Exoplanetary Atmosphere Retrievals from Transit Spectroscopy

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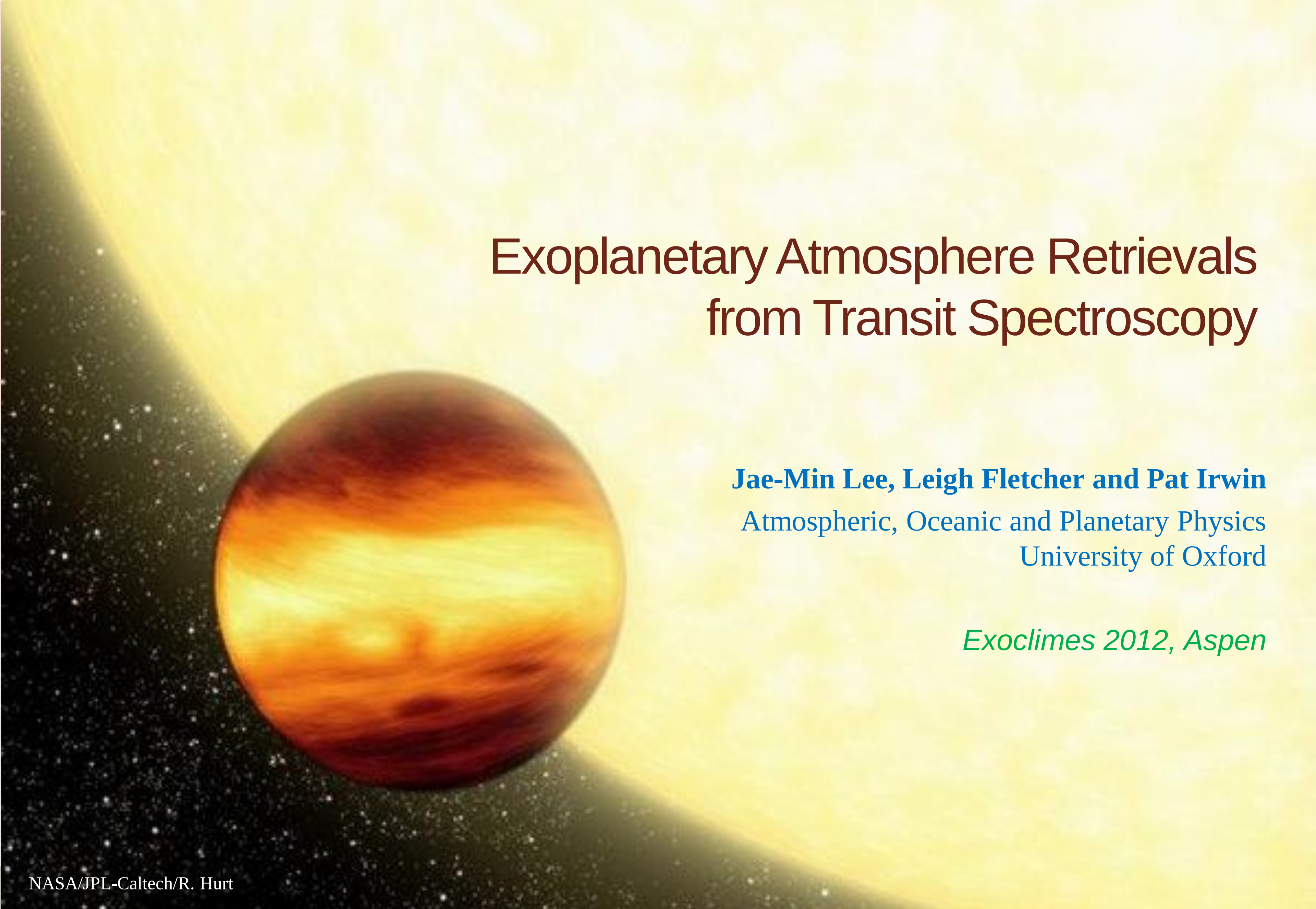
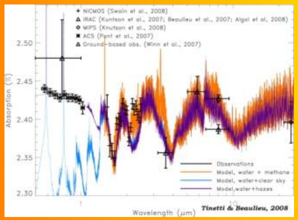
Exoclimes 2012, Aspen



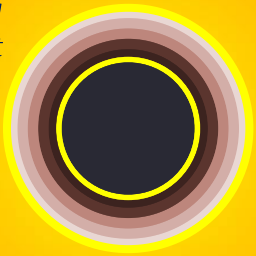
NASA/JPL-Caltech/R. Hurt

Sources of uncertainty in transit spectroscopy

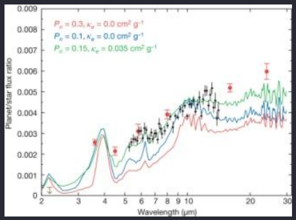
Transmission during primary transit



Tinetti & Beaulieu, 2008



IR Emission from secondary transit



What do cause uncertainty in transit spectroscopy

> *A small number of measurements*

- Secondary eclipse of HD 189733b (only 71 points) (cf. HD 209458b – 34 points ?)
- Not enough constraints to say something about the atmospheres

> *Variability in the exoplanet atmospheres*

- Temporal variability

> *Instrument systematics*

- Various transit curve decorrelation methods
- Noisy measurements

> *Less matured line data for high temperature applications*

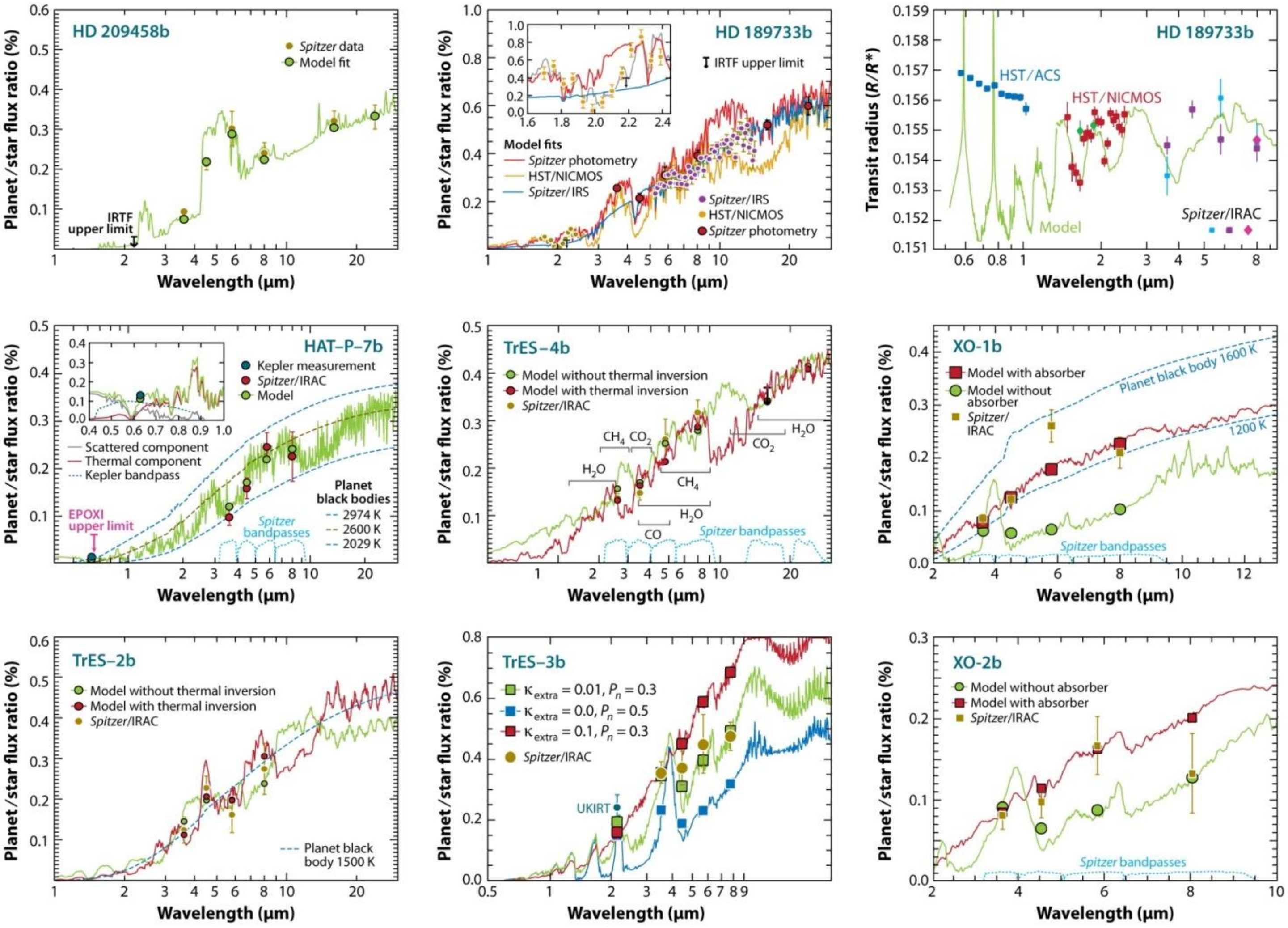
- Some data available such as HITEMP2010, CDSD-1000 (for CO_2), HITEMP1995, and STDS (for CH_4).

> *Model assumptions*

- Radius of planet (the terminator vs dayside atmosphere)

Motivation : “How to develop an efficient and robust technique for characterising the atmospheric temperature, composition and aerosol properties from transit spectroscopy”

How to characterise remotely sensed atmosphere



Seager S, Deming D. 2010.
Annu. Rev. Astron. Astrophys. 48:631–72

Retrievals of atmosphere of exoplanets

What lessons can we learn from the exoplanet spectra available to date?

- How to retrieve the best estimates of temperature structure and composition with reasonable error range

  → Solving the inverse problem – probabilistic techniques

  → Quantifying the degeneracy between properties – a myriad of solutions

Maximize information from the given datasets BUT, at the same time,
Retain a conservative approach

Optimal estimation retrieval & Correlated-k approx.

