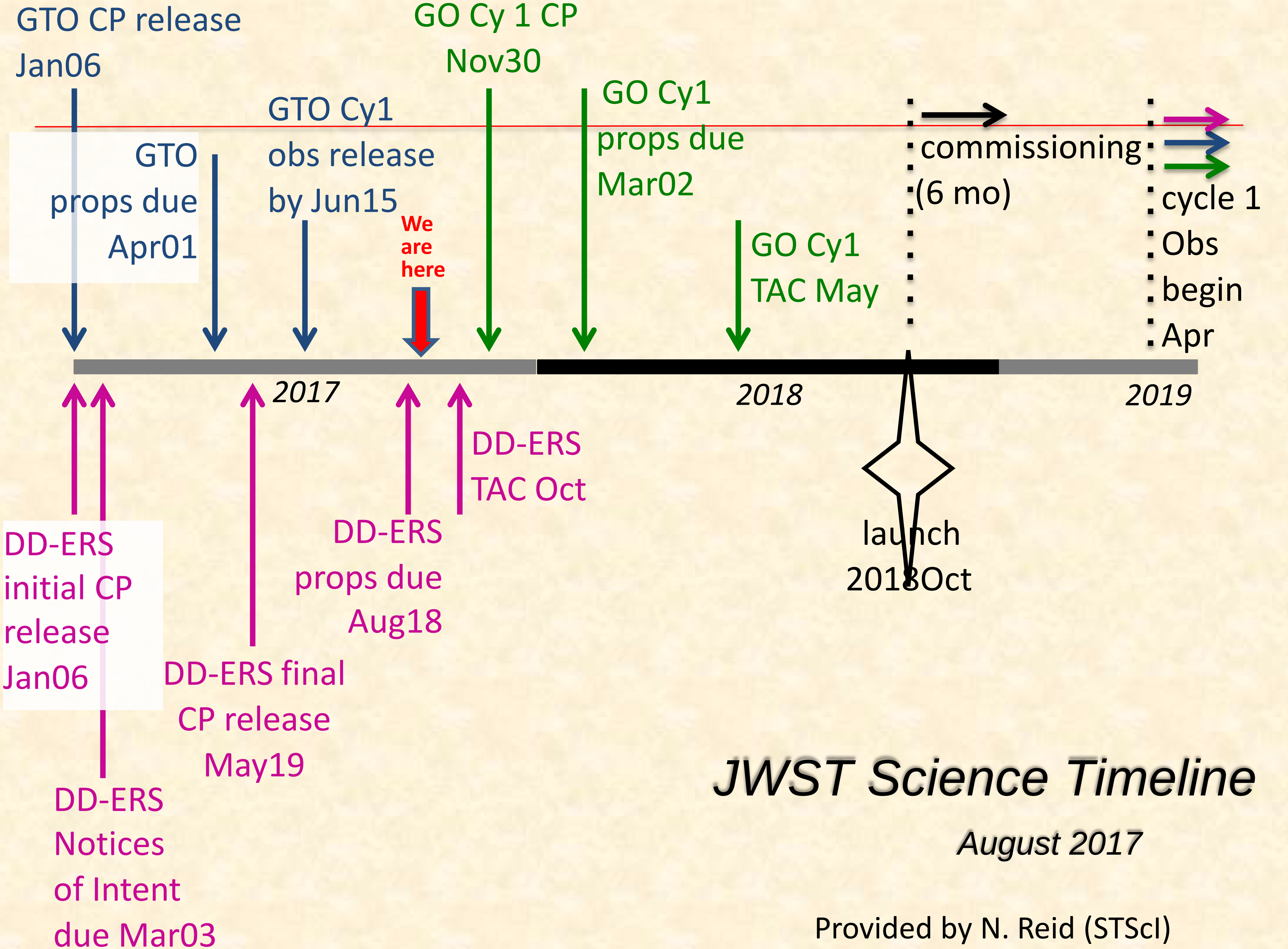


Mass – Metallicity with JWST



How to optimize JWST observations?

