Towards identifying biological processes with transit spectroscopy: Atmospheric retrieval of exoplanets

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Pathways to habitable planets II
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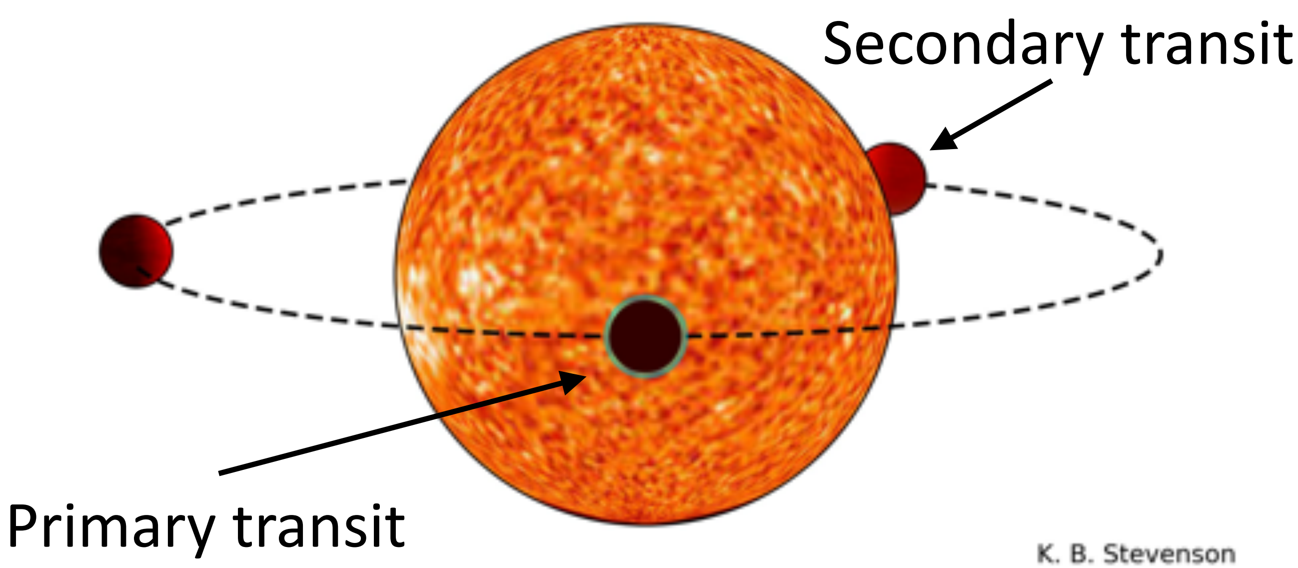
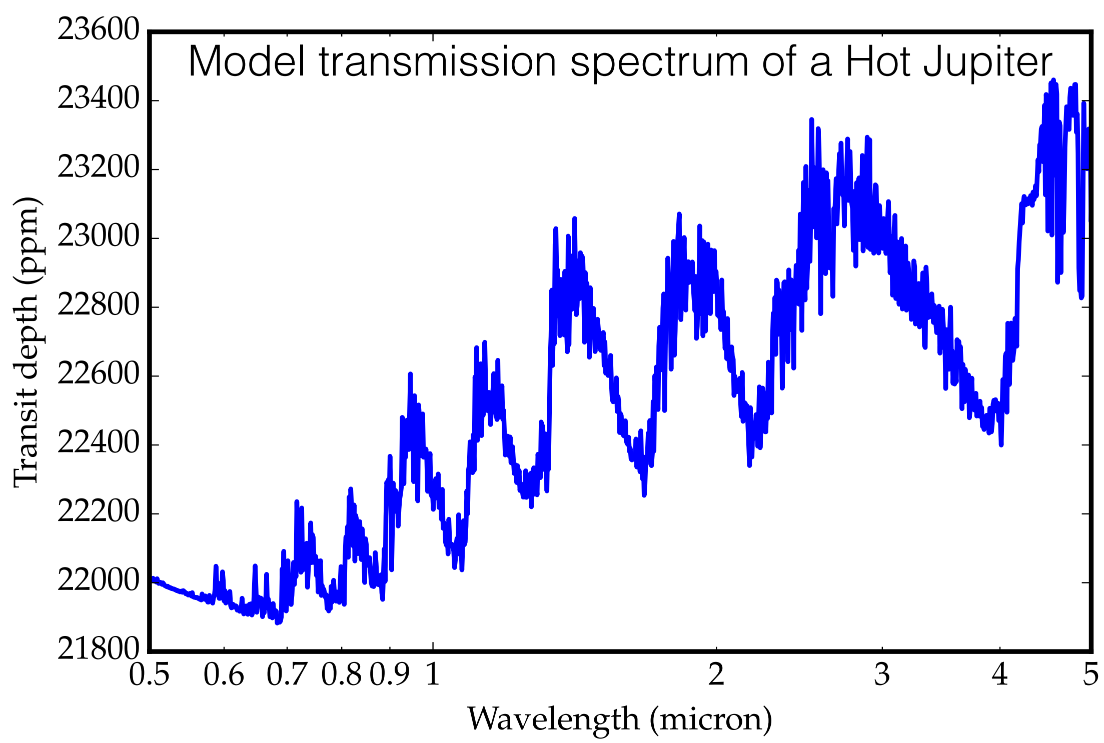
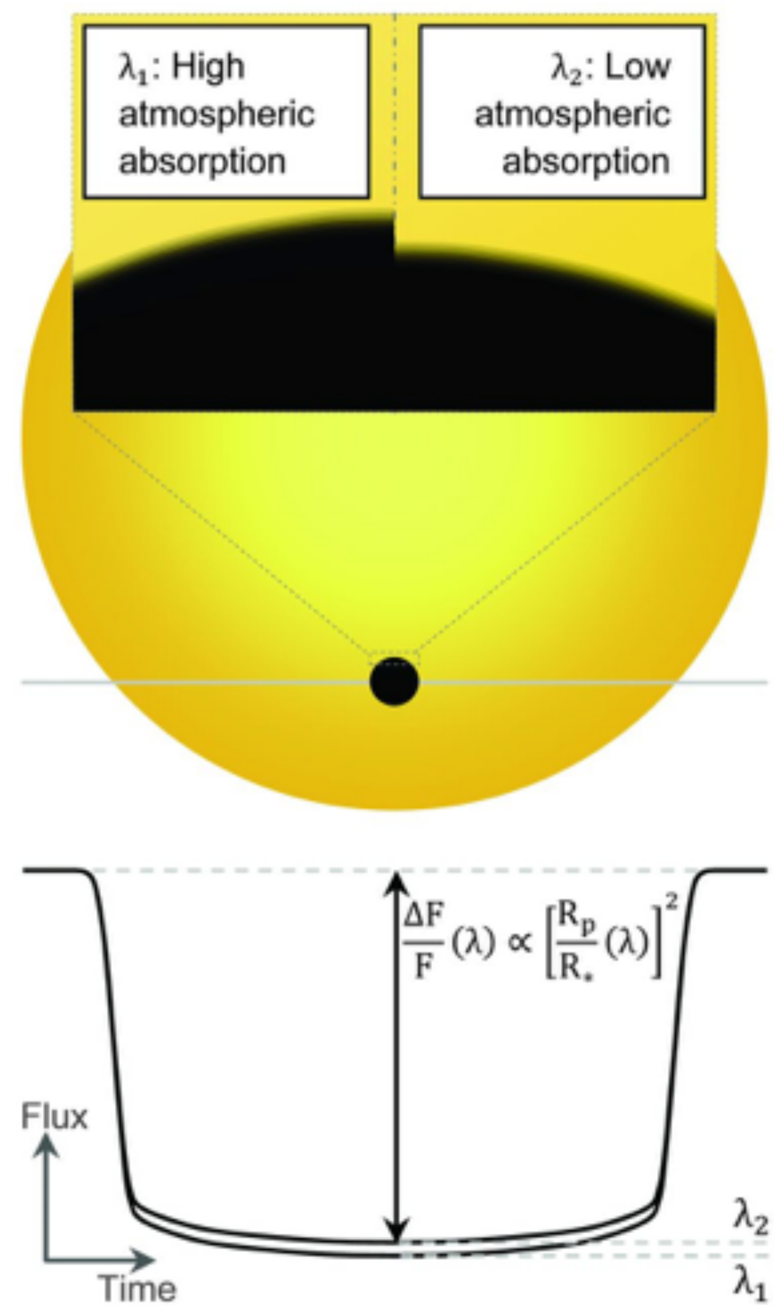
Transmission Spectroscopy:
Probing the atmosphere at the terminator