- **Optimal estimation retrieval** (Rodgers 2000, also see Line et al. 2011)
  - Iterative scheme & Bayesian approach ← *"Solving the Inverse Problem"*

Bayes' Theorem

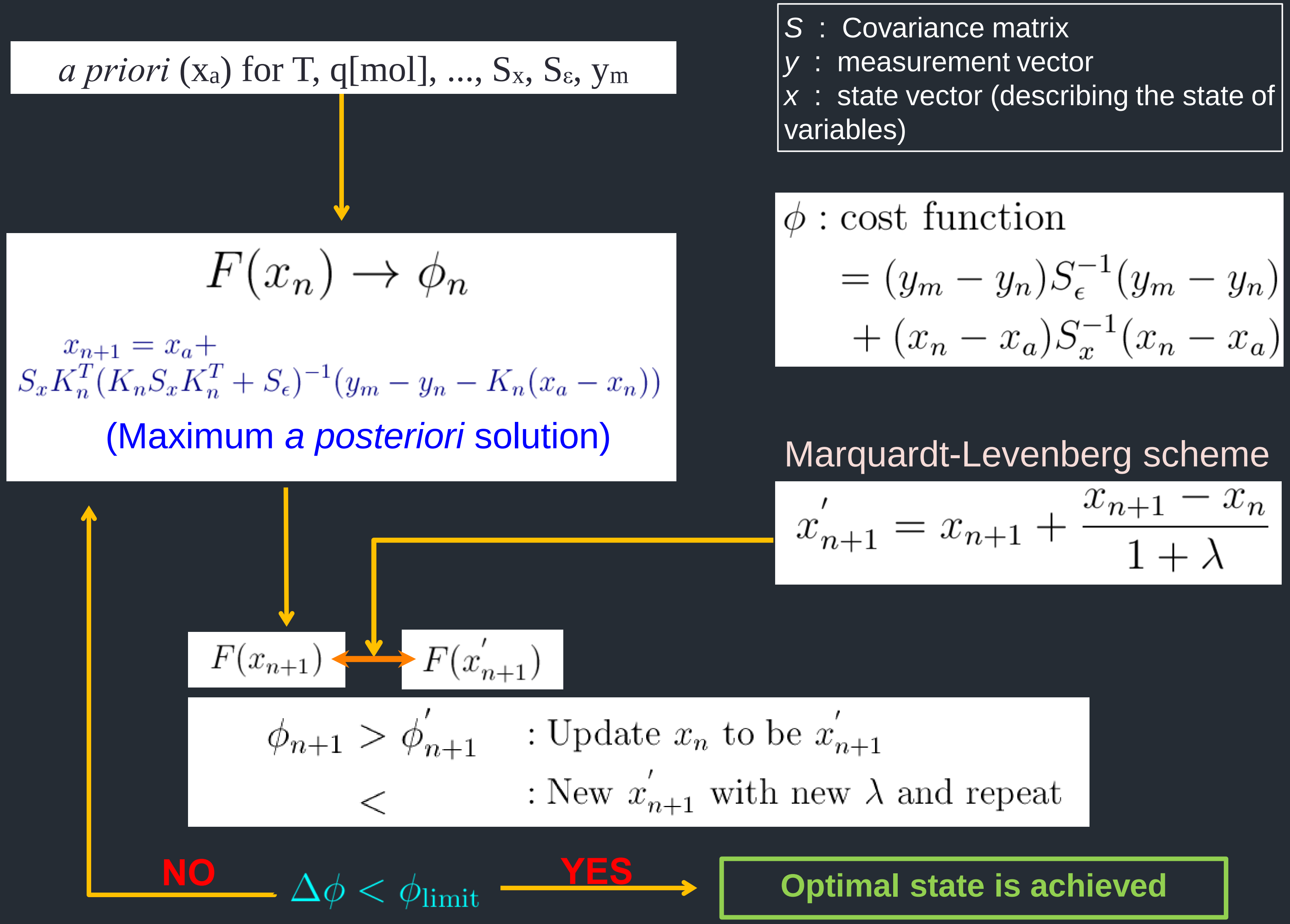
$$\underbrace{P(x|y)}_{\text{Posterior probability}} = \frac{\overbrace{P(y|x)}^{\text{likelihood}}\,\overbrace{P(x)}^{\text{a priori}}}{\underbrace{P(y)}_{\text{measurement}}}$$

  - Covariance matrix analysis – formal quantification of uncertainties (diagonal elements) and characterizing degeneracy (off-diagonal)

  - Tools to understand the sensitivity of spectra to temperature and composition [i.e. Functional derivatives (or Jacobian), $\partial F(x)/\partial x$]

- **Correlated-*k* technique** for rapid & accurate radiative transfer

Optimal Estimation Retrieval Scheme



S : Covariance matrix
y : measurement vector
x : state vector (describing the state of variables)

a priori (x_a) for T, q[mol], ..., S_x, S_ε, y_m

$$F(x_n) \rightarrow \phi_n$$

$$x_{n+1} = x_a + S_x K_n^T (K_n S_x K_n^T + S_\epsilon)^{-1} (y_m - y_n - K_n(x_a - x_n))$$

(Maximum *a posteriori* solution)

ϕ : cost function

$$= (y_m - y_n) S_\epsilon^{-1} (y_m - y_n) + (x_n - x_a) S_x^{-1} (x_n - x_a)$$

Marquardt-Levenberg scheme

$$x'_{n+1} = x_{n+1} + \frac{x_{n+1} - x_n}{1 + \lambda}$$

$$F(x_{n+1}) \longleftrightarrow F(x'_{n+1})$$

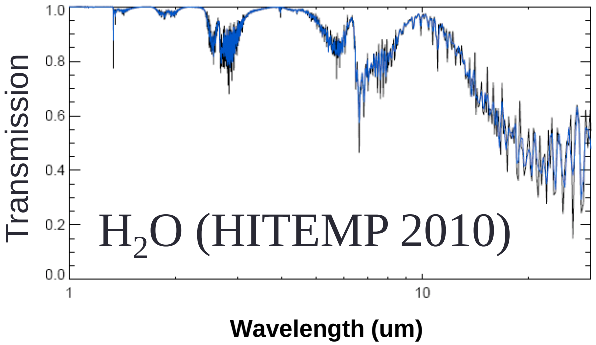
$\phi_{n+1} > \phi'_{n+1}$: Update x_n to be x'_{n+1}
$<$: New x'_{n+1} with new λ and repeat

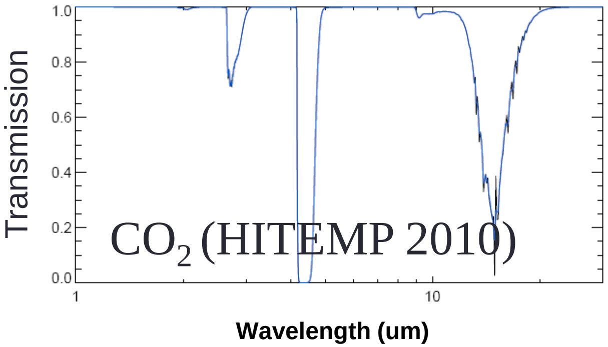
NO $\Delta\phi < \phi_{\text{limit}}$ **YES**

