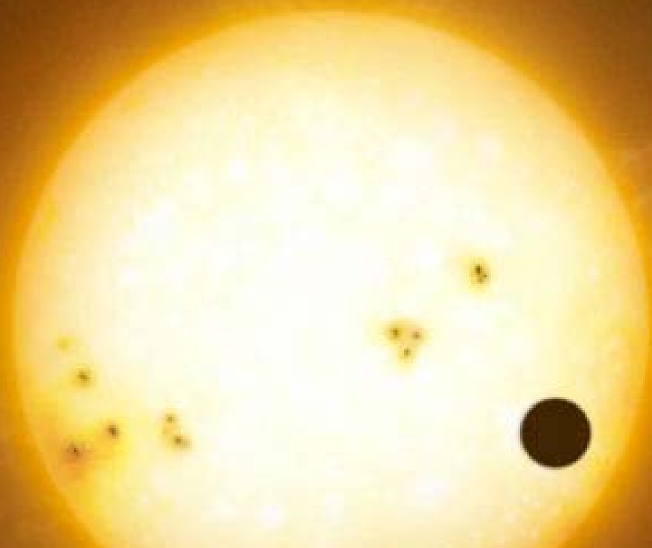
Characterizing transiting planets with JWST spectra: Simulations and Retrievals



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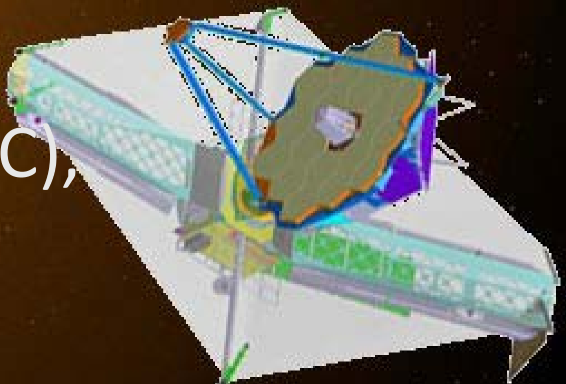


Questions about exoplanet atmospheres

- ***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

New JWST Simulation / Retrieval Assessment

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

- Select archetypal planets from known system parameters
  - Hot Jupiter, warm Neptune, warm sub-Neptune, cool super-Earth
- Create model transmission and emission spectra (M. Line)
- 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
  - Code based on instrument models & data, detector parameters, JWST background models, random & systematic noise
  - 1 transit or eclipse per spectrum
- 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 Planet Signals (S_λ) & Noise (N_λ)

$$Tr_\lambda = \frac{S_\lambda(F_*) + Bkg - (S_\lambda(F(*+p)_{Tr}) + Bkg)}{S_\lambda(F_*) + Bkg - \langle Bkg \rangle}$$

and

$$Em_\lambda = \frac{S_\lambda(F(*+p)_{Em}) + Bkg - (S_\lambda(F_*) + Bkg)}{S_\lambda(F_*) + Bkg - \langle Bkg \rangle}$$

$$N_\lambda = \sqrt{S_\lambda + Bkg + N_{d,tot}^2}$$

$$N_{d,tot} = N_d \sqrt{n_{pix} n_{ints} R_{native}/R}$$

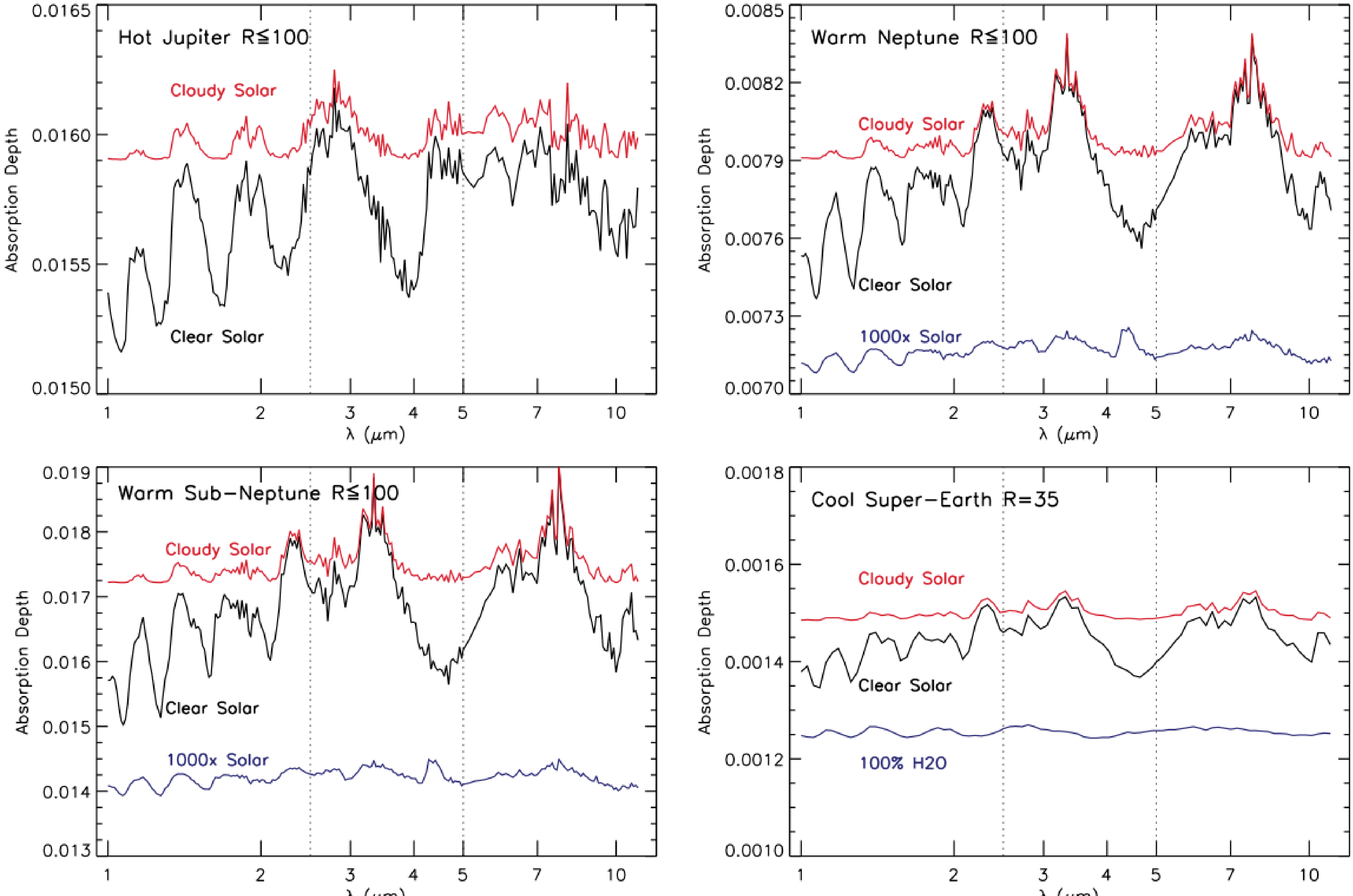
λ (μm)	Noise floor	
1.0 – 2.5	20 ppm	NIRISS
2.5 – 5.0	30 ppm	NIRCam
5.0 - 12	50 ppm	MIRI LRS