- NIRISS (1 – 2.5 μm) transmission spectra alone sometimes constrain mixing ratios of *dominant* molecules in clear solar atmospheres (H_2O, CH_4, NH_3)
- Cloudy solar atmospheres are often constrained (~ 1 dex or better mixing ratios) with λ = 1 - 11 μm spectra
- High MMW atmospheres identified by high [Fe/H]
- C/O is constrained to 0.2 dex for hot Jupiters with λ = 1 – 5+ μm spectra
  - Probe C/O for hot planets via H_2O; also C_2H_2, HCN (Venot+)
- σ[Fe/H] < 0.5 dex for warm, clear planets (λ = 1-5+ μm)
- λ = 2.5 – 11 μm emission spectra probe bulk atmospheres of T > 700 K planets, R > ~few Re


GTO CP release Jan06
GTO props due Apr01
GTO Cy1 obs release by Jun15
We are here
GO Cy 1 CP Nov30
GO Cy1 props due Mar02
GO Cy1 TAC May
commissioning (6 mo)
cycle 1 Obs begin Apr
2017
2018
2019
launch 2018Oct
DD-ERS initial CP release Jan06
DD-ERS Notices of Intent due Mar03
DD-ERS final CP release May19
DD-ERS props due Aug18
DD-ERS TAC Oct
JWST Science Timeline
August 2017
Provided by N. Reid (STScI)