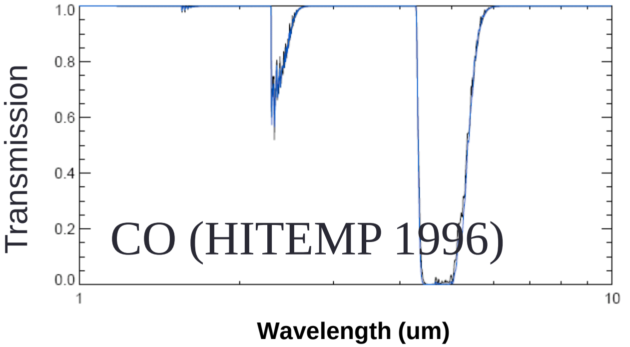
Optimal state is achieved

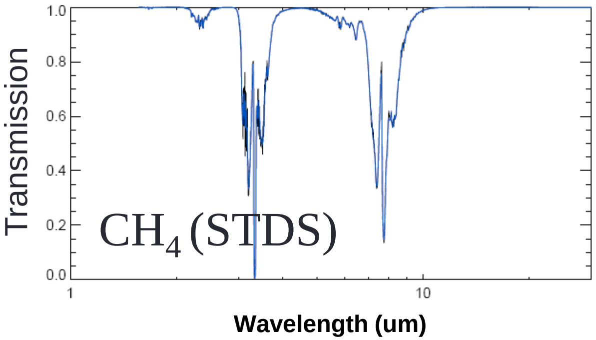
Correlated-k vs. line-by-line

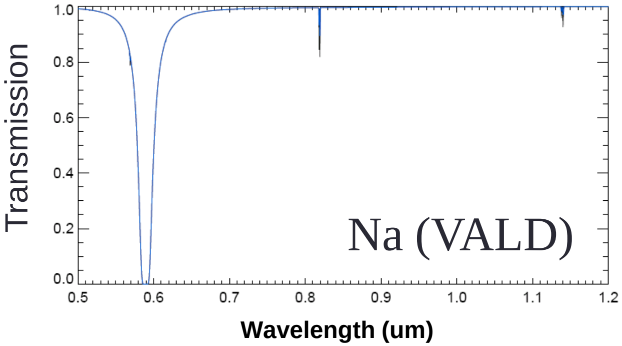
line-by-line k-distribution

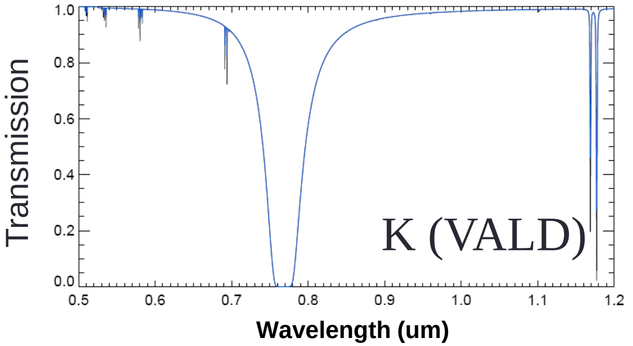


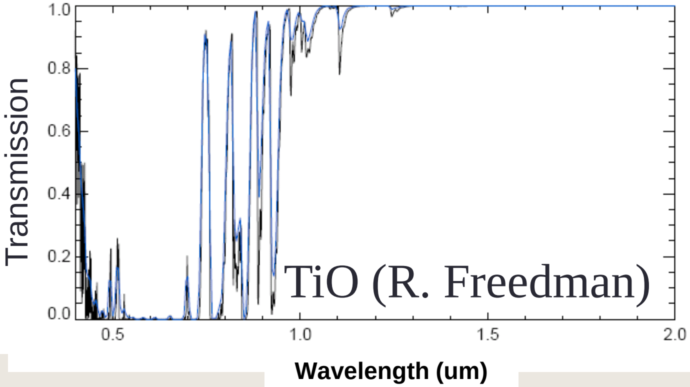


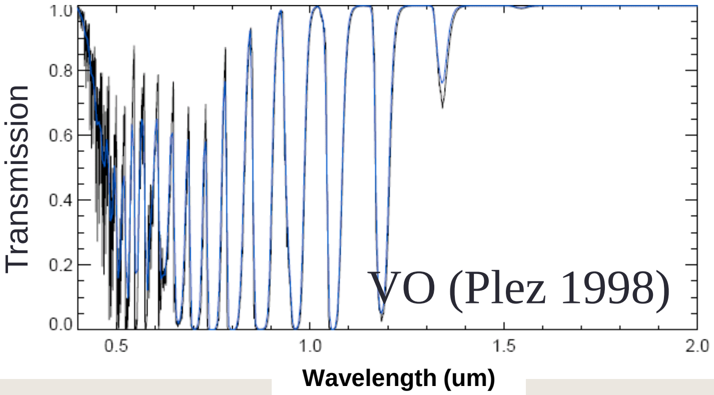






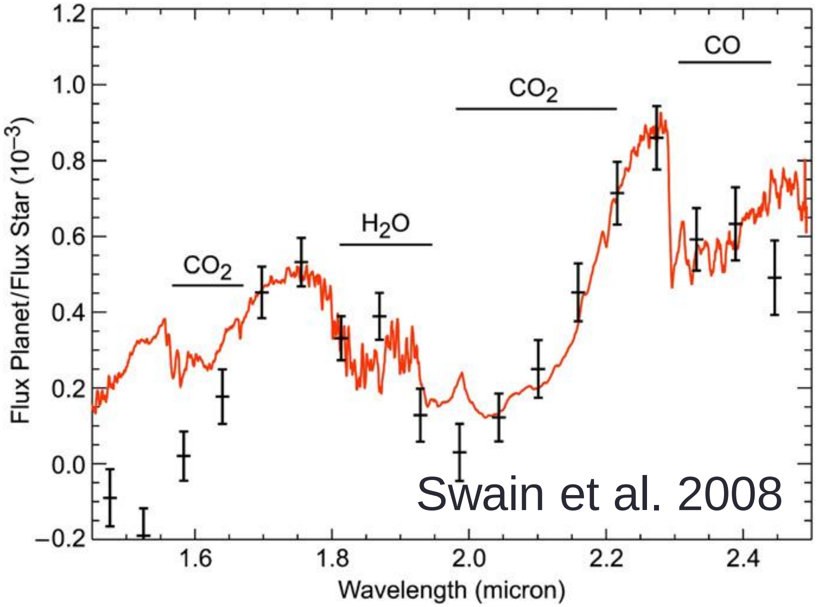




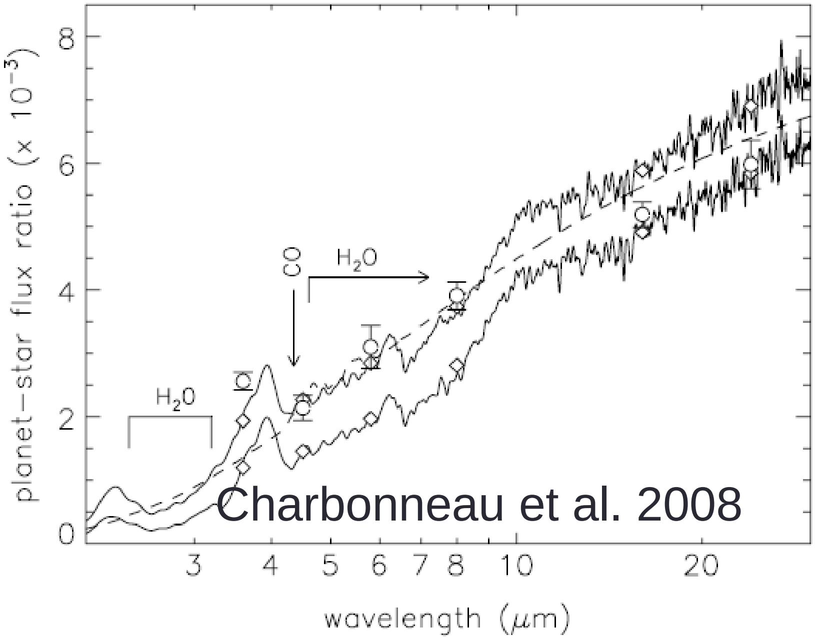


More molecules? i.e. NH_3, hydrocarbons, etc.