Selected Model Systems

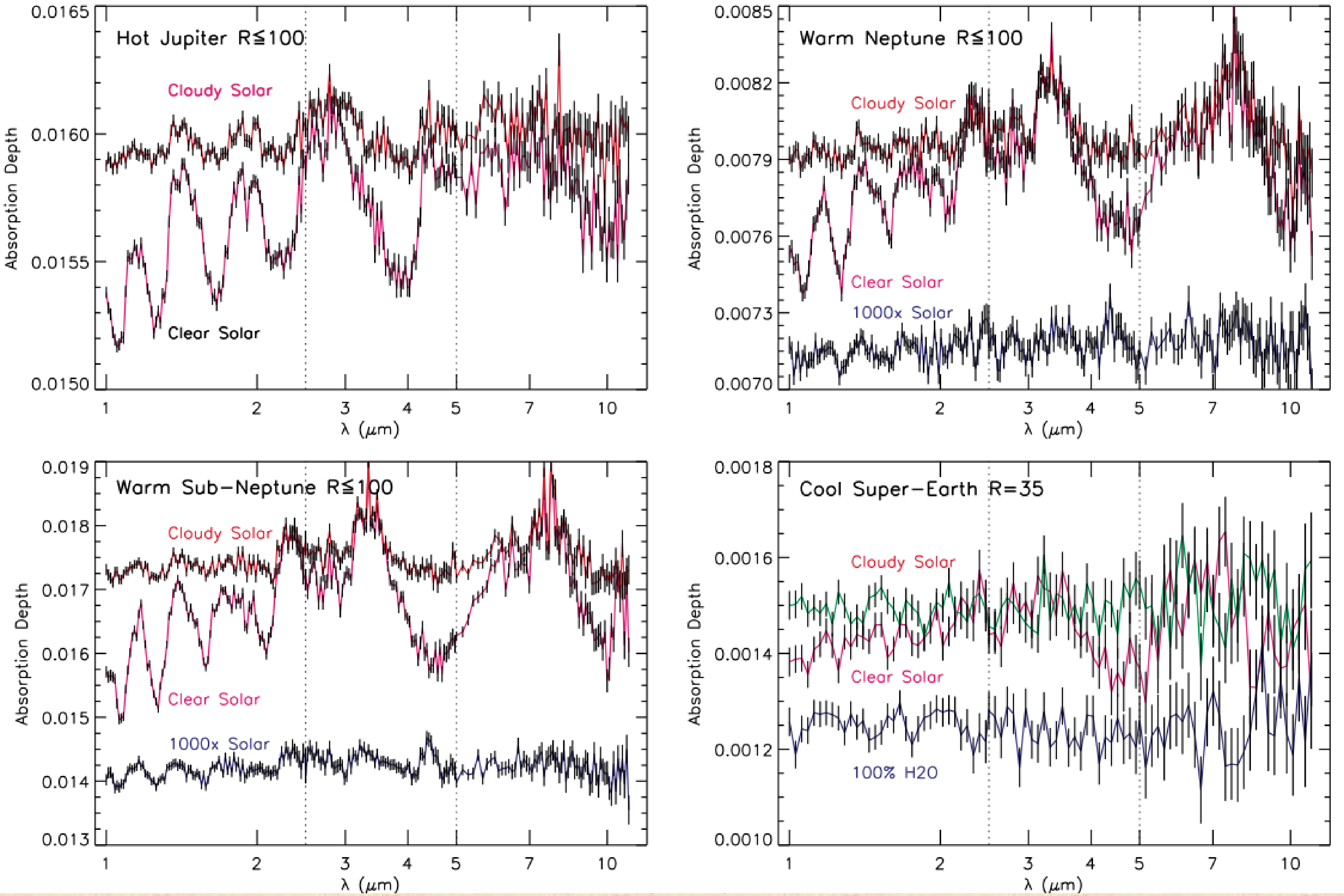
Planet Type	System Parameters	Composition	Clouds	Geometry
Hot Jupiter	HD 209458b	1x Solar	Clear	Trans, Emis
			1 mbar	Trans
Warm Neptune	GJ 436b	1x Solar	Clear	Trans, Emis
			1 mbar	Trans
		1000x Solar	Clear	Trans, Emis
Warm Sub-Neptune	GJ 1214b	1x Solar	Clear	Trans, Emis
			1 mbar	Trans
		1000x Solar	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} (K)	M_p (M_{Jup})	R_p (R_{Jup})	H[a] (km)	T_{14} (s)
Hot Jupiter	HD 209458b	6065	1.155	6.3	1500	0.69	1.359	580	11,000
Warm Neptune	GJ 436b	3350	0.464	6.1	700	0.073	0.377	200	2740
Warm Sub-Neptune	GJ 1214b	3030	0.211	8.8	600	0.020	0.239	240	3160
Cool Super-Earth	K2-3b	3900	0.561	8.6	500	0.017	0.191	160	9190