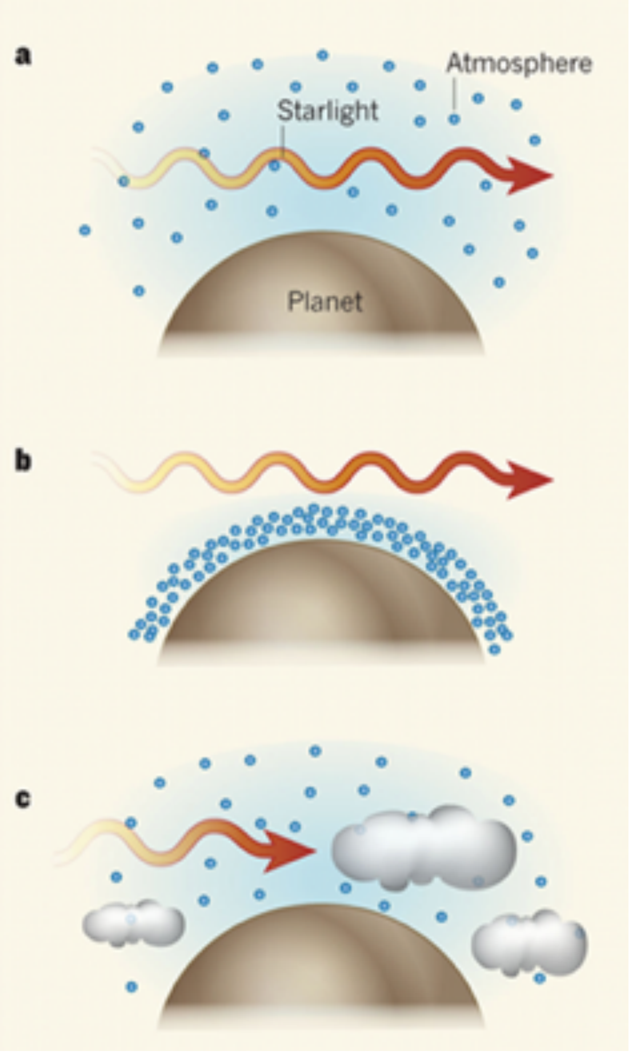
Primary transit at multiple wavelengths



de Wit & Seager (2014)

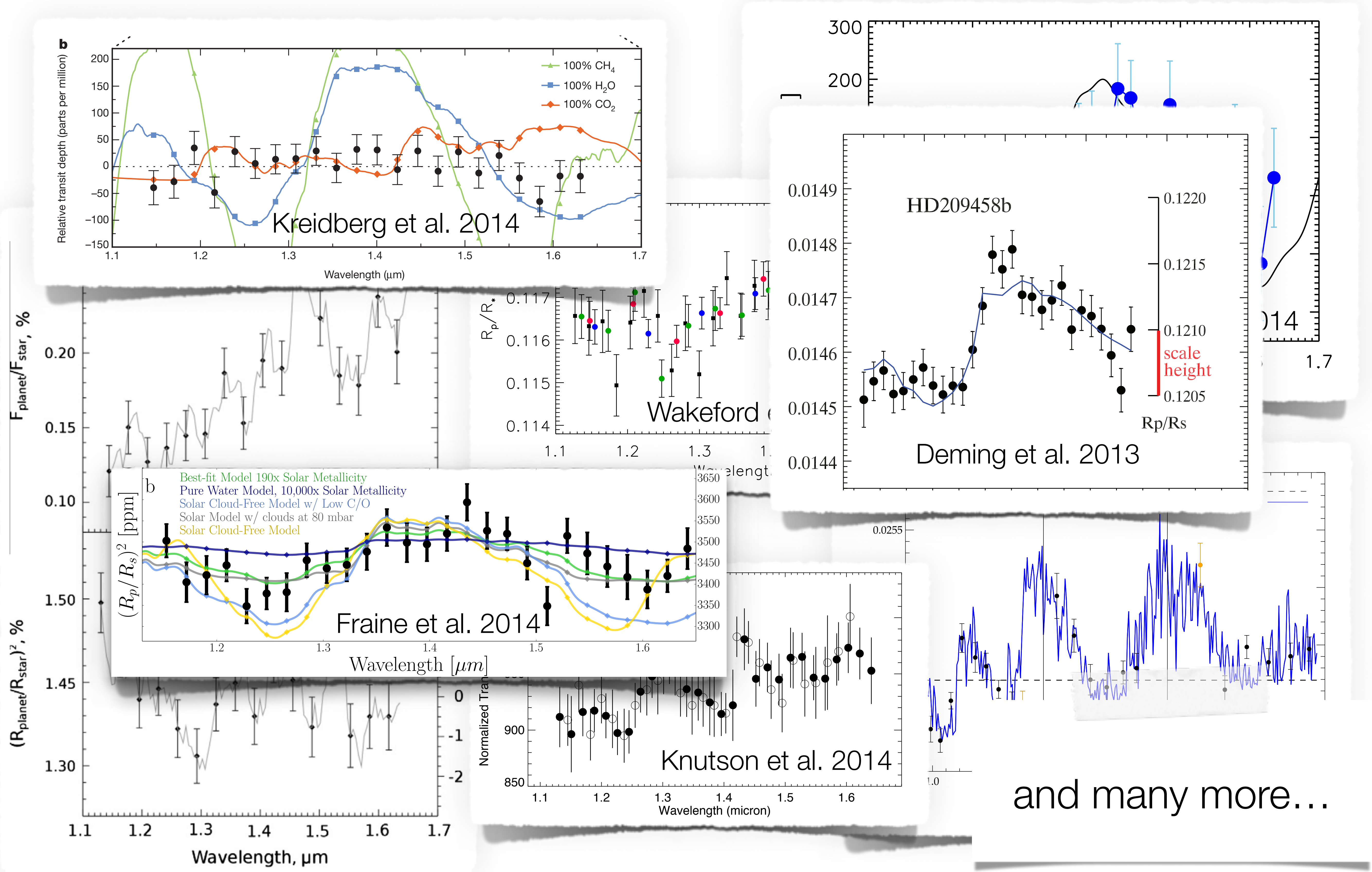
Transmission spectra: what do they tell us?