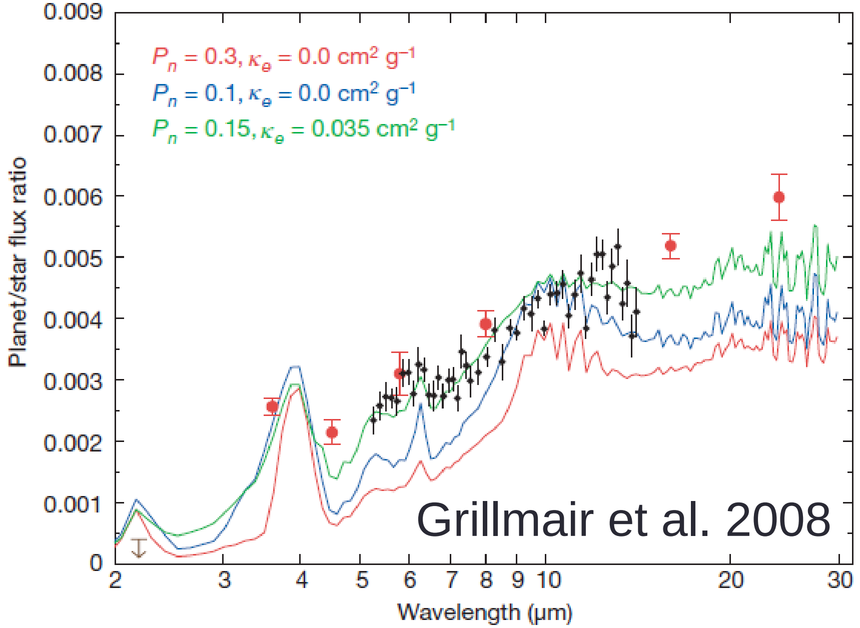
Dayside emission spectrum of HD 189733b



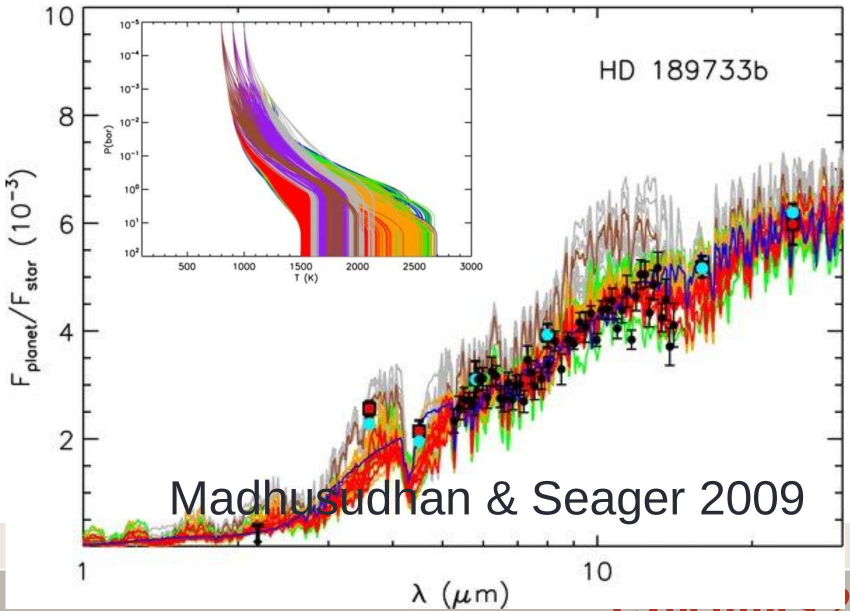
Swain et al. 2008



Charbonneau et al. 2008

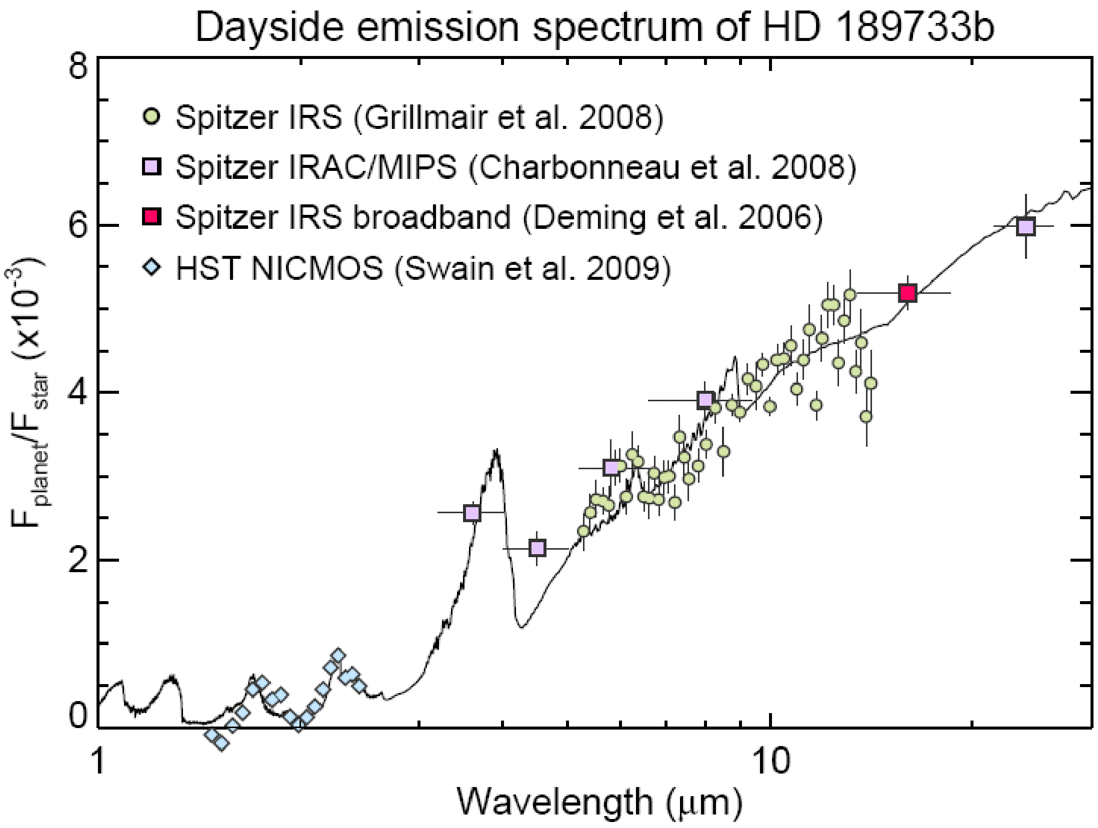


Grillmair et al. 2008



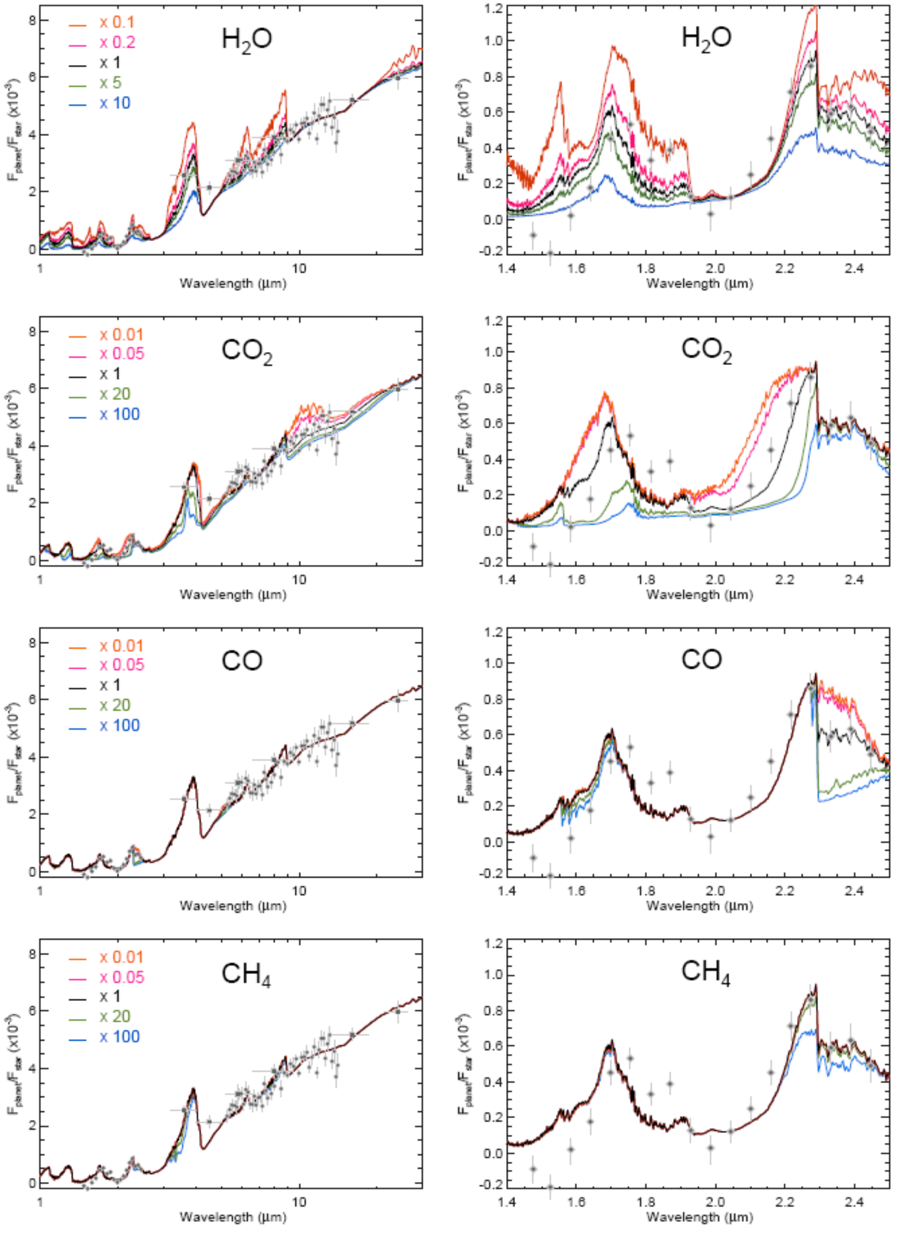
Madhusudhan & Seager 2009

Dayside emission spectrum of HD 189733b



Best-fitted spectrum to available observations (Spitzer and HST)

Dayside emission spectrum of HD 189733b



Fisher-test *(Ockham's razor)*
Does addition of molecules really increase fitting quality?

H_2O + CO_2 (simple model) vs.
H_2O + CO_2 + CO + CH_4 (complex model, confidence levels <<95%)

Enough CO & CH_4 information not provided by the given datasets

Dayside emission spectrum of HD 189733b

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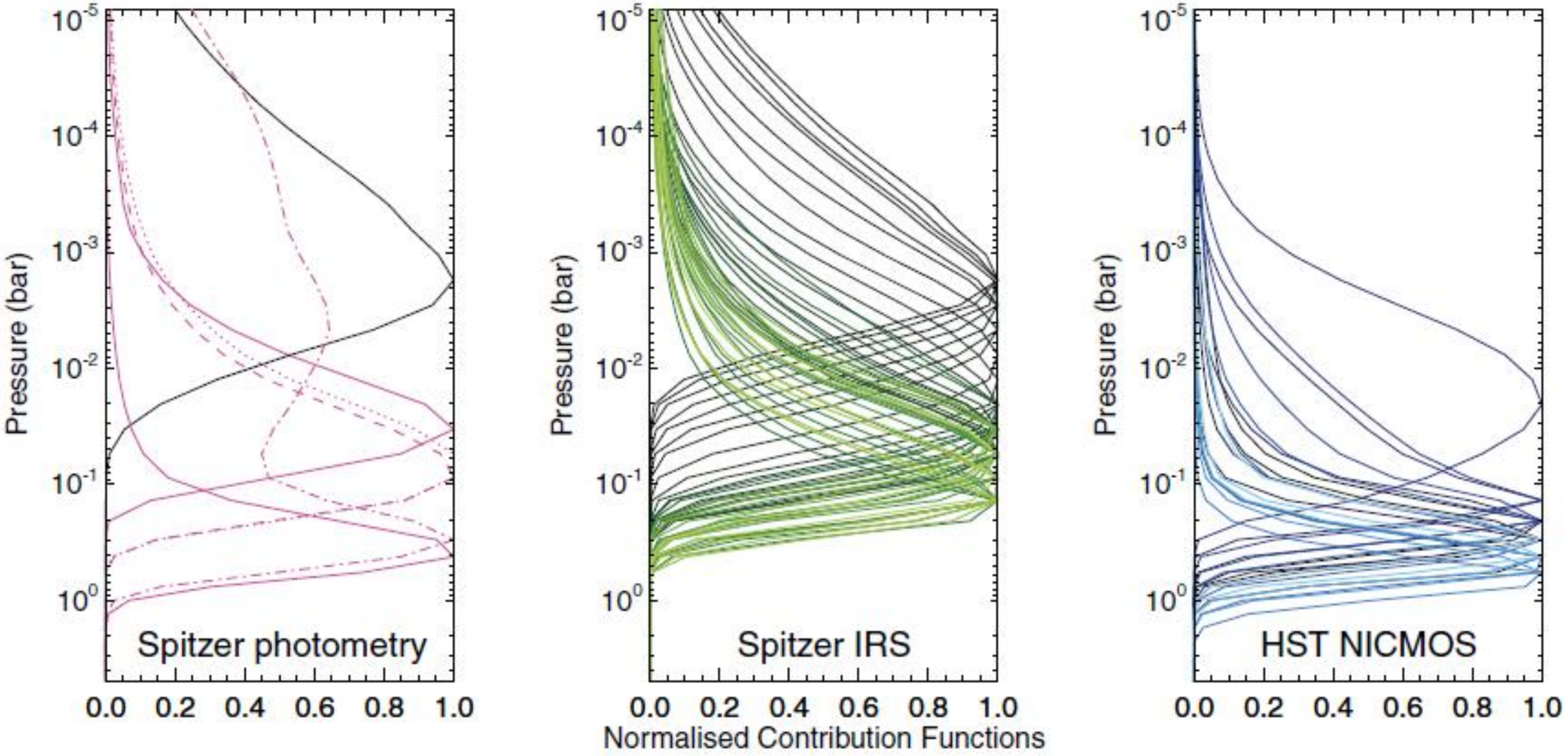
Contribution functions



Temperature profile can be constrained
between 2-600 mbar where the contribution functions cover