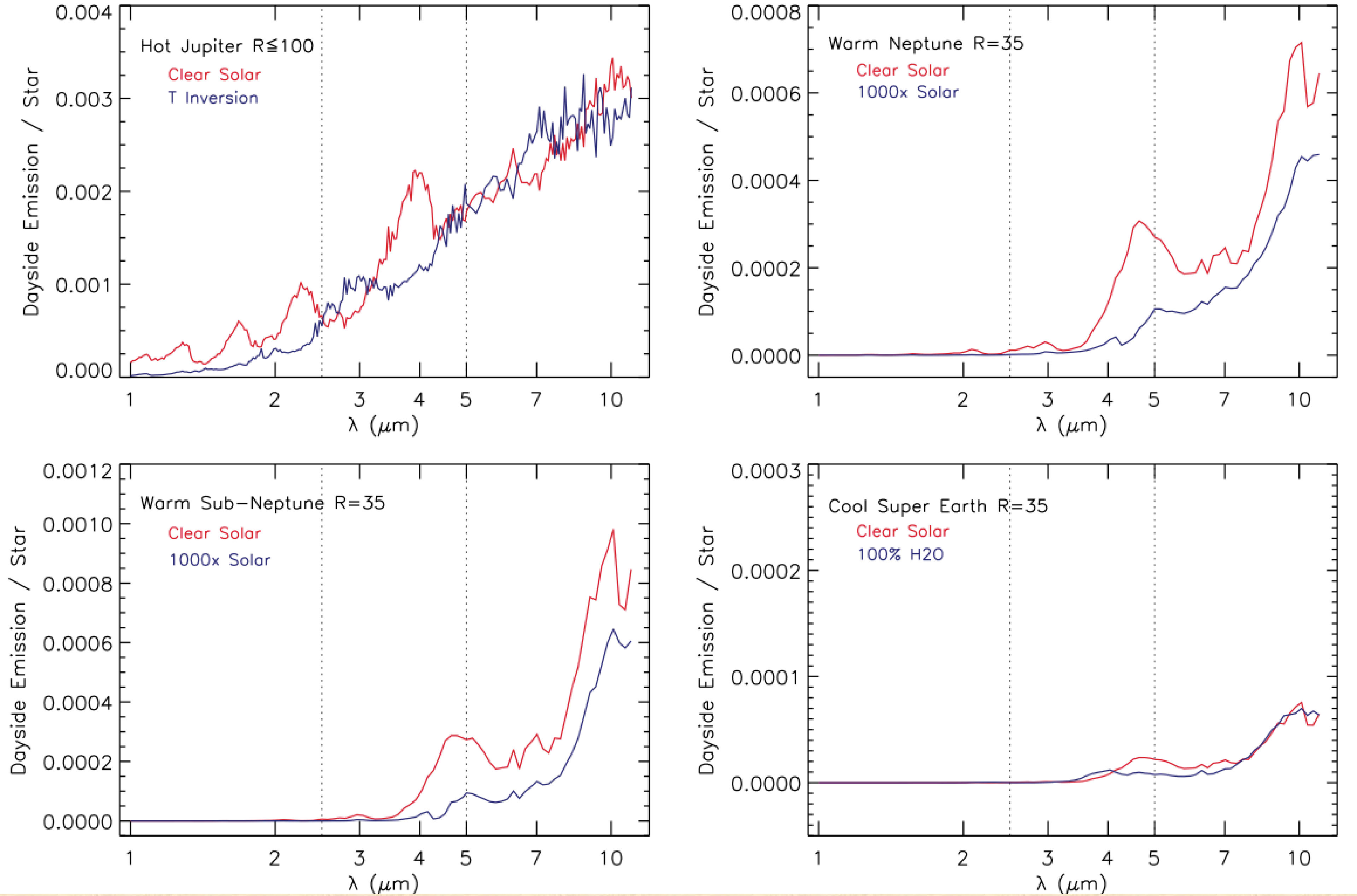
Model Transmission Spectra