- Presence of **absorbing molecules** such as water, methane, etc. and their relative abundances
- Mean molecular weight (*μ)*
- Scale height
- Mean temperature
- Presence or absence of clouds
- Exoplanet mass (de Wit & Seager 2014)



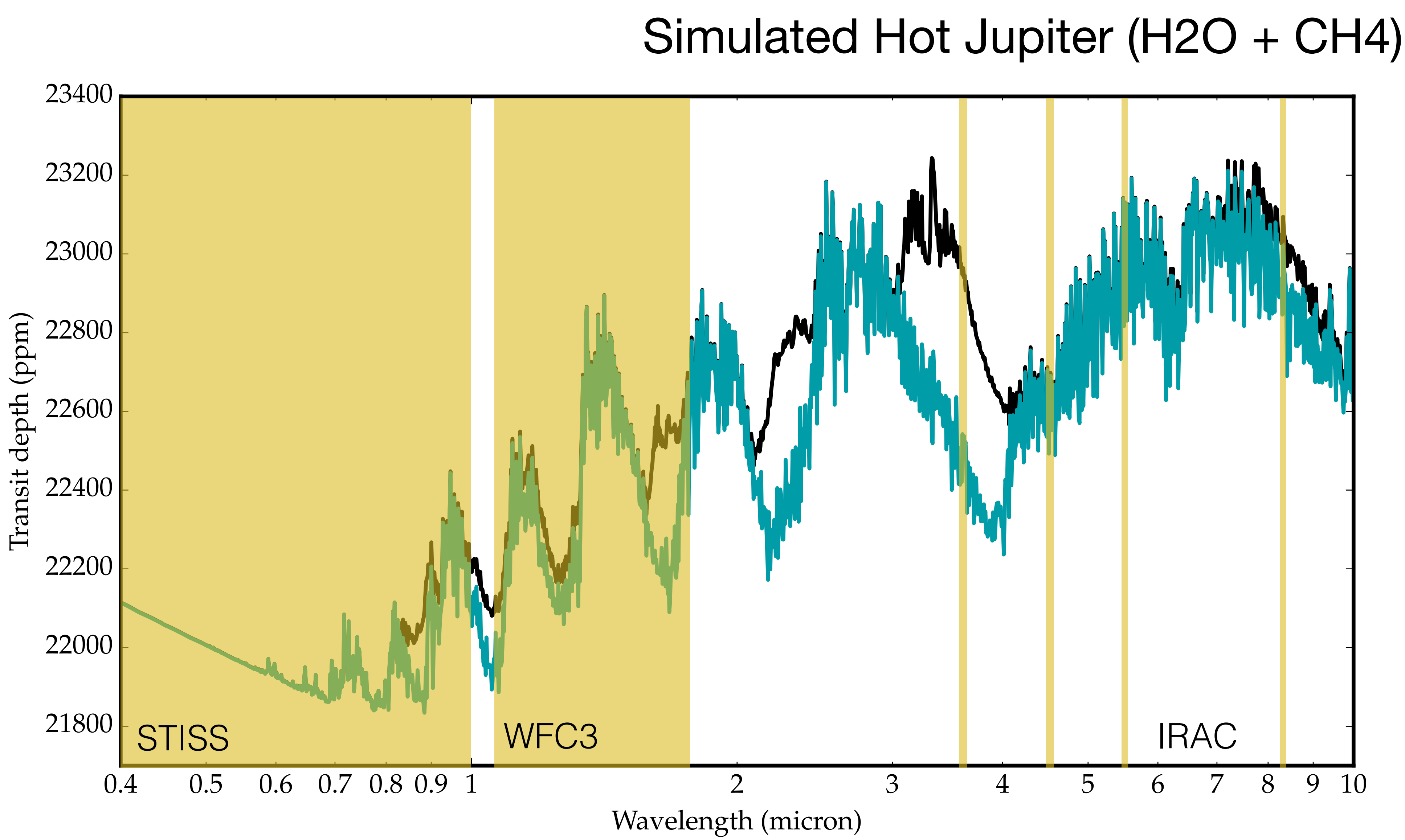
All these parameters are highly degenerate…

Current observations



and many more…

Identifying molecular constituents

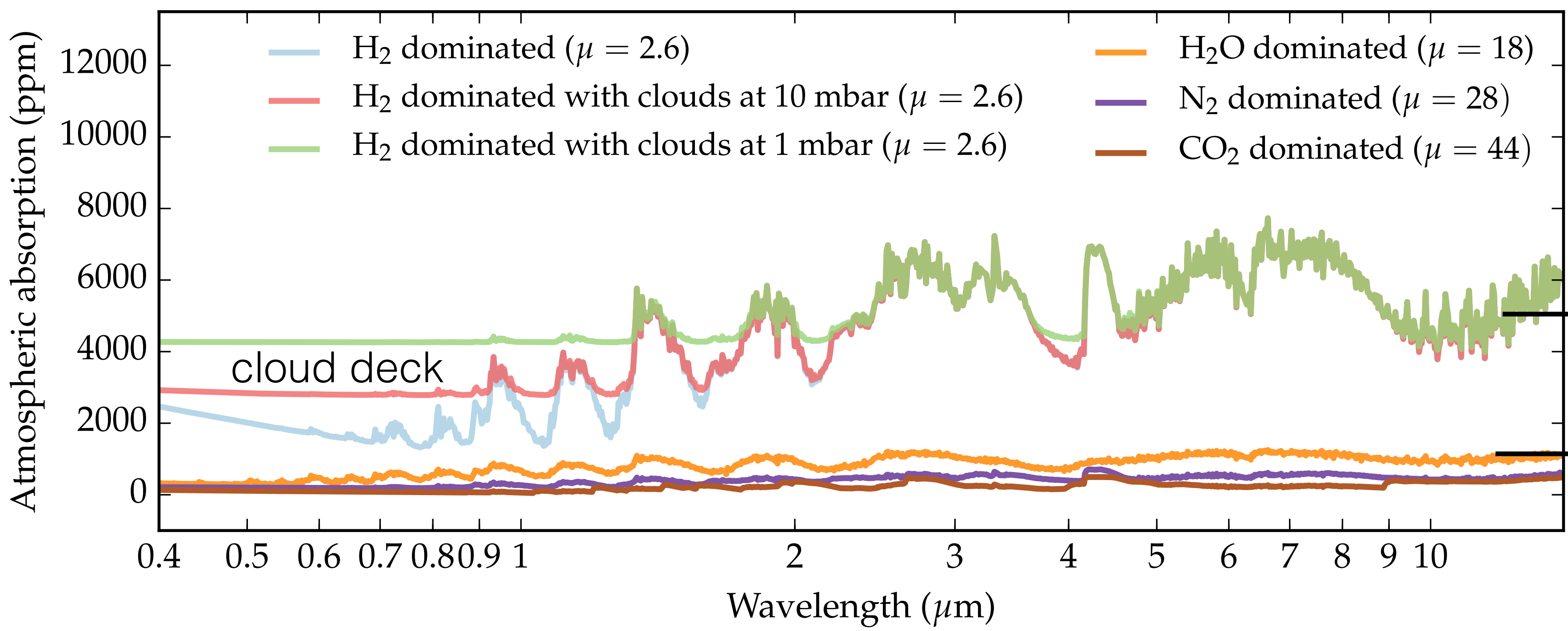


Extending the wavelength range breaks most of the degeneracies

See Giovanna Tinetti's talk on Thursday about ARIEL

Distinguishing between atmospheric constituents

Simulated spectra for a hot super-Earth



Low μ, high H → large signal

High μ, low H → small signal

The heavier is the main atmospheric component, the more compact is the atmosphere, the smaller is the signal detected. While **clouds** can mimic this effect to a degree, they mostly influence the short wavelengths. See also Miller-Ricci et al. 2010.