Dayside emission spectrum of HD 189733b

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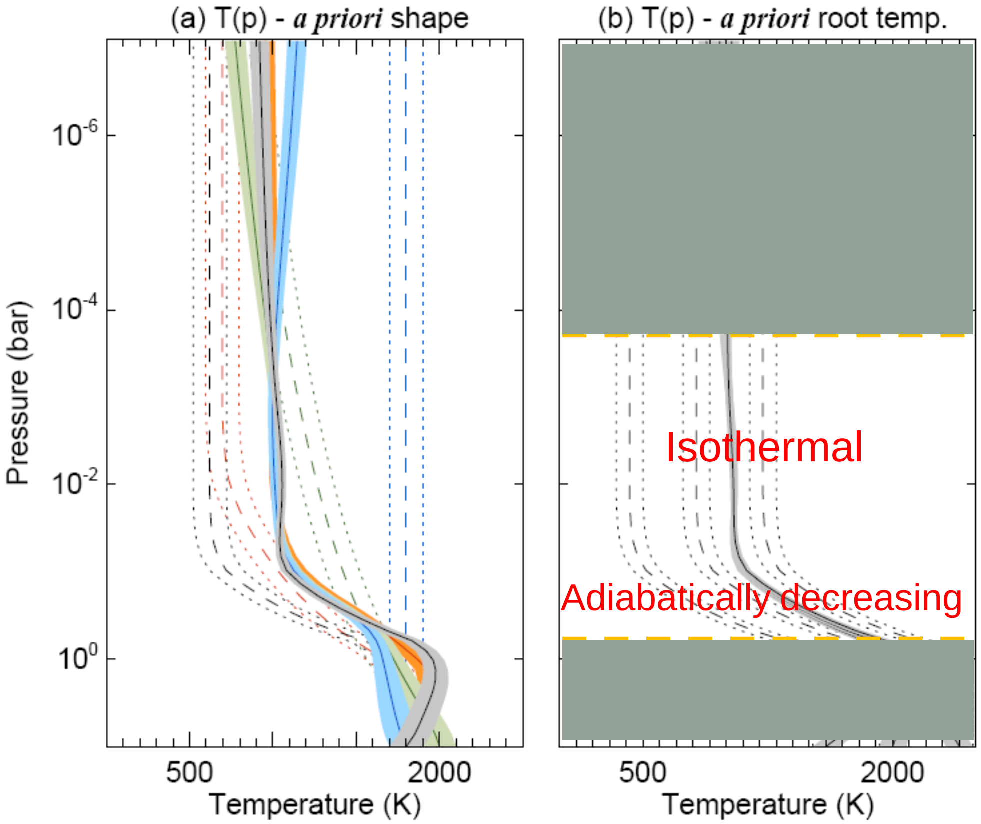
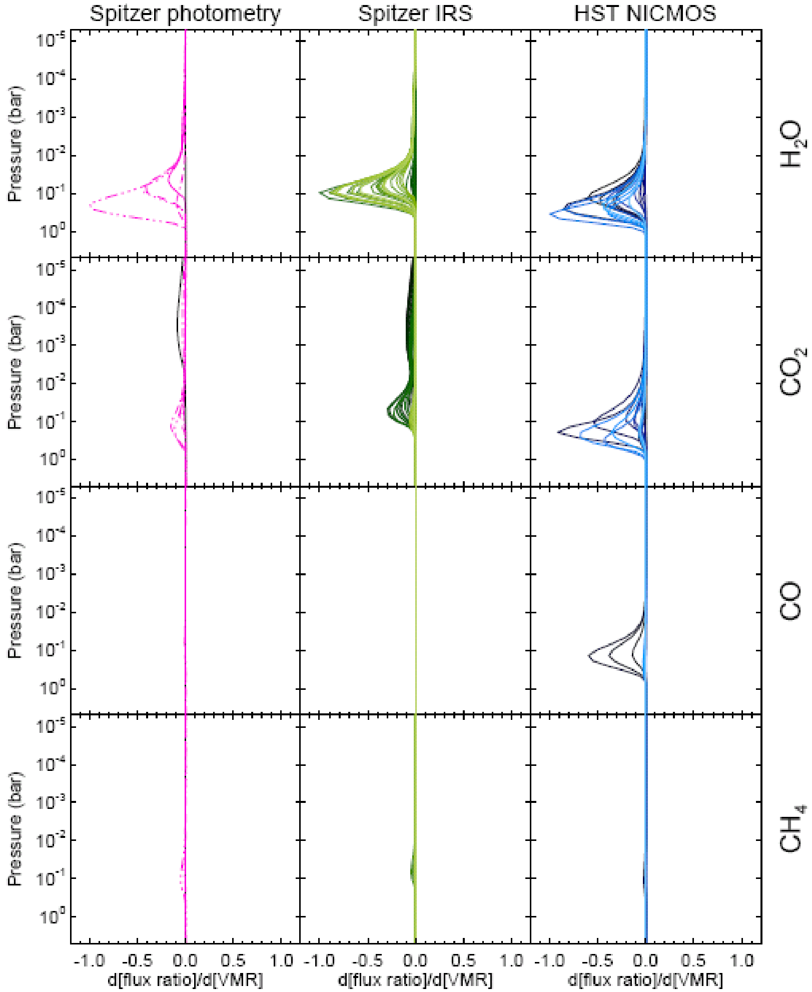
Retrieved temperature profile



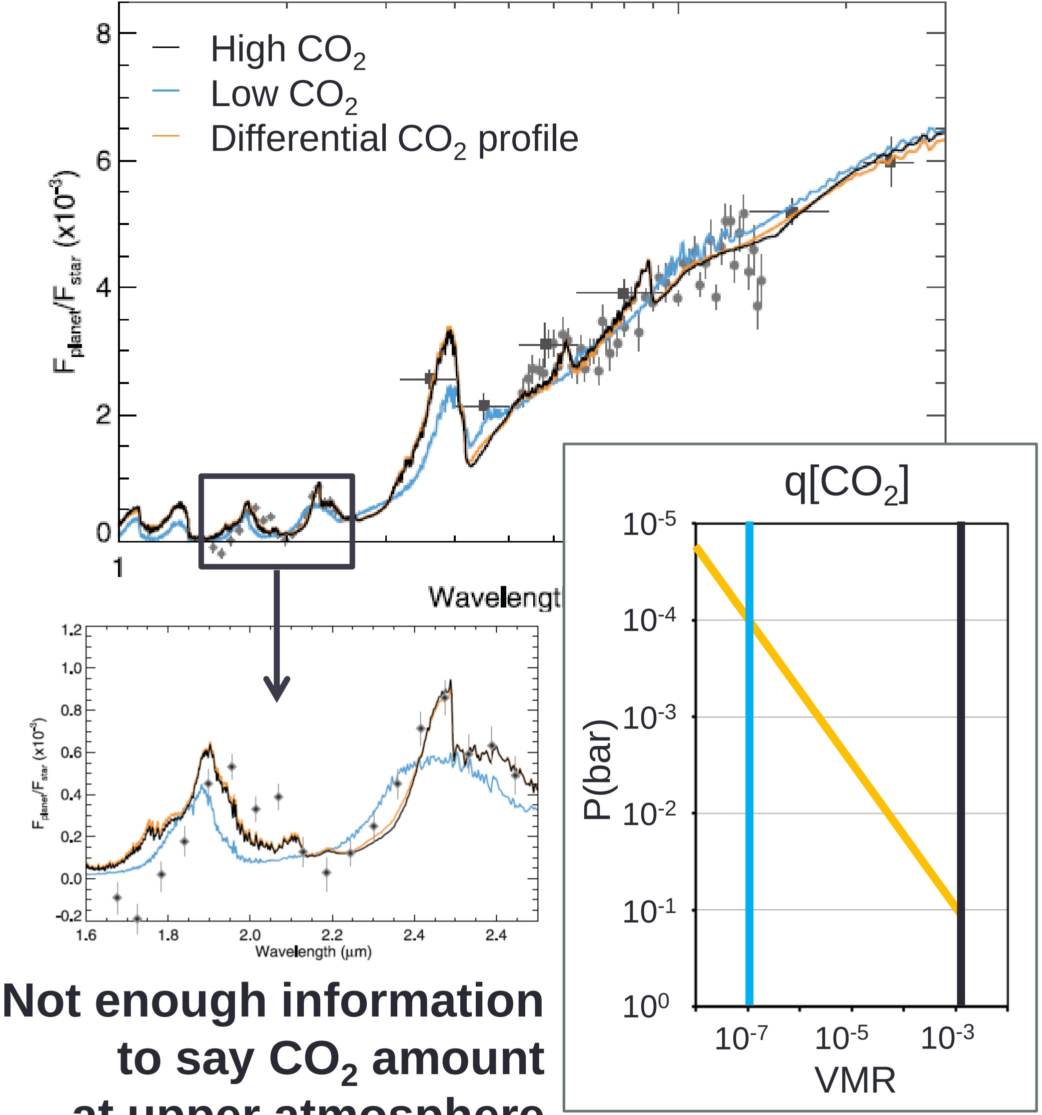
Temperature profile can be constrained
between 2-600 mbar where the contribution functions cover

Dayside emission spectrum of HD 189733b

Sensitivity (Functional derivatives)



CO_2 sensitivity



Not enough information to say CO_2 amount at upper atmosphere

Dayside emission spectrum of HD 189733b

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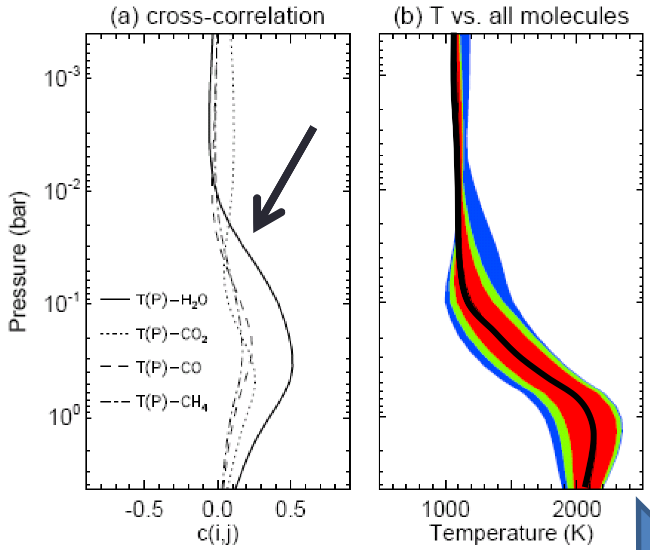
Characterzing degeneracy

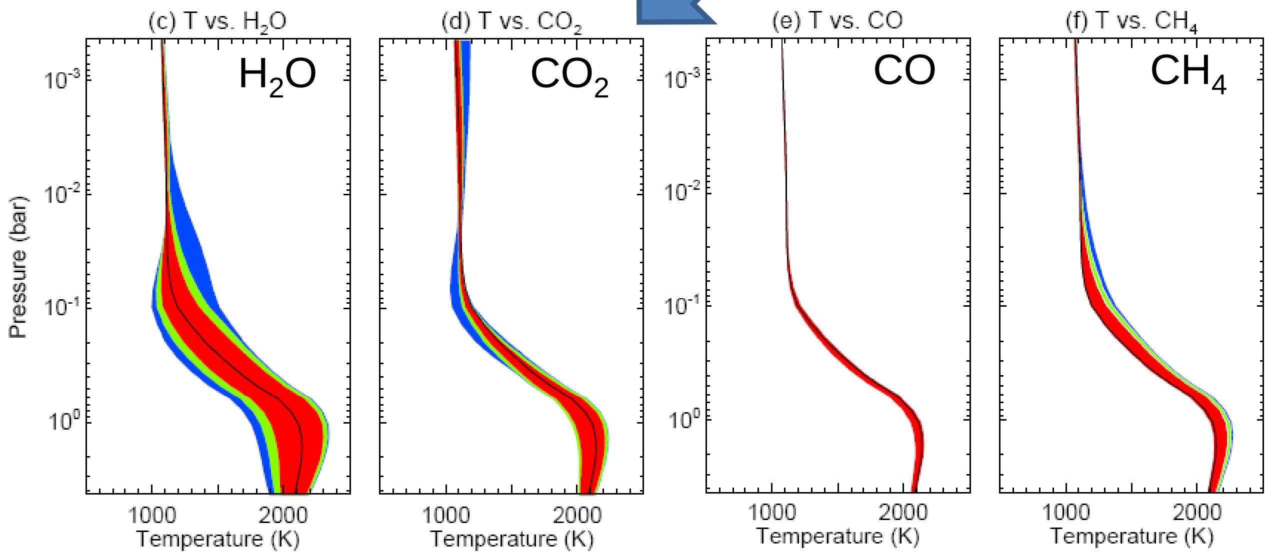


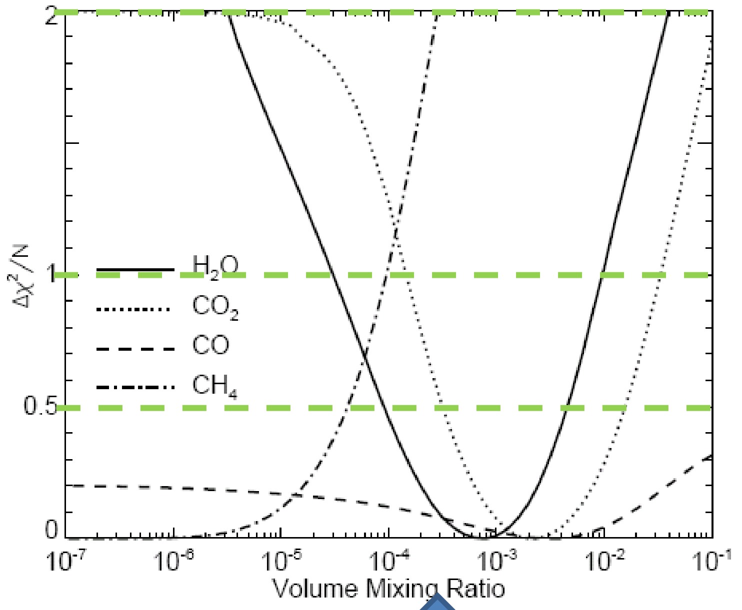
Cross-correlation

$= S_{ij} / (S_{ii} \times S_{jj})^{1/2}$

Temperature Degeneracy

The retrieved P-T profiles with various mixing ratios are presented with $\Delta\chi^2/N$<0.5(red), <1.0(green), <2.0(blue), respectively.