THE END

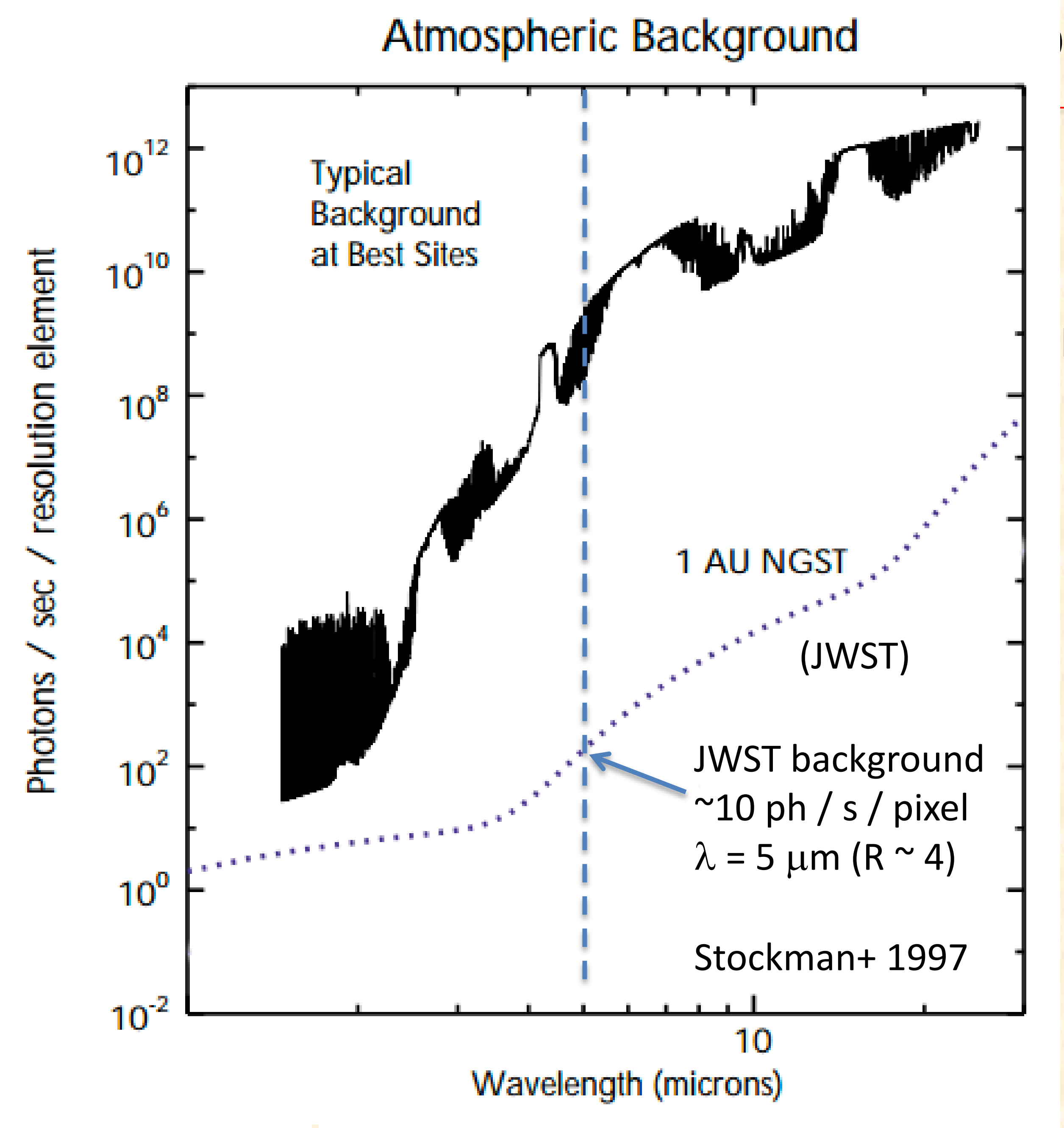
GTO Program Science Goals

- Exoplanet atmsophere compositions, metallicity, C/O?
  - How do they vary with planet mass, and how does this compare to host stars and the Solar System?
- Search for non-equilibrium chemistry
- Probe clouds and hazes
- Measure temperature-pressure profiles
- Global structure and energy transport (transmission + emission)
- Study a range of ice- and gas-giant planets
  - 20 M_E to 1 M_J and T_{eq} = 700 – 1200 K

Why are ... od?

High p

- JWST pr ... ral range (0
- High Sta
  - Precise ... emissi
- Slitless S
  - No jitt
  - Very lo



Selected Model Systems

Planet Type	System Parameters	Composition	Clouds	Geometry
Hot Jupiter	HD 209458b	1x Solar	Clear	Trans, Emis
			1 mbar	Trans
Warm Neptune	GJ 436b	1x Solar	Clear	Trans, Emis
			1 mbar	Trans
		1000x Solar	Clear	Trans, Emis
Warm Sub-Neptune	GJ 1214b	1x Solar	Clear	Trans, Emis
			1 mbar	Trans
		1000x Solar	Clear	Trans, Emis
Cool Super-Earth	K2-3b	1x Solar	Clear	Trans, Emis
			1 mbar	Trans
		100% H_2O	Clear	Trans, Emis

Planet Type	System Parameters	T_* (K)	R_* ($R_\odot$)	K (mag)	T_{eq}[a] (K)	M_p ($M_\oplus$)	R_p ($R_\oplus$)	H[b] (km)	T_{14} (s)
Hot Jupiter	HD 209458b	6065	1.155	6.3	1500	220	15	560	11,000
Warm Neptune	GJ 436b	3350	0.464	6.1	700	23	4.2	190	2740
Warm Sub-Neptune	GJ 1214b	3030	0.211	8.8	600	6.5	2.7	230	3160
Cool Super-Earth	K2-3b	3900	0.561	8.6	500	5.3[c]	2.1	150[c]	9190