$$p(z) = p_0 \exp(-z/H)$$

Scale height: $$H \equiv \frac{k_B T}{\mu\, g}$$

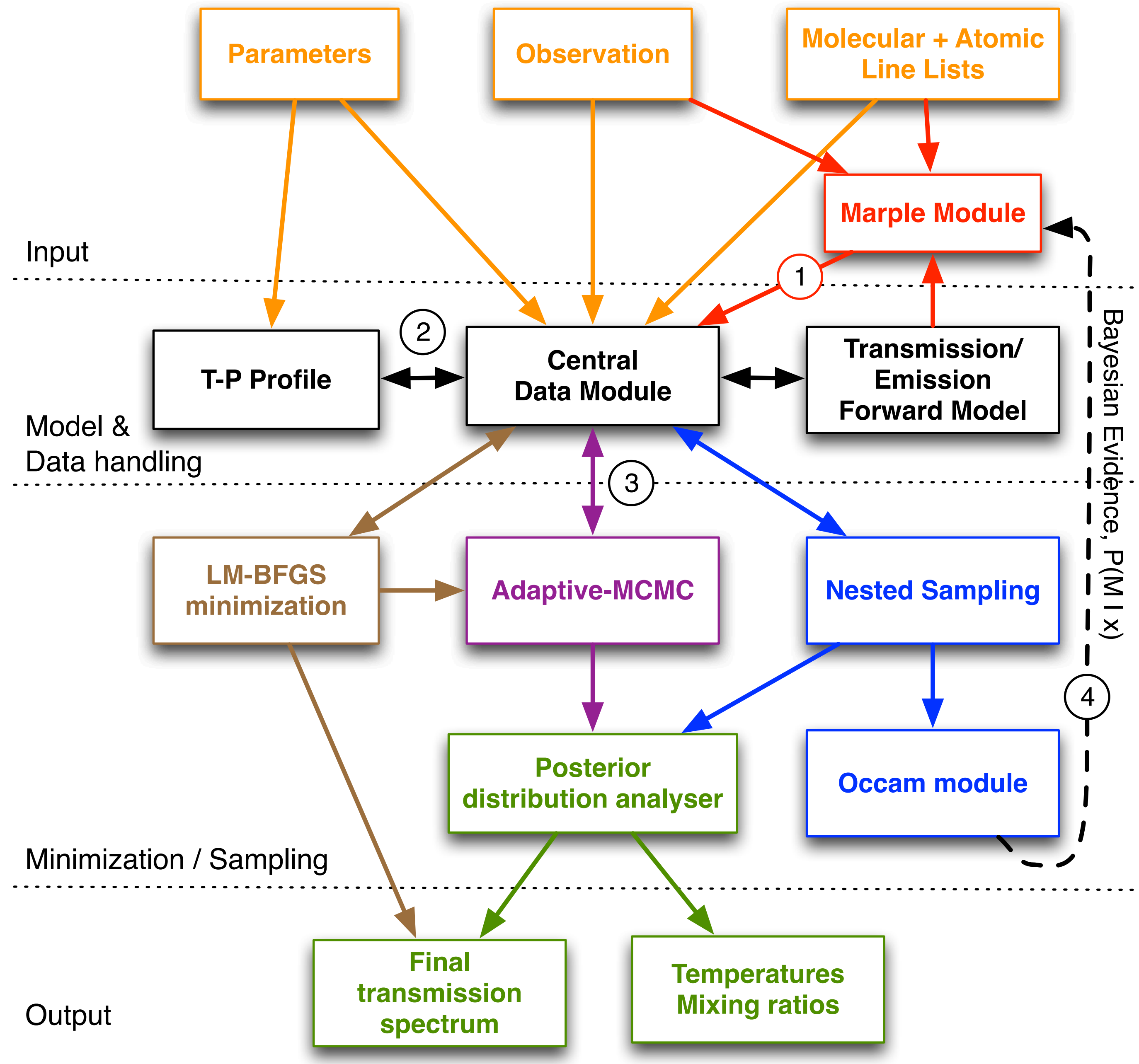
Atmospheric retrieval

- Ab-initio forward models (Burrows et al. 2005, 2007; Fortney et al. 2005)
  - no statistical retrieval, difficult to estimate uncertainties
- Multidimensional grid search approaches (Madhusudhan & Seager 2009)
- Optimal estimation approach (Irwin et al. 2008, Lee et al. 2012; Line et al. 2012)
- Markov chain Monte Carlo (MCMC) approach (Madhusudhan et al. 2011; Benneke & Seager 2012, 2013; Line et al. 2013)

Retrieval of Exoplanet atmospheres

Tau-REx - Next Gen atmospheric retrieval

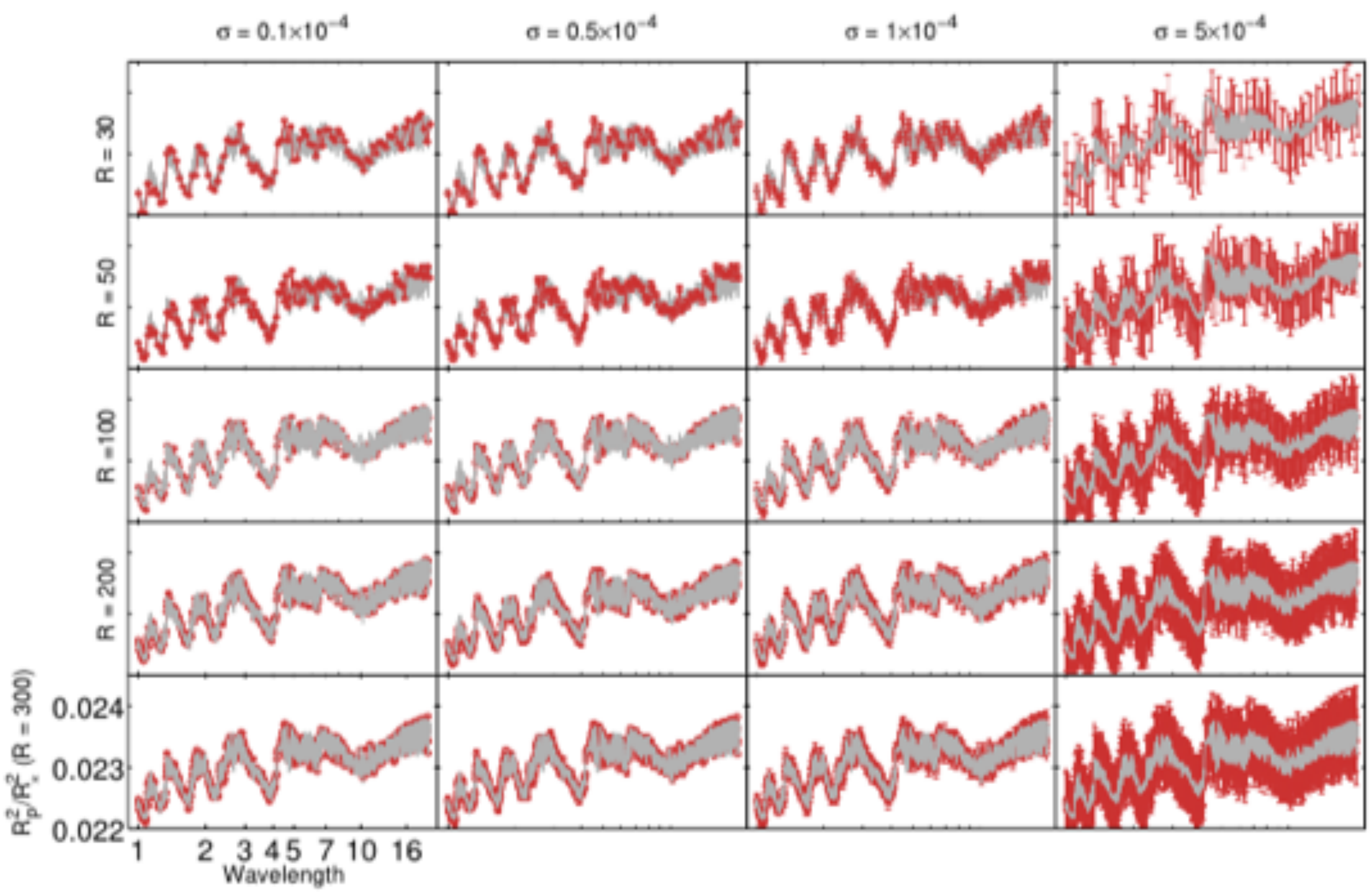
- **Fully Bayesian Retrieval**
  - MCMC
  - Nested Sampling
- **Custom made opacity line-lists** from the ExoMol project
- Prior composition selection through **pattern recognition software**
- **Full parallelisation for cluster computing**