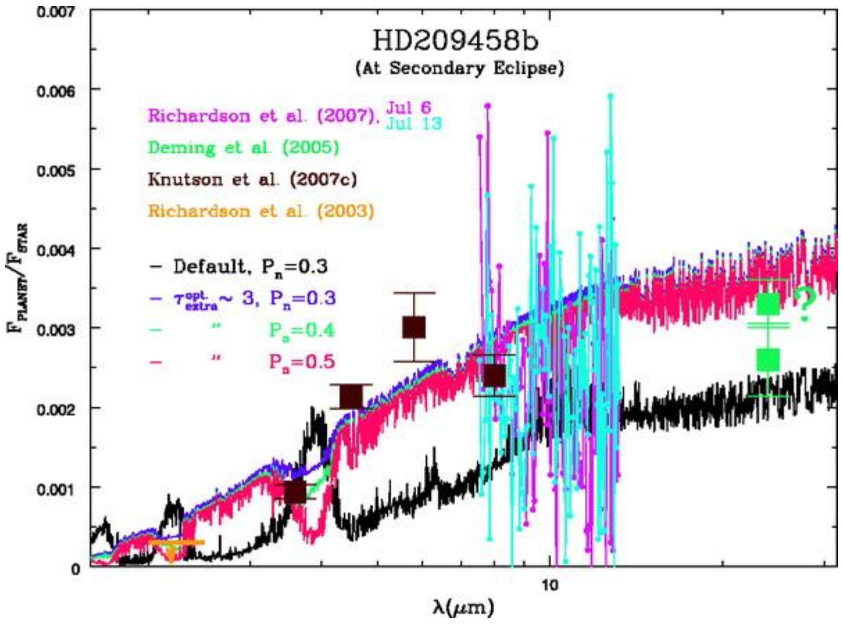




Molecular Degeneracy

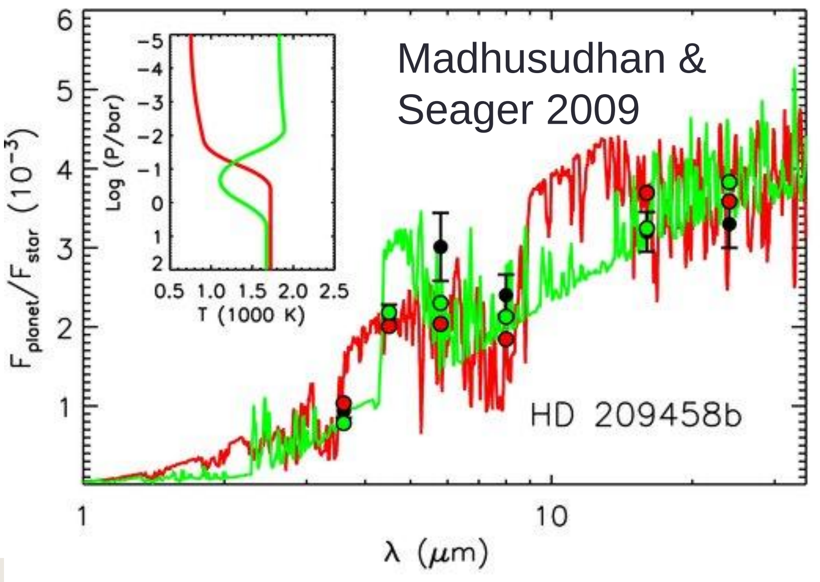
Each line shows resultant χ^2/N with respect to given abundances. Lower bounds of CO and CH_4 uncertainties are unconstrained because of their low contribution to the spectrum.

Dayside emission spectrum of HD 209458b

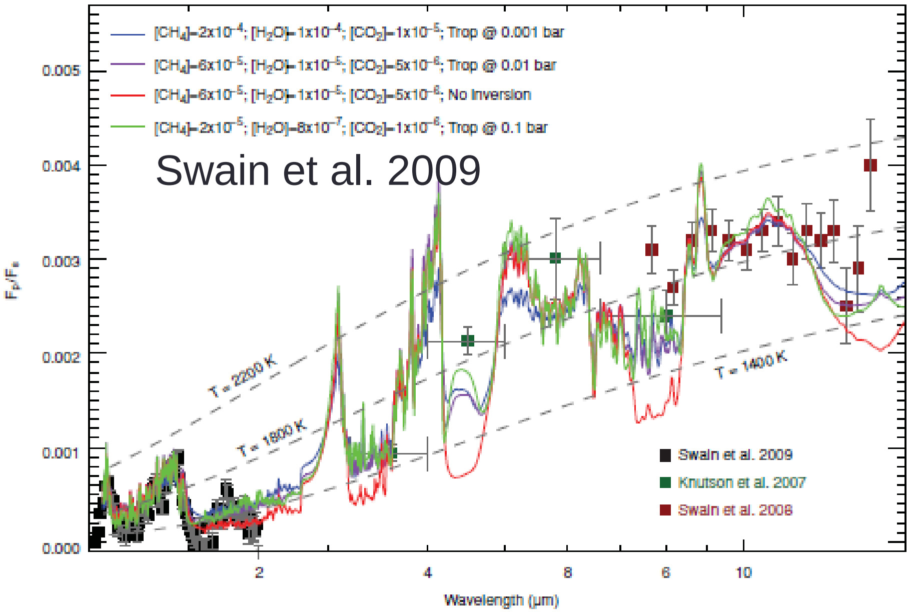


Major findings

- *Temperature Inversion?*
- *High C/O?*



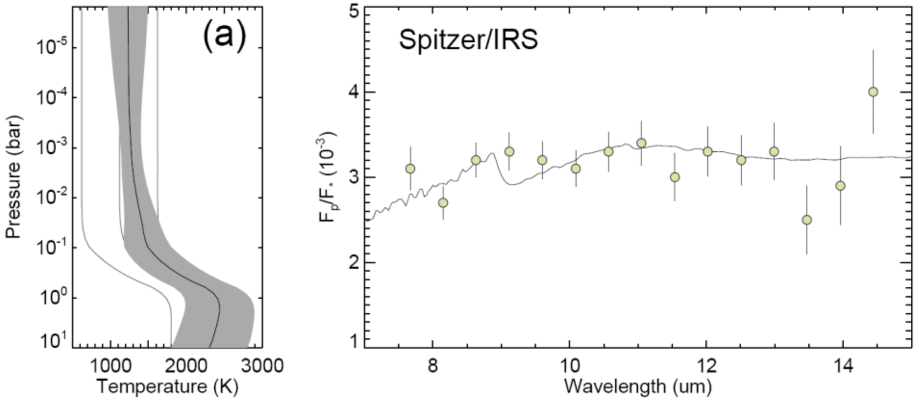
Madhusudhan & Seager 2009



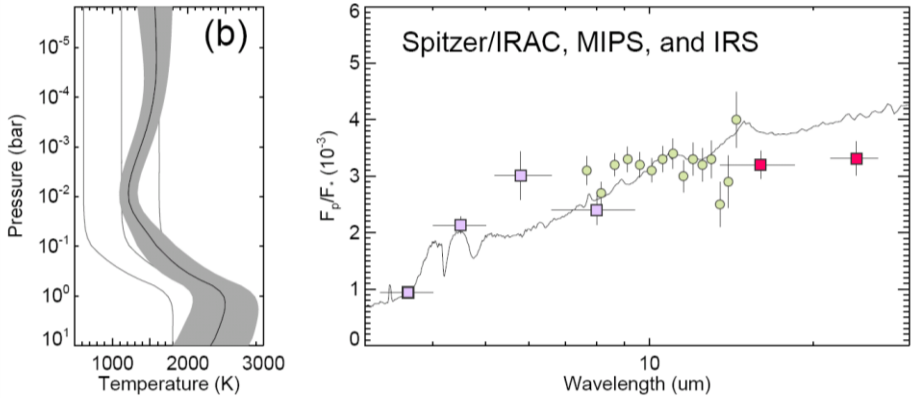
Swain et al. 2009

Dayside emission spectrum of HD 209458b

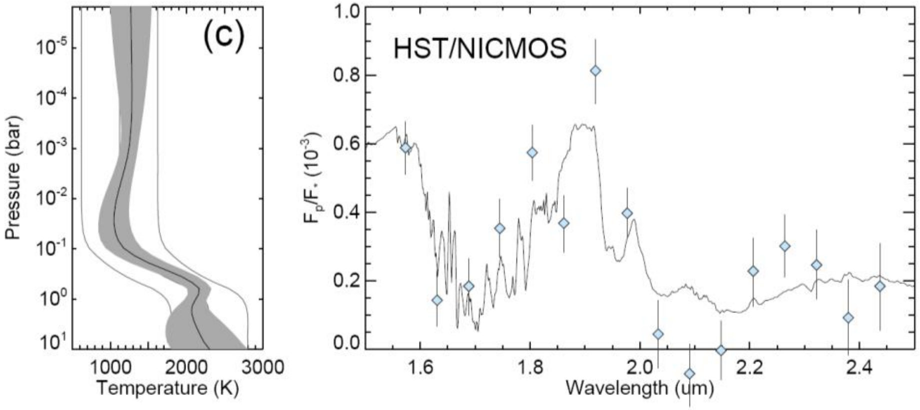
Retrievals using each measurement



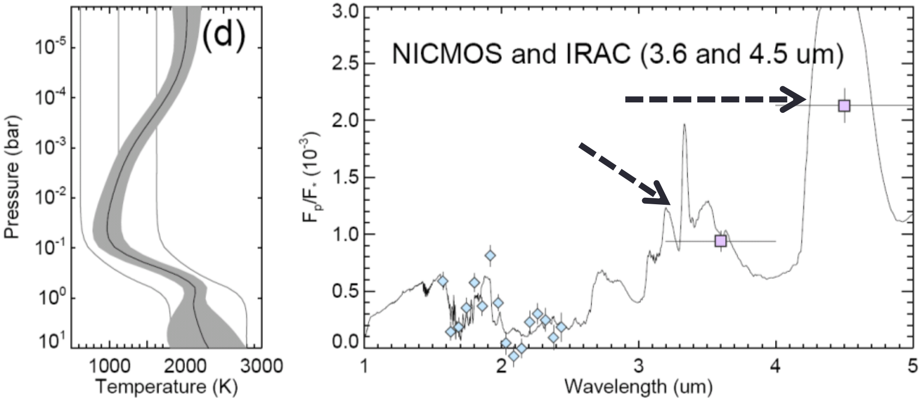
featureless, no specific T feature required