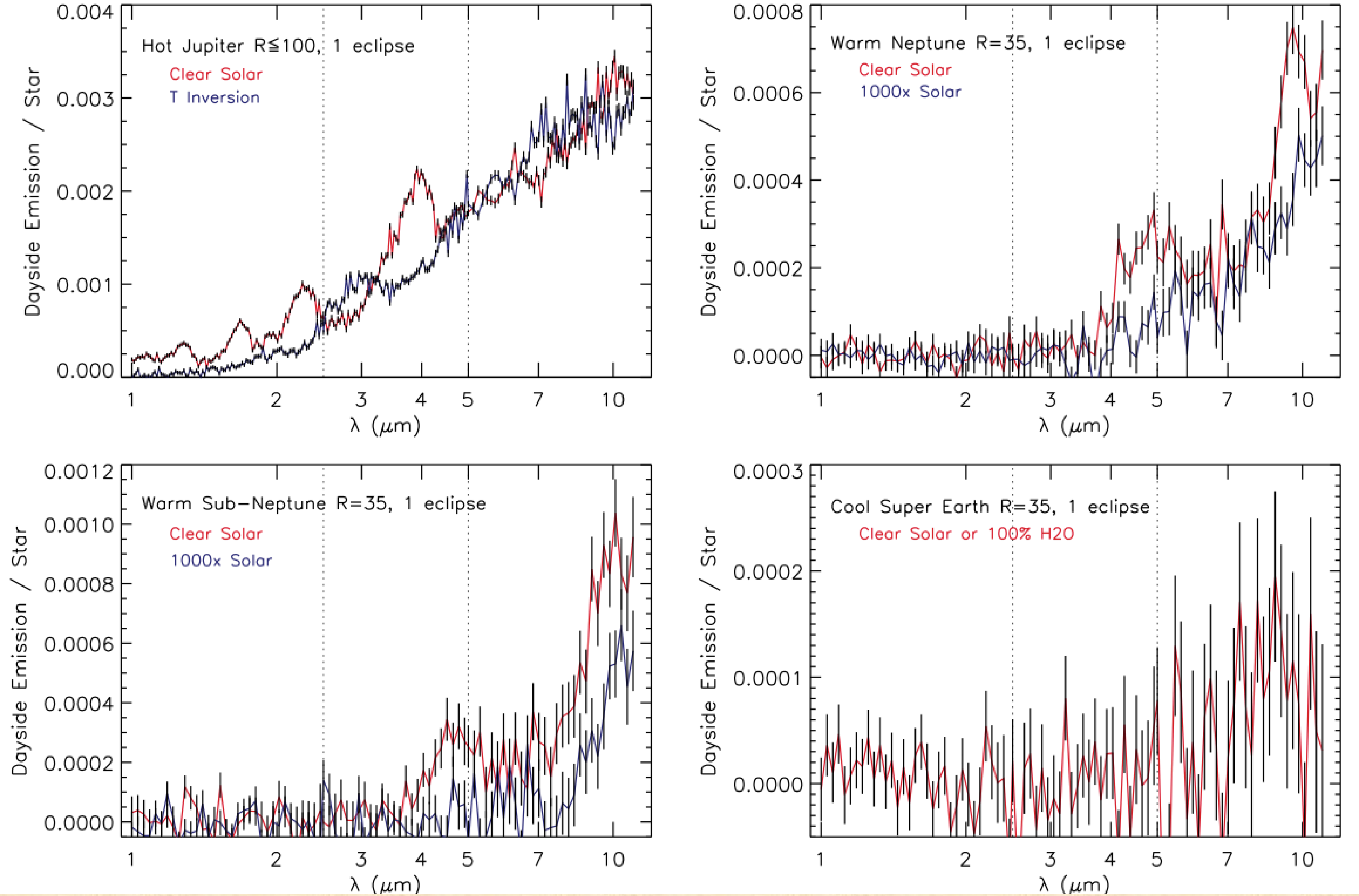
Simulated JWST Trans Spectra (1 transit)