Waldmann et al. 2015a,b

Retrievability of individual model parameters

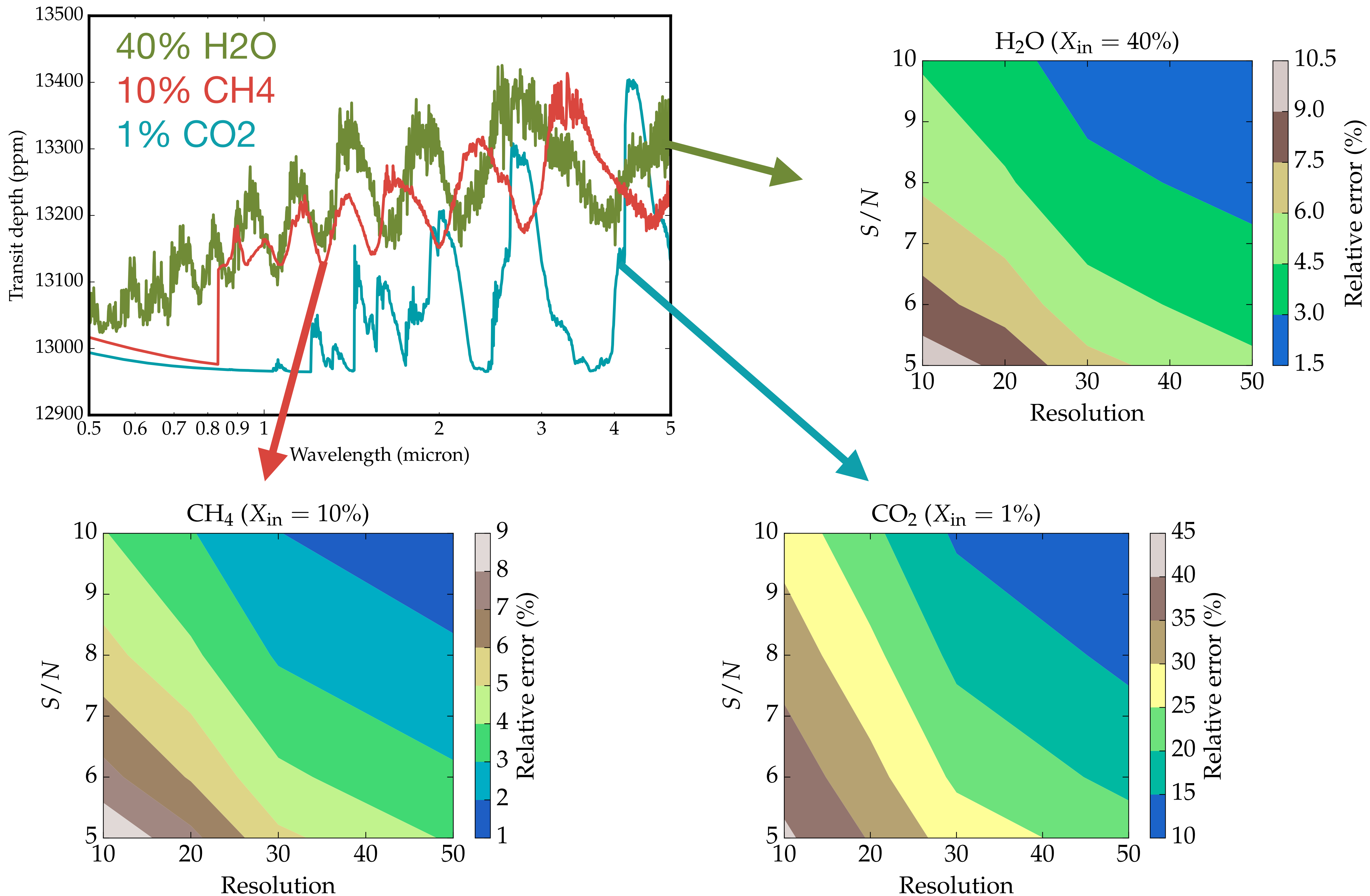
We use **Tau-Rex** to model and interpret the transmission spectra of different classes of transiting exoplanets



We investigate the degeneracies in the model parameters as a function of **signal to noise**, **resolution** and **wavelength coverage**

Super Earth

$R = 0.2\ R_{Jup},\ M = 0.02\ M_{Jup},\ T = 500\ K,\ \mu = 10$



Retrieving atmospheres of gas giants…

… is relatively straight forward.

1. Don’t need to bother about the **unit sum constraint** of mixing ratios:

$$0 < X_i < 1$$

$$\sum_i^N X_i = 1$$

- >>99% of the atmosphere is **made of H and He**
- active absorbers (H2O, CH4 etc) are **trace gases** (<<1%)

2. There is **no surface**, assume a maximum pressure of 10 bar

3. Fitted parameters are usually:
    - Temperature
    - Mean molecular weight
    - 10 bar radius
    - Mixing ratios of absorbers (H2O, CH4, NH3 etc.)

Modelling super Earths is more challenging

1. Presence of **inactive gases** is not known a priori (N2? He? H2?)

2. The active absorbers (H2O, CH4, etc) can make up a large fraction of the atmosphere: Taking care of the **unit sum constraint** in the fitting becomes important!

    The unit sum constraint implies that variables are not free to vary independently (Aichison 1986), as it implies spurious correlations (Chayes, 1960)

3. The **surface pressure** is also not known

The parameter space is larger and more degenerate!