inversion? poor fit for IRAC3 & MIPS



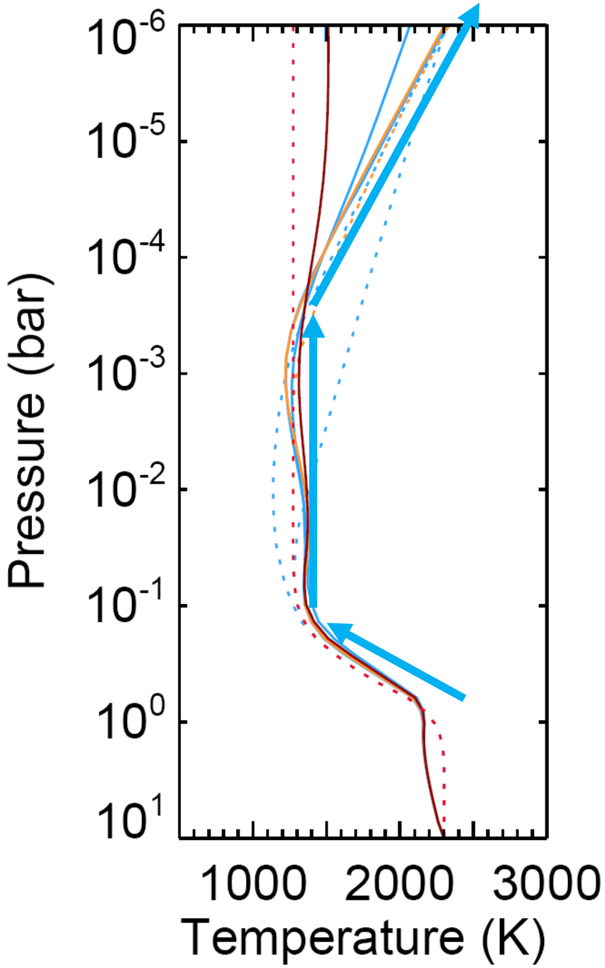
decreasing T in troposphere required

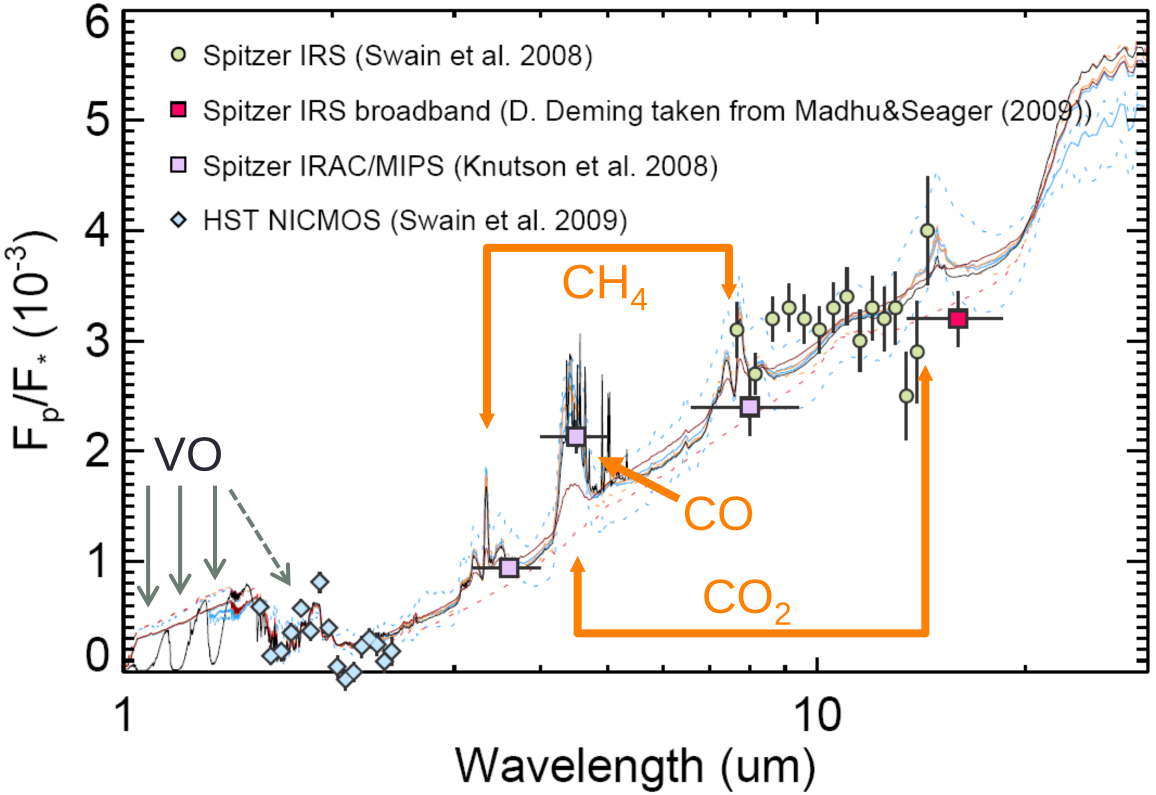


decreasing T in troposphere required,
inversion at upper atmosphere [CO_2+CH_4]

Dayside emission spectrum of HD 209458b

Retrievals except IRAC3 & MIPS

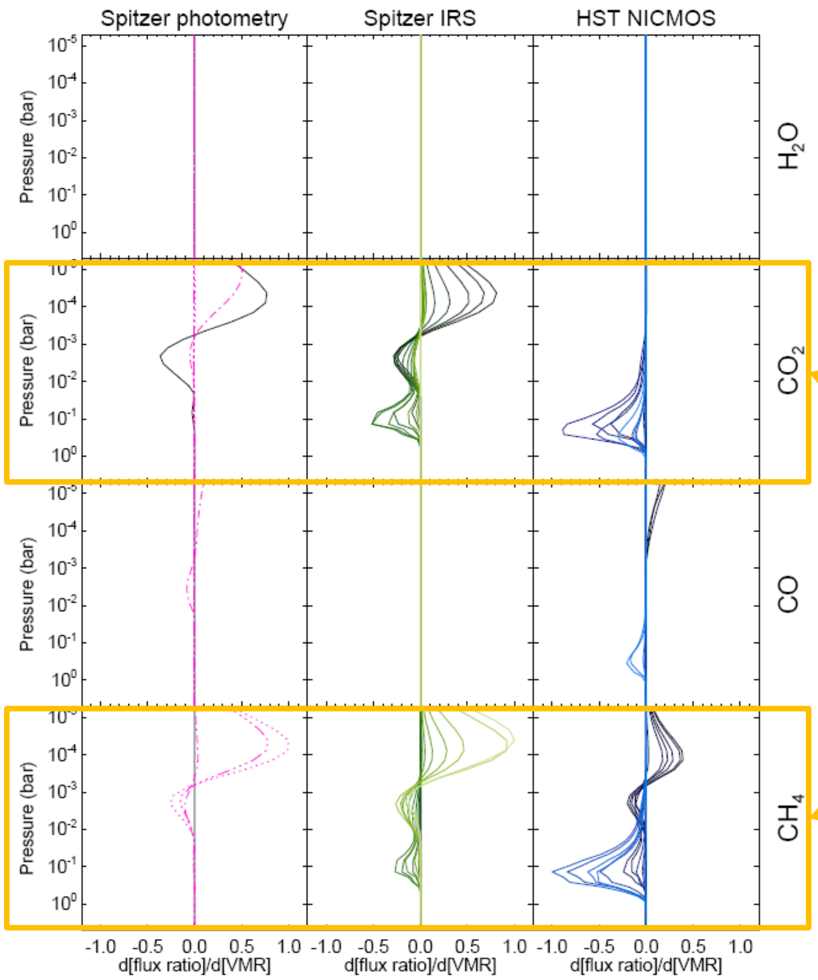




- ***T inversion at upper atmosphere***
- ***High CO_2 & CH_4 emission from upper atmosphere***
- ***Slight fitting quality improvement by VO at NIR***