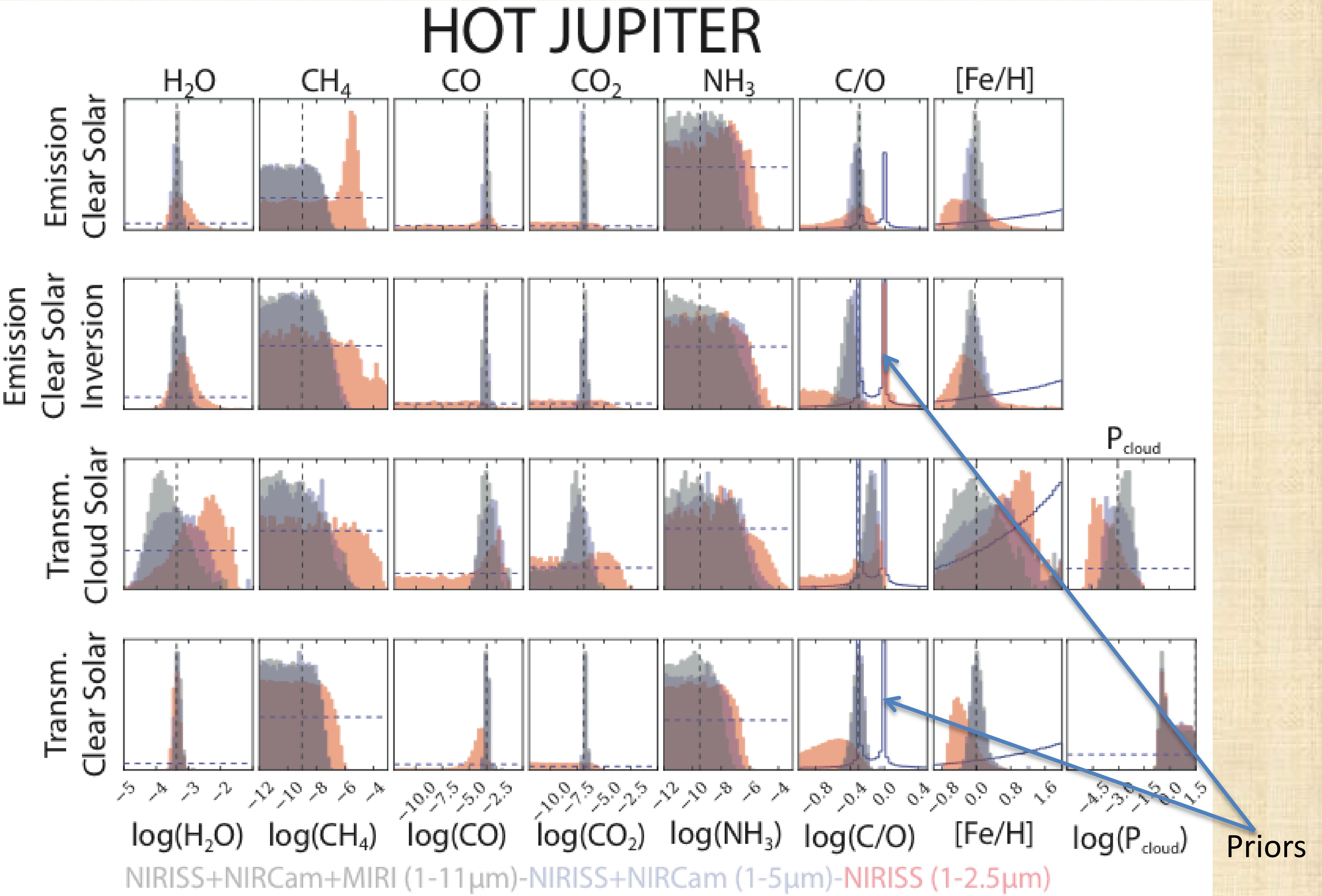
Model Emission Spectra



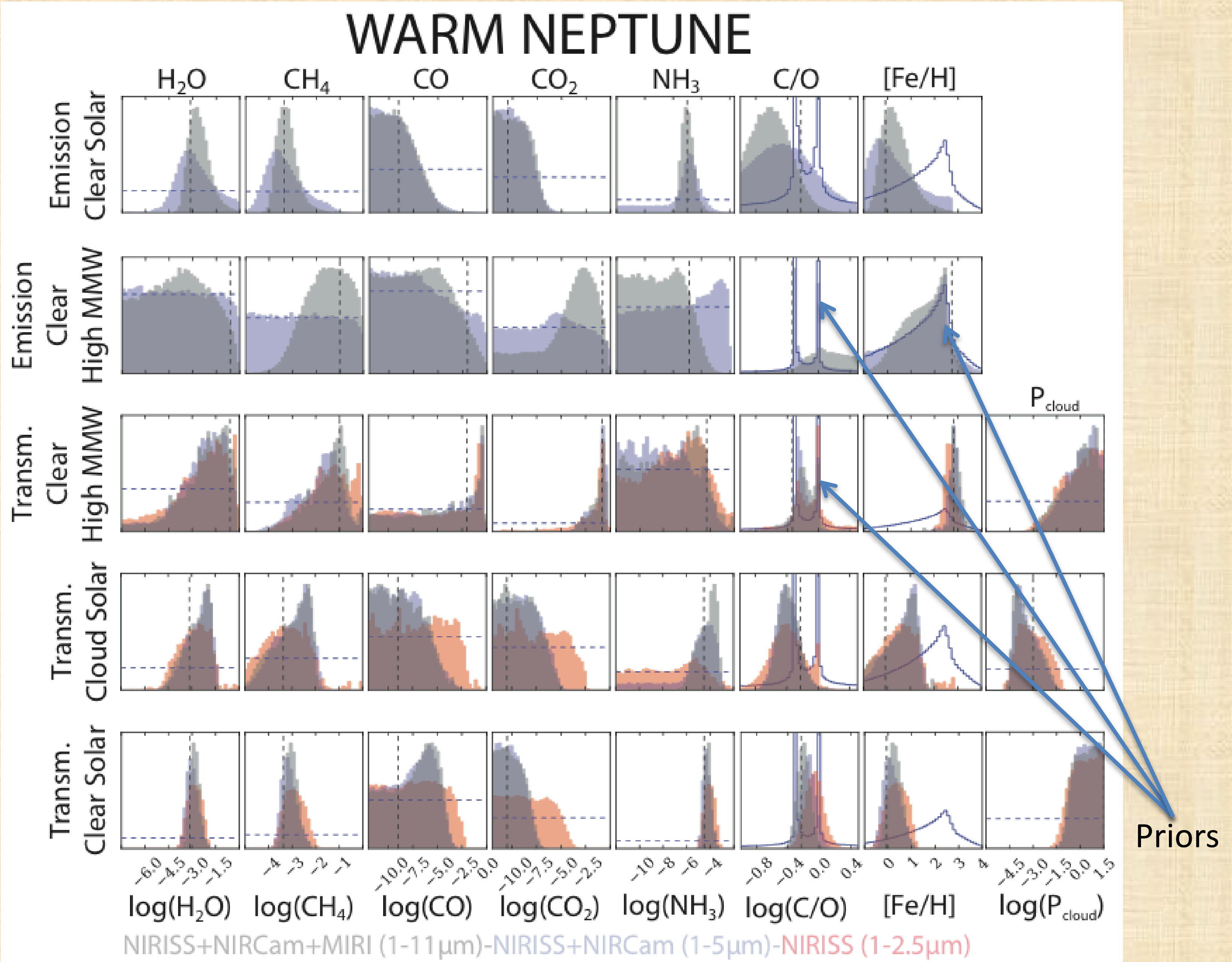
Simulated JWST Emission Spectra (1 eclipse)