→ The parameter space for the atmospheric composition is the Simplex
→ Couple μ to the atmospheric composition
→ Include the inactive gases in the fitting

Rocchetto et al. 2015 (in prep.), Bennecke & Seager (2012, 2013)

Modelling super Earths composition in the Simplex space

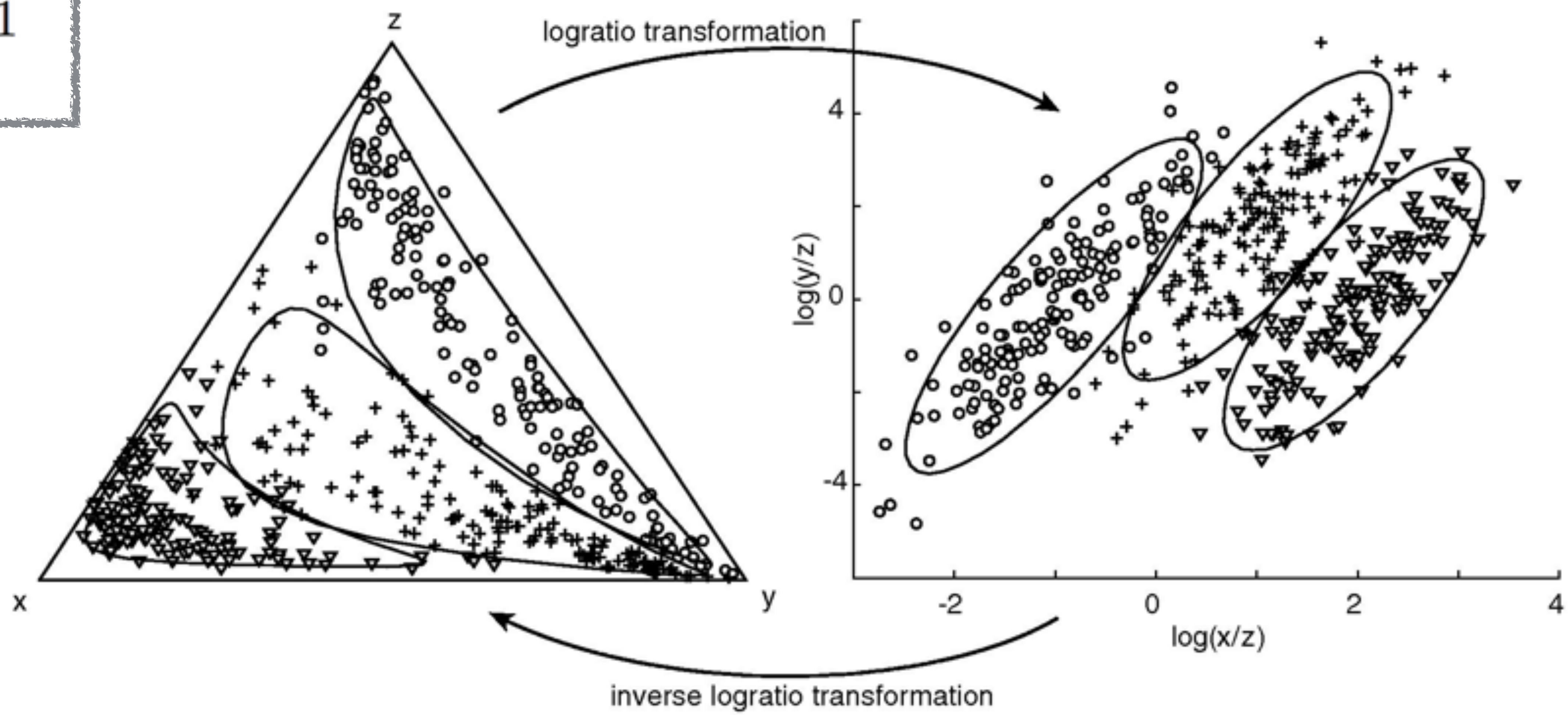
The Simplex:

$$0 < X_i < 1$$

$$\sum_{i}^{N} X_i = 1$$

Log ratio transformation

Aichison (1986)



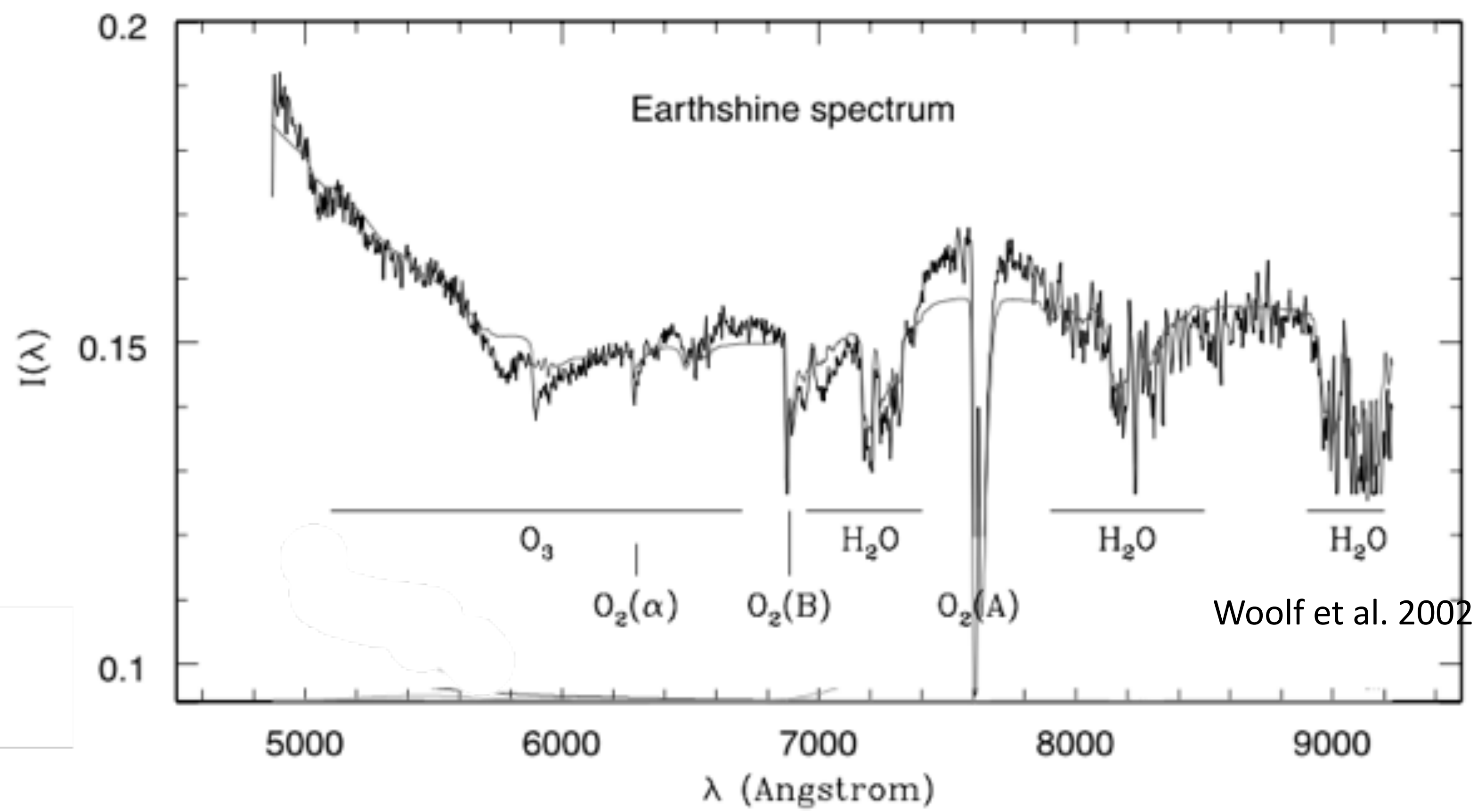
Applied to transmission spectroscopy: Rocchetto et al. 2015 (in prep.), Bennecke & Seager (2012, 2013)

What about retrievability of biosignatures?