Dayside emission spectrum of HD 209458b

Sensitivity

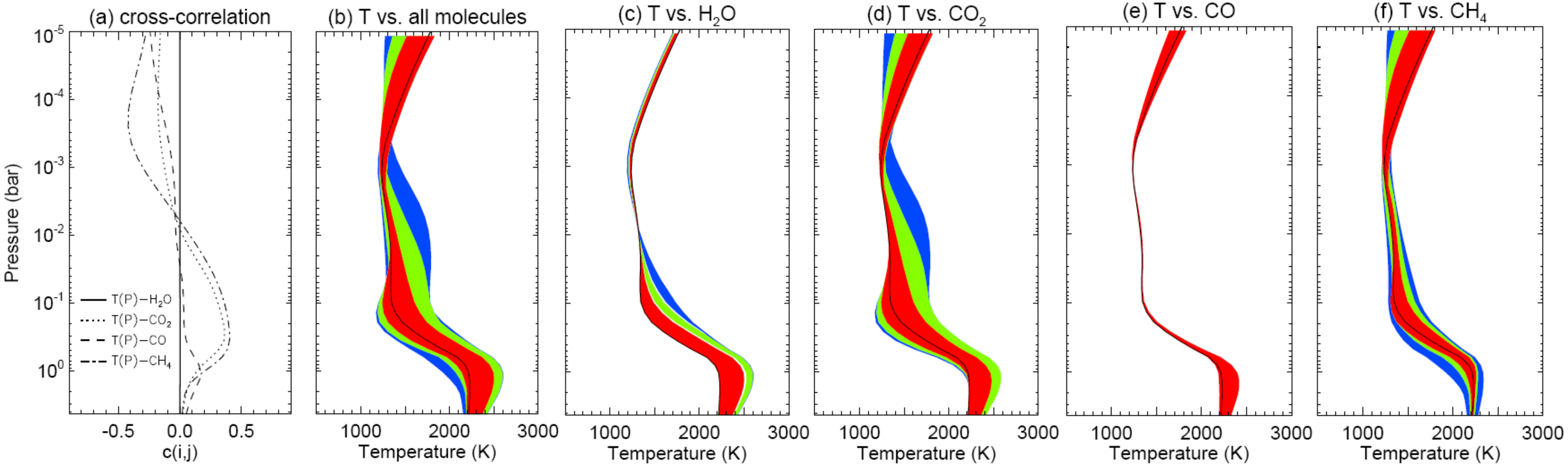


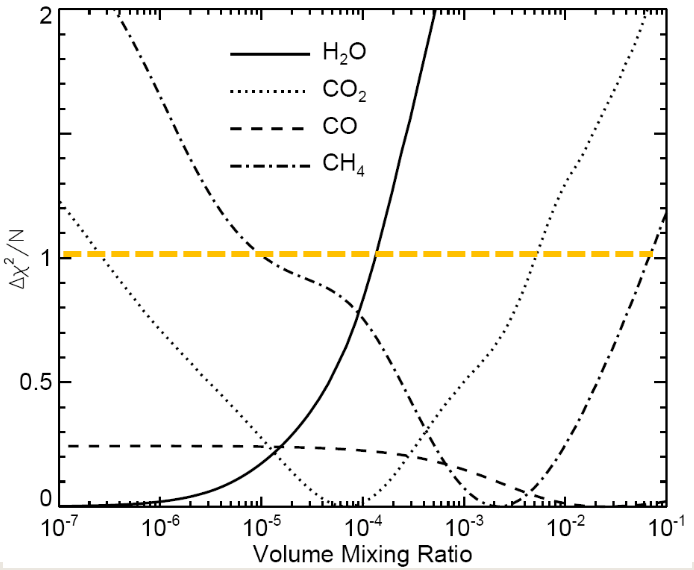
CO_2 and CH_4

absorption at lower atmosphere

emission at upper atmosphere

Dayside emission spectrum of HD 209458b





Molecular degeneracy

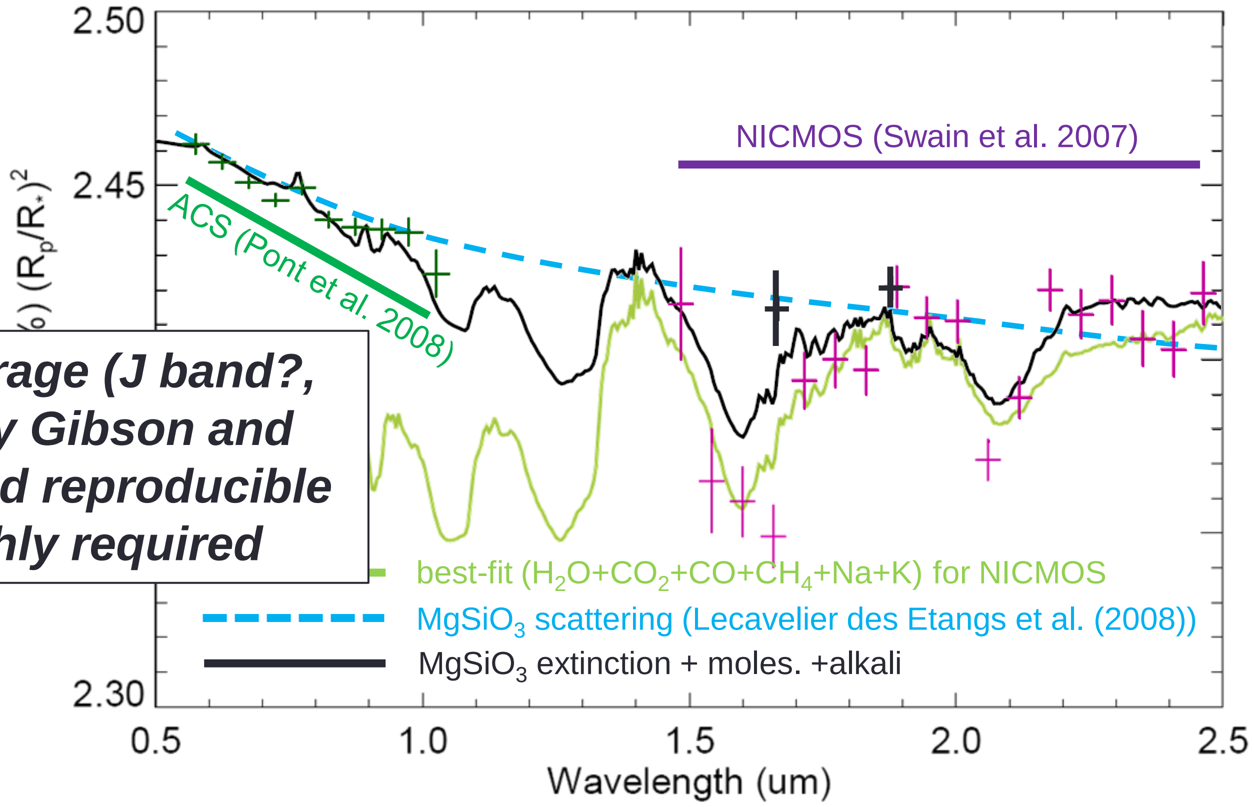
H_2O	$<1.5\text{X}10^{-4}$
CO_2	$3\text{X}10^{-7} \sim 5\text{X}10^{-3}$
CO	-
CH_4	$10^{-5} \sim 7\text{X}10^{-2}$
C/O	>>1

So… Can we suggest high C/O ratio & T inversion in HD 209458b ?

Possibly, but we need more data

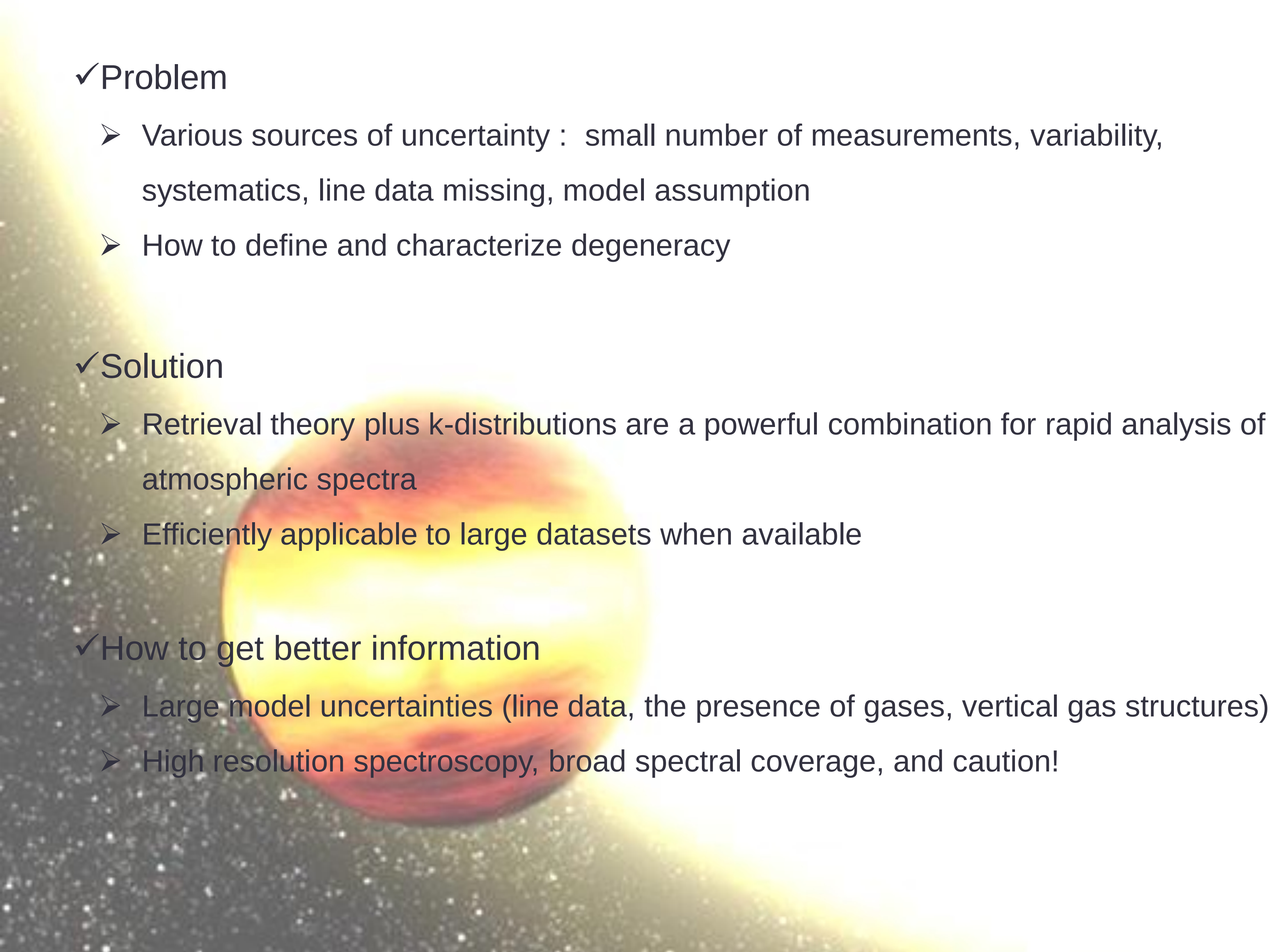
Transmission spectrum of HD 189733b

- HST/NICMOS (Swain et al. 2008) : mostly by H_2O + CH_4
- HST/ACS spectrum (Pont et al. 2008) : Rayleigh scattering by $MgSiO_3$
- ***Or extinction effect by haze/cloud?***



More coverage (J band?, posters by Gibson and Husnoo) and reproducible data highly required

Conclusions



✓Problem

- Various sources of uncertainty : small number of measurements, variability, systematics, line data missing, model assumption
- How to define and characterize degeneracy

✓Solution

- Retrieval theory plus k-distributions are a powerful combination for rapid analysis of atmospheric spectra
- Efficiently applicable to large datasets when available

✓How to get better information

- Large model uncertainties (line data, the presence of gases, vertical gas structures)
- High resolution spectroscopy, broad spectral coverage, and caution!