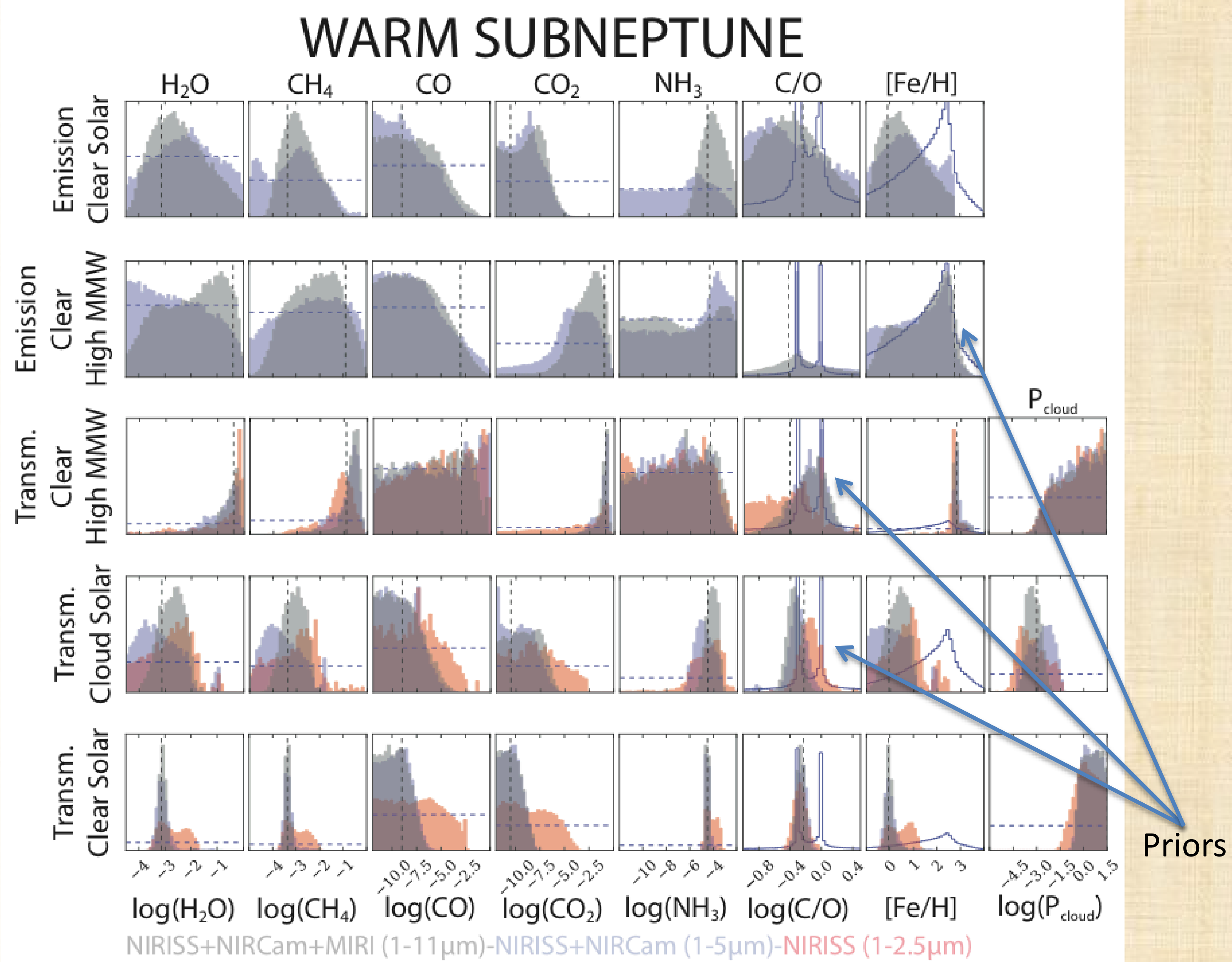
Retrieval: Hot Jupiter Gasses



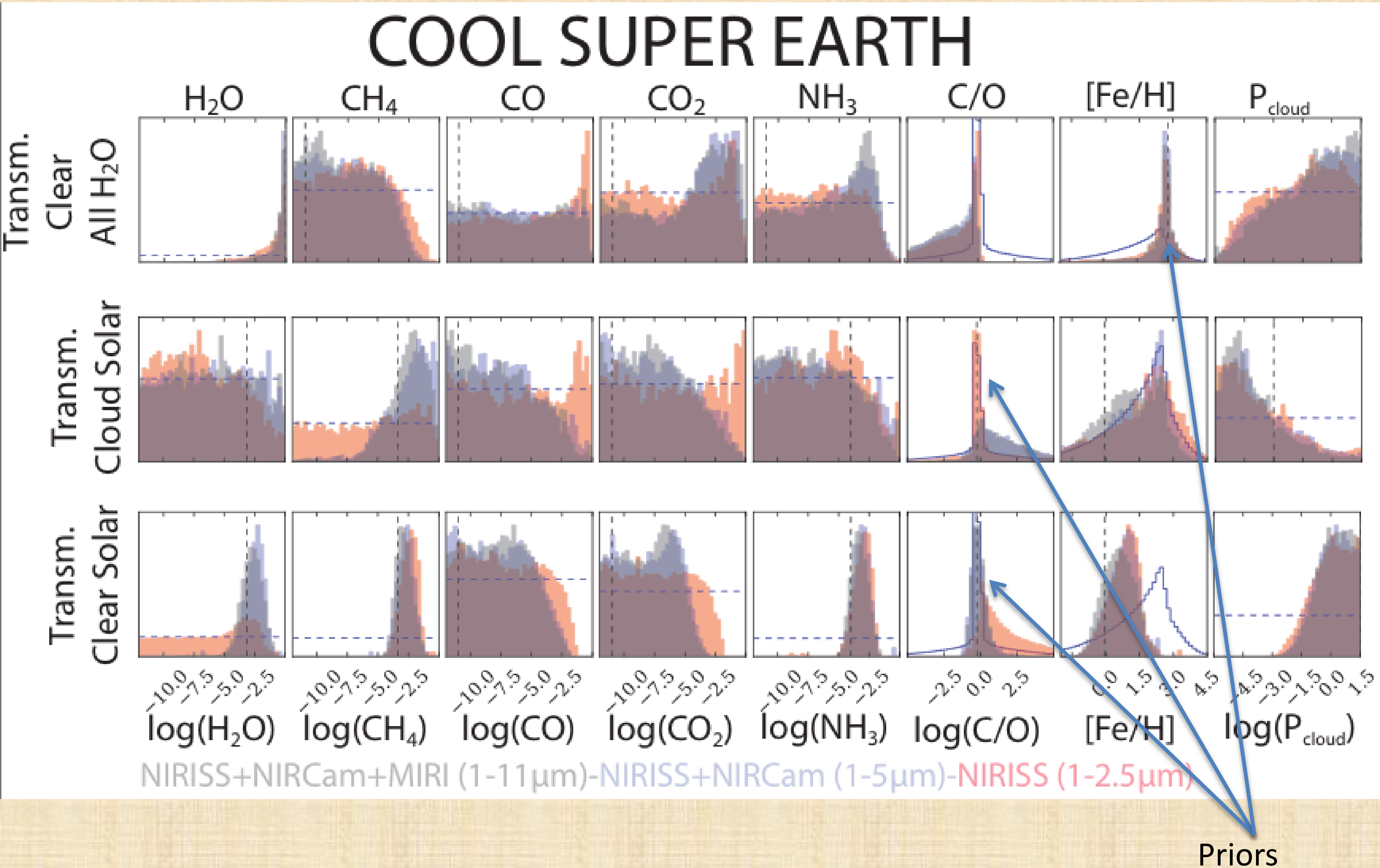
Retrieval: Warm Neptune Gasses



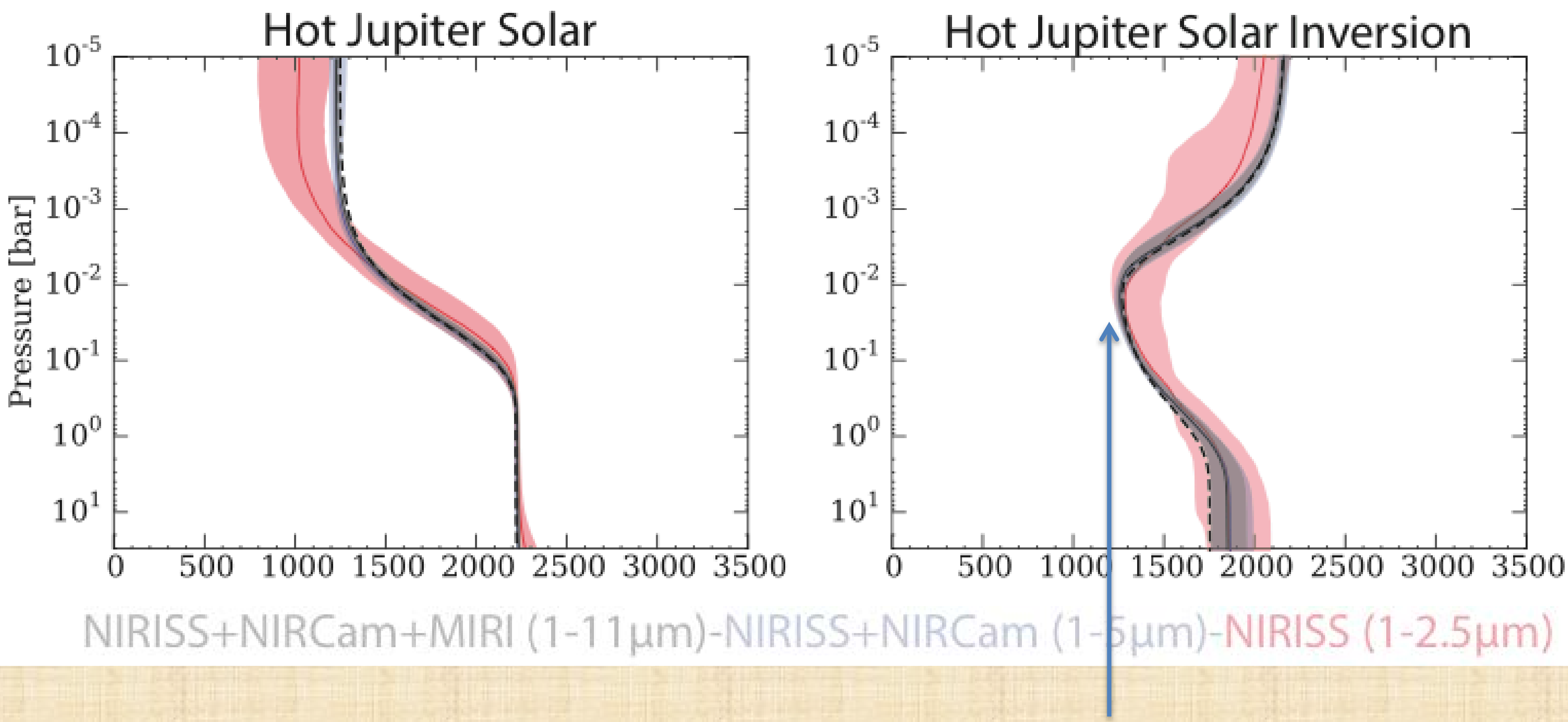
Retrieval: Warm Sub-Neptune Gasses



Retrieval: Cool Super-Earth Gasses



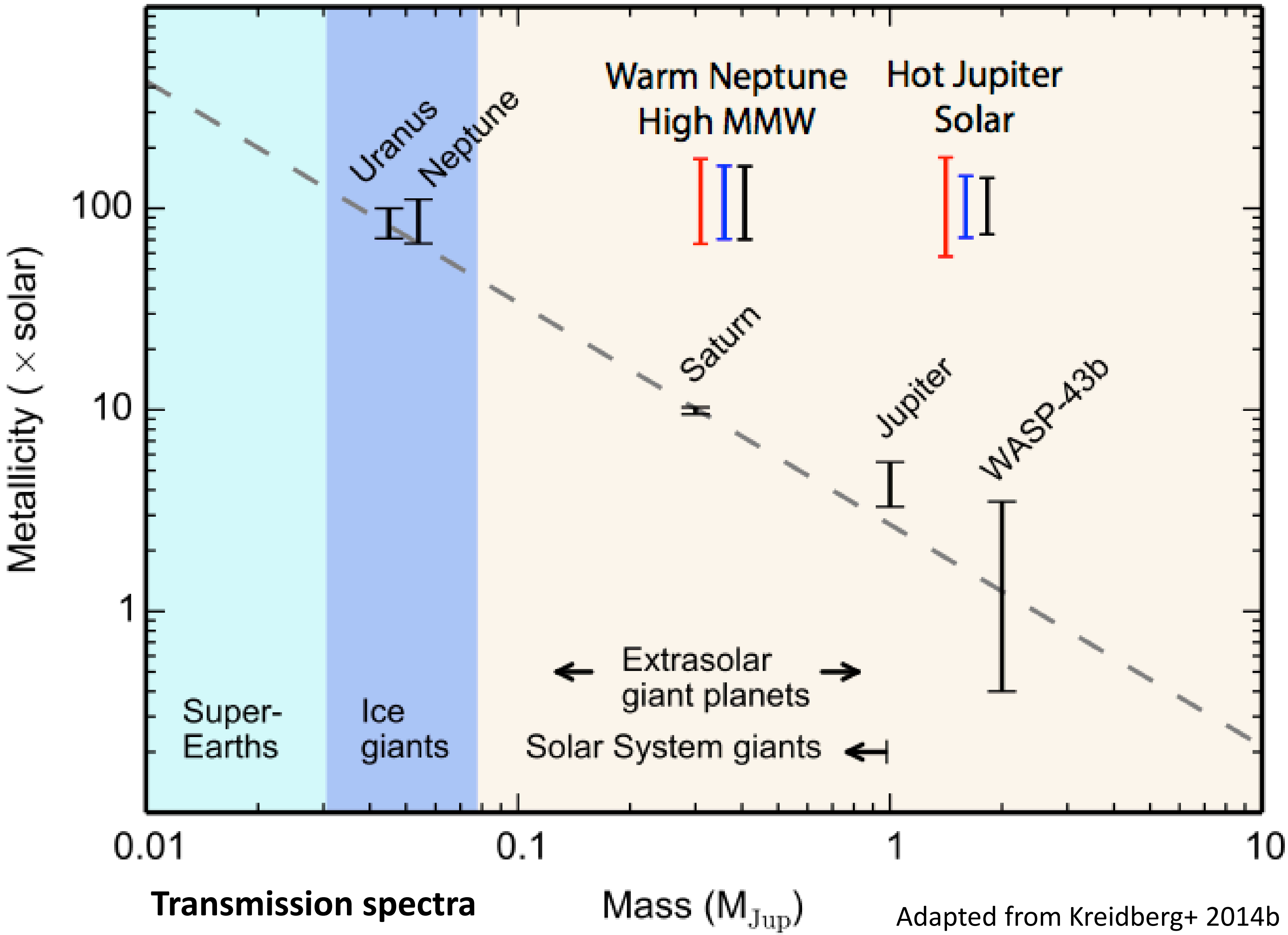
Emission retrievals: T-P Profiles



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

Detect inversion at 4 sigma
with NIRISS only (red)

Mass - Metallicity



Transmission spectra

Adapted from Kreidberg+ 2014b

Summary / Conclusions (1)

- NIRISS (1 – 2.5 μm) transmission spectra alone often constrain mixing ratios of *dominant* molecules in clear solar atmosphere planets