Atmospheric biosignatures

- O2, O3, H2O, CH4, CO2 in Earth-sized planets
  (Lovelock 1965, 1975; Lovelock & Hitchcock 1967; Owen 1980; Rye and Holland 1998, Woolf et al. 2002, Snellen et al. 2013, Barstow et al. 2014)
- NH3 in H2 dominated Super Earths (Seager et al. 2013)

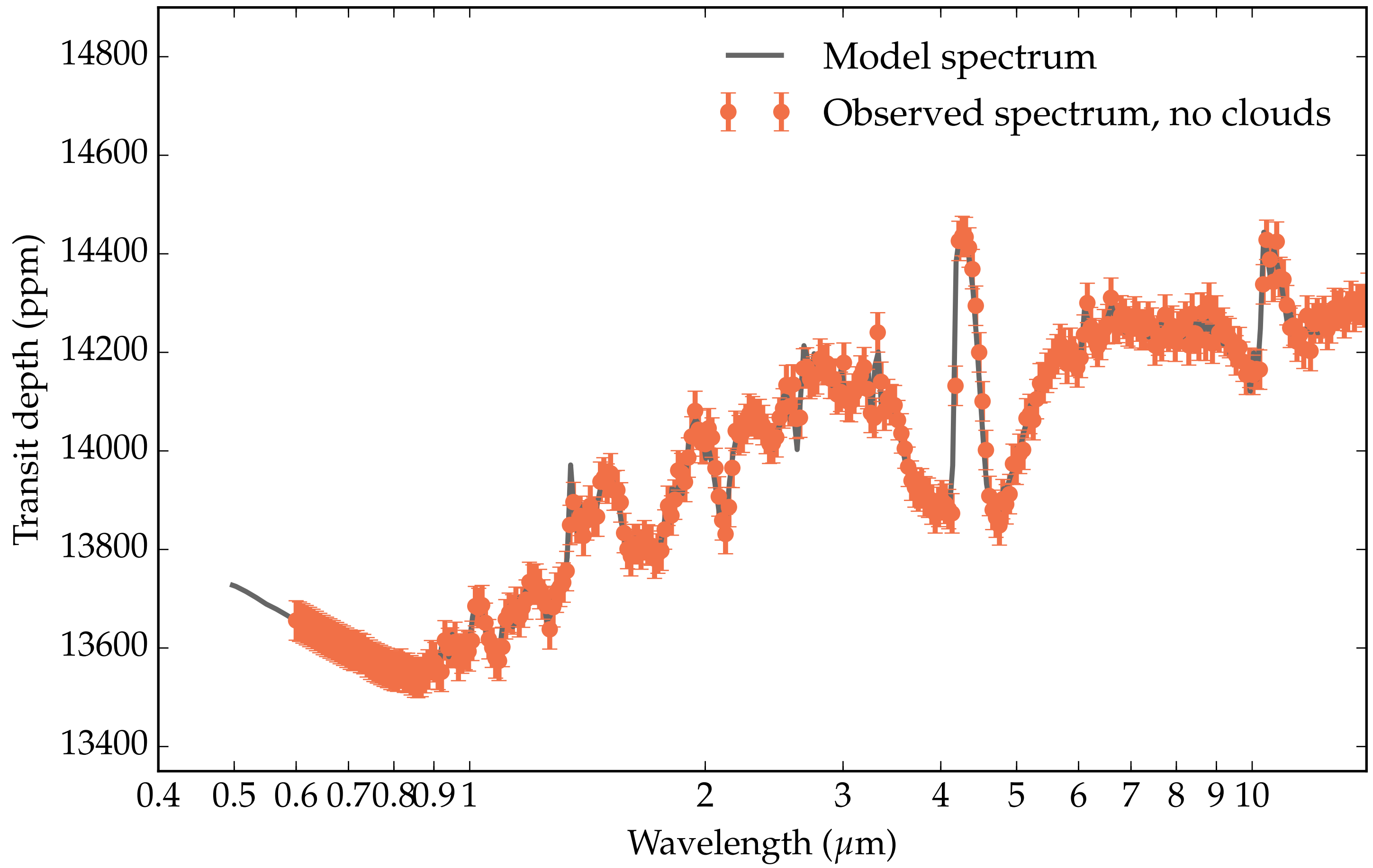
  3H2 + N2 → 2NH3 (Haber process)



Woolf et al. 2002

Retrievability of biosignatures in H2 dominated super Earths

- Super-Earth orbiting a UV quiet M dwarf at 0.037 AU
- Thin H2 atmospheres: 90% H2, 10%N2
- Habitable surface temperature: T = 300 K
- Composition: CH4, CO2, H2O, NH3