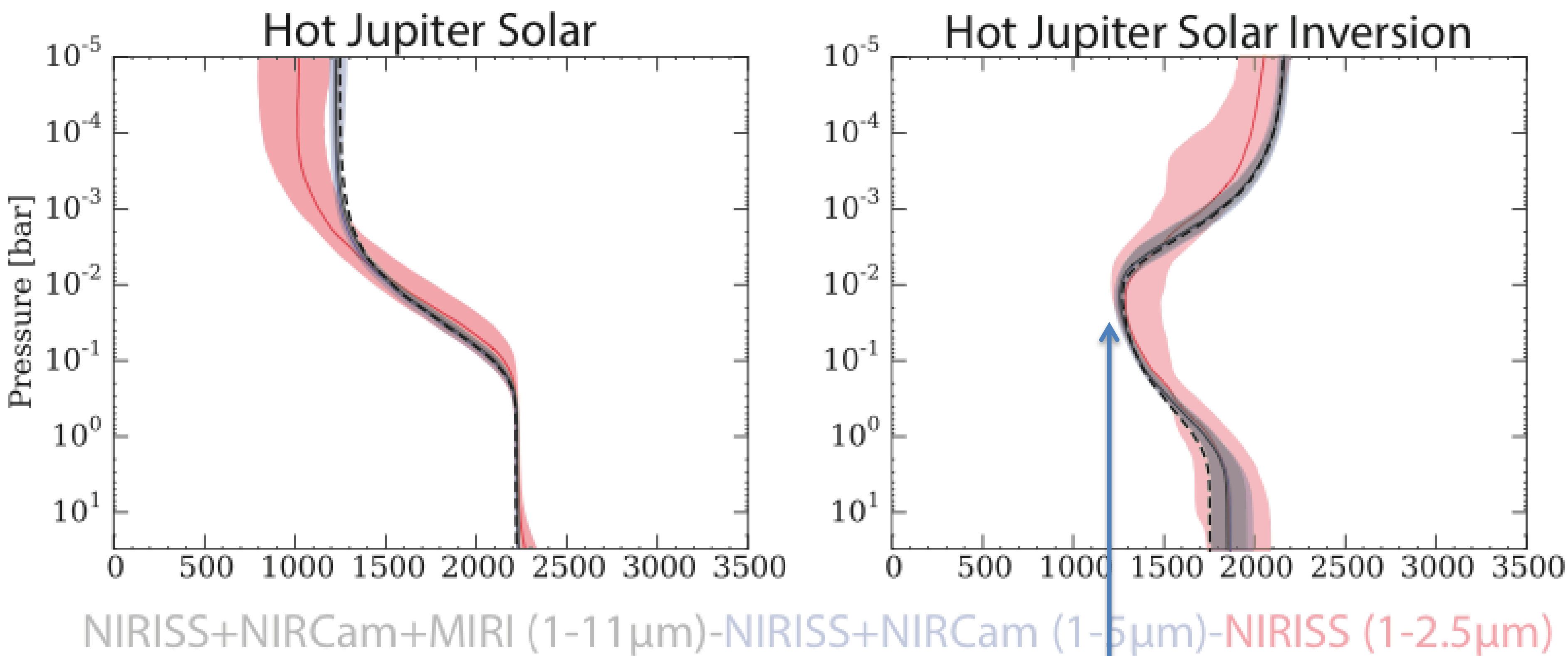
Note. — Tabulated system values were taken from the exoplanets.org compilation (Han et al. 2014) and Crossfield et al. (2015).

[a] Equilibrium temperature T_{eq} was computed from the listed system values assuming albedo = 0 and energy re-distribution over 4π str.

[b] The planetary atmosphere scale height $H = kT_{eq}/(\mu m_H g)$ for the clear solar atmosphere of each planet ($\mu = 2.3$) is provided as a convenience for scaling to other systems.