  - C/O and [Fe/H] sometimes constrained with only NIRISS
  - $\lambda \geq 5$ μm spectra needed in a number of cases
- Cloudy solar atmospheres are often constrained (~ 1 dex or better mixing ratios) with λ = 1 - 11 μm spectra
  - Transmission is better than emission for warm sub-Neptune
  - Hot Jupiter and warm Neptune do better with emission
    - Need sufficient F_p and high F_p/F_* for useful emission spectra
- High MMW atmospheres can be identified by high [Fe/H]
- C/O is constrained to 0.2 dex for hot Jupiters with λ = 1 – 5+ μm spectra. Also: C/O for hot planets with H2O + Teq
- σ[Fe/H] < 0.5 dex for warm, clear planets (λ = 1-5+ μm tr)

Summary / Conclusions (2)

- Non-equilibrium vertical mixing cannot be detected via molecular mixing ratios
  - May be better to look for unexpected spectral features
- Observing 5 planets from Uranus to Jupiter mass should measure [Fe/H] vs. Log (M) slope to $1\sigma = 0.13$
  - $\lambda =$ 1-5+ μm transmission spectra
  - More than adequate (~5%) for detecting Solar System slope
- These results are for observations of single transits or eclipses. We will not know the actual JWST data quality – and how noise will decrease with co-adding – until after launch
- Many more retrieval issues to be explored (binning, Bayesian estimators, priors, 3D, parameterization), but will largely be driven by future data

The End