CH4: 5 x 10-6

CO2: 3 x 10-6

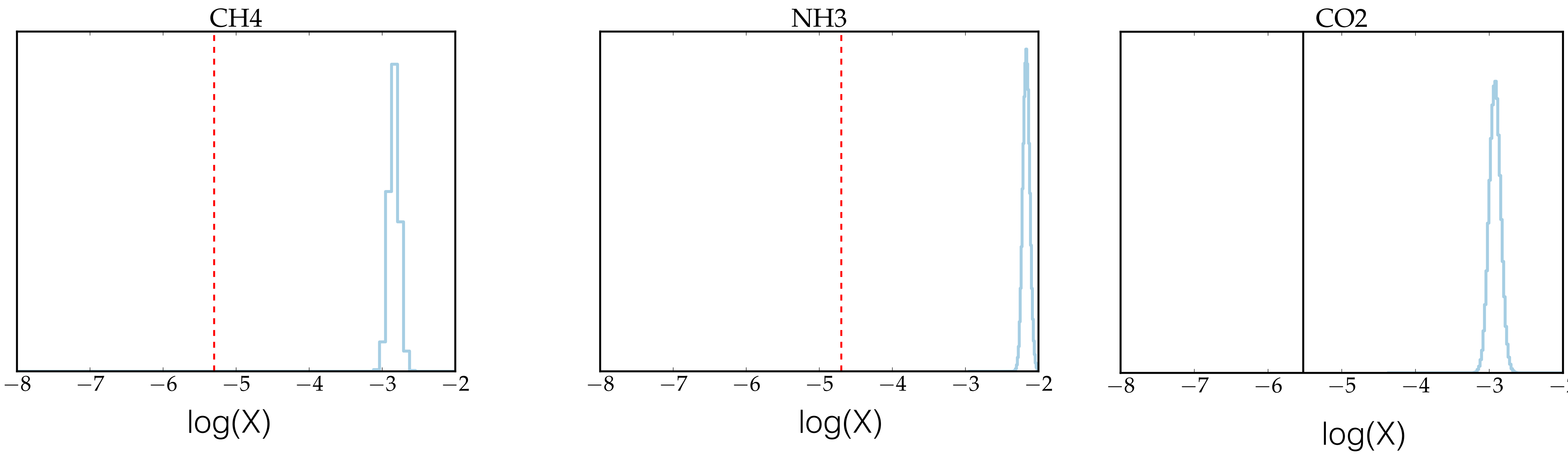
H2O: 1 x 10-5

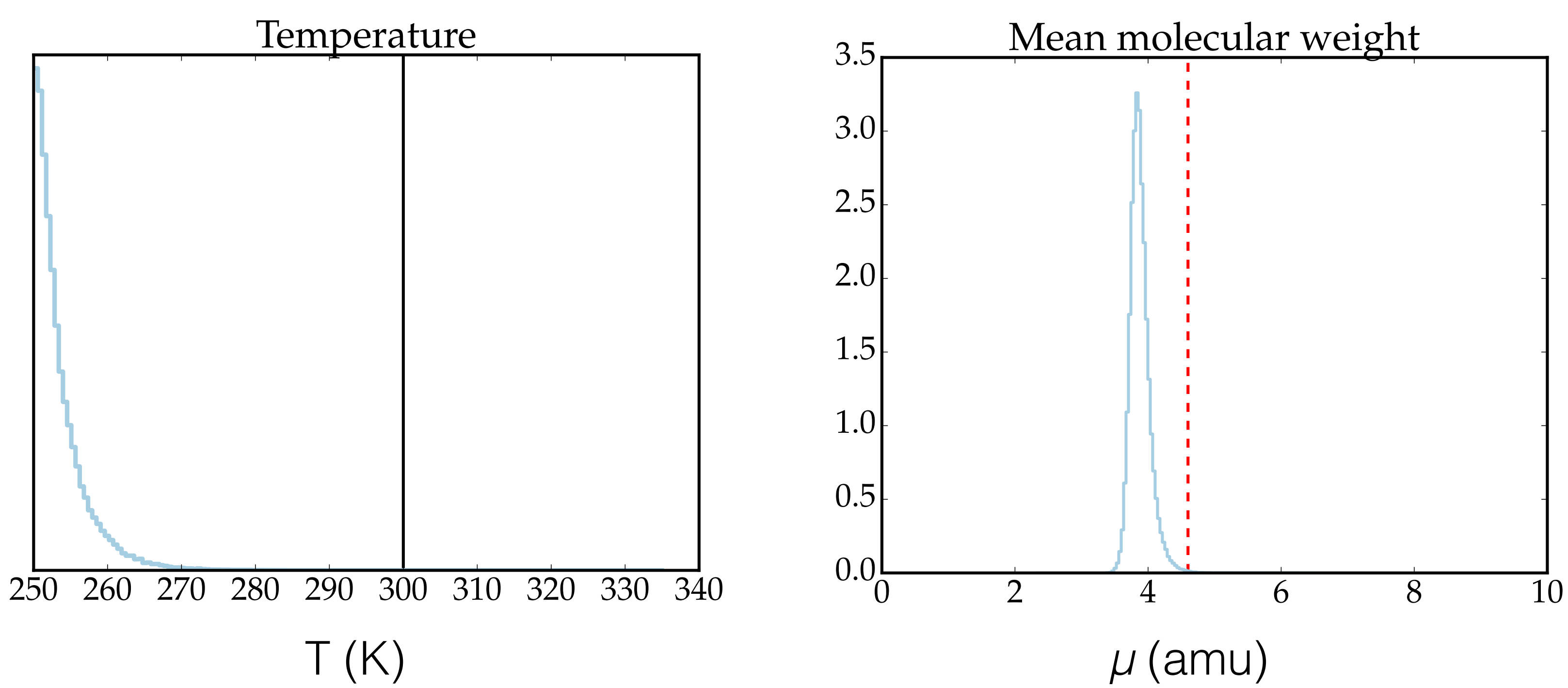
NH3: 2 x 10-5

Observed spectrum

0.6 - 14 μm, R = 100, 50 ppm

Retrieving absolute abundances, cloud free case

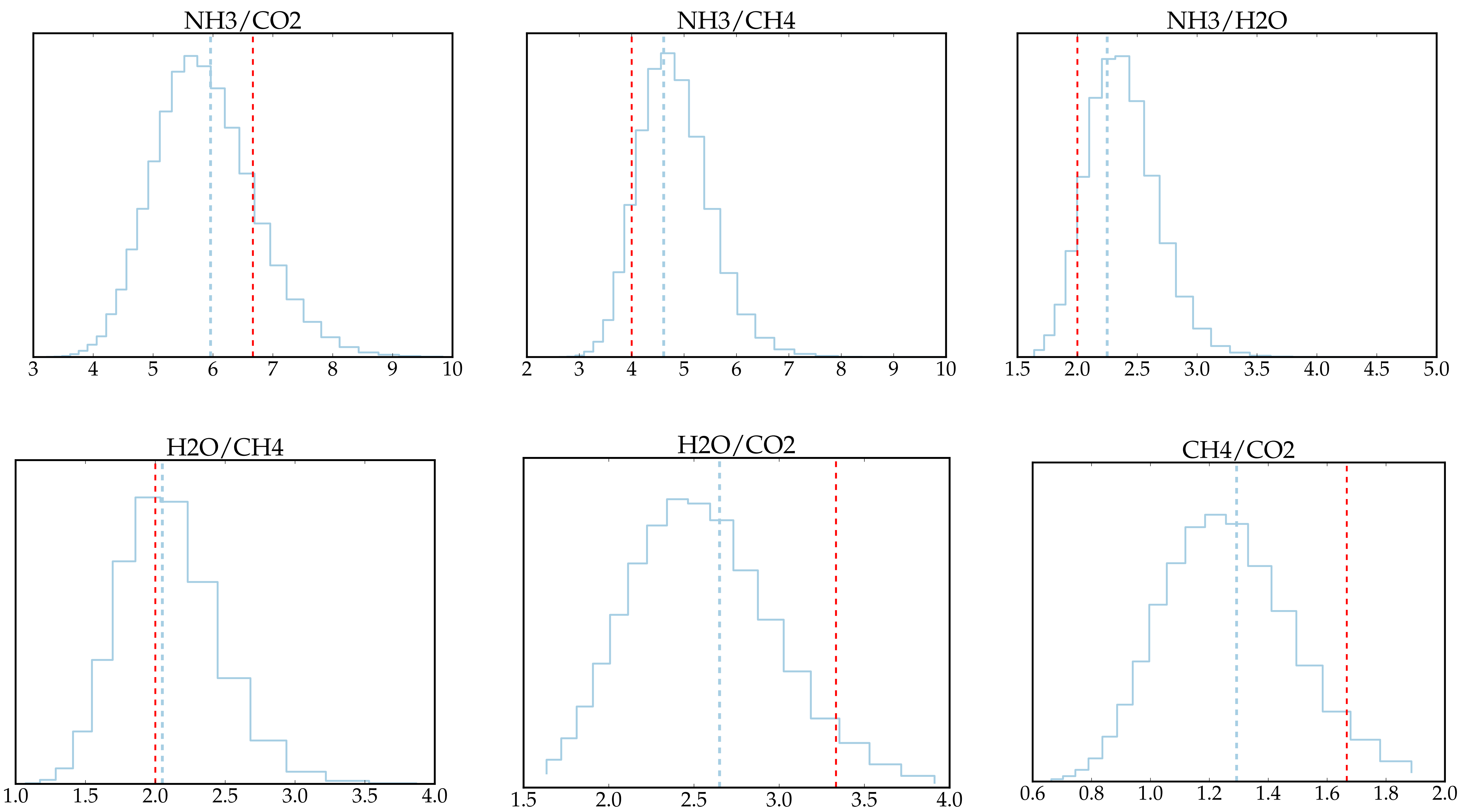




$$H \equiv \frac{k_B T}{\mu g}$$

Temperature needs to be constrained by other means (e.g. emission spectra), otherwise parameter space is too degenerate

Retrieving abundances ratios



Conclusions

- Transmission spectroscopy offers unique ways to study and characterise exoplanetary atmospheres
- Retrieval frameworks are essential to retrieve atmospheric parameters and to explore their degeneracies
- We have used TauREx, a new fully Bayesian retrieval framework, to characterise and understand the degeneracies of parameters as a function of S/N, resolution a wavelength coverage
- We have investigated the retrievability of NH3, a candidate biosignature, in super Earth atmospheres, and found that only the relative abundances can be retrieved if the atmosphere is properly parametrised. This still provides important clues on the chemistry of the planet of potentially habitable planets

Thanks!

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