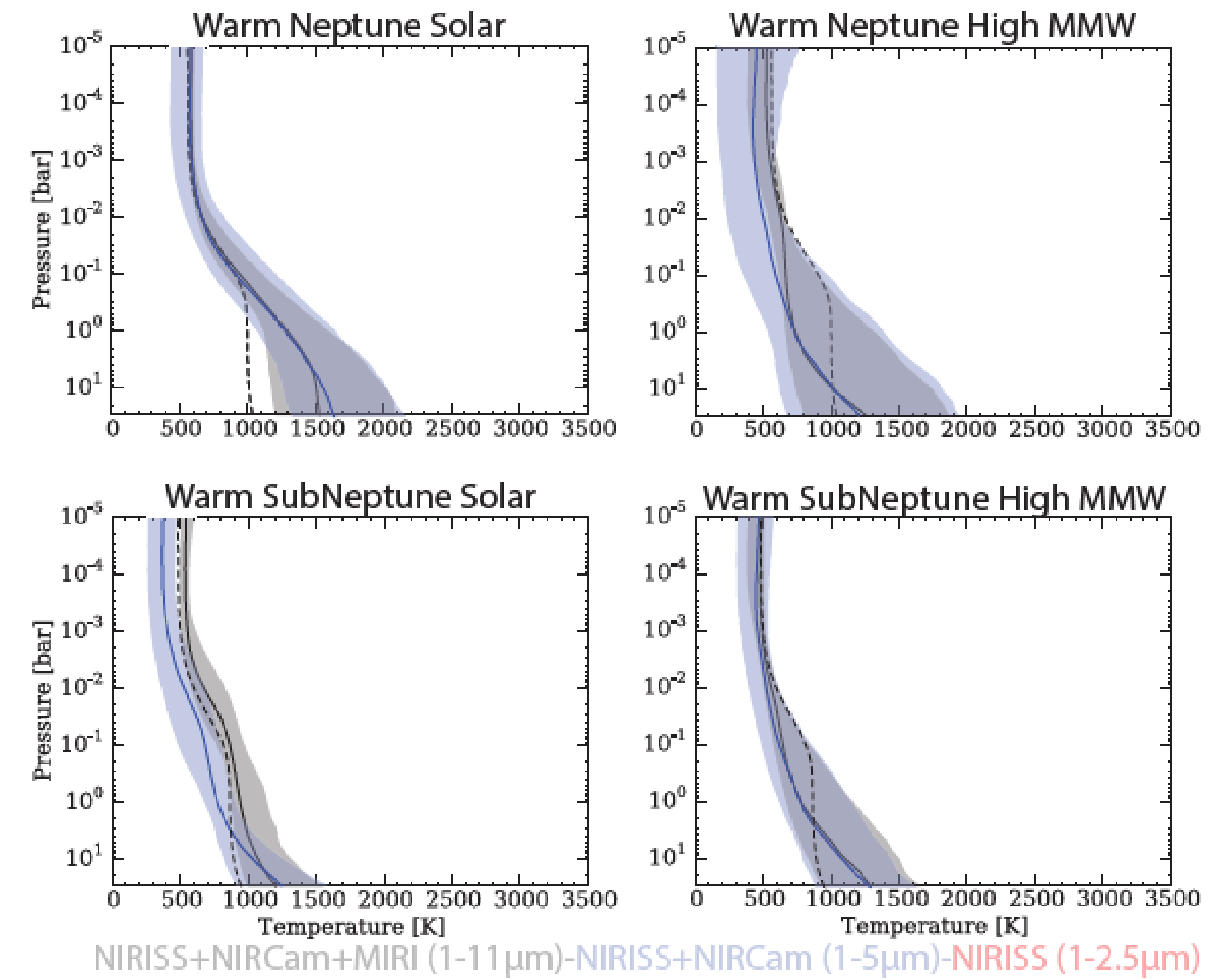
[c] The mass of this planet has been recently measured to be $8.4 \pm 2.1 M_\oplus$ (Almenara et al. 2015), somewhat higher than the tabulated value we used in our investigation. This increased mass would decrease the scale height, decrease the SNR of transmission spectral features, and worsen the derived abundance precisions by roughly 40%.

Emission retrievals: T-P Profiles



Dashed: True value
Solid line: Retrieved mean value
Shaded: 1 sigma

Detect inversion at 4 sigma
with NIRISS only (red)



Warm Neptune Solar
Warm Neptune High MMW
Warm SubNeptune Solar
Warm SubNeptune High MMW
Pressure [bar]
Temperature [K]
NIRISS+NIRCam+MIRI (1-11μm)-NIRISS+NIRCam (1-5μm)-NIRISS (1-2.5μm)

Why are Earth & Venus atmospheres hard?

- O_3 & CO_2 features in transmission spectra of Earth- or Venus-like planets of M5V stars are in ~10 ppm range
- This is undetectable with HST precision; JWST maybe also

1 σ noise Floor?