



# Atmospheric retrieval for the ARIEL spectral database

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## Aim of retrieval

- Derive the atmospheric composition from the ARIEL spectra
  - 1) molecular abundances
  - 2) elemental abundances
  - 3) thermal structure of the atmosphere
- The retrieval is always right (your question might be irrelevant though...)
  - Retrieval answers the question:

What is the best set of parameters - and the accompanying uncertainty - representing the data given all the assumptions in the forward model?

What are the exact physical parameters of the system observed?

Sometimes it feels like....



This is the retrieval giving us the answer 42



This is us thinking about what the real question actually was. Using:

- Complex disequilibrium chemistry
- GCM modelling
- Cloud formation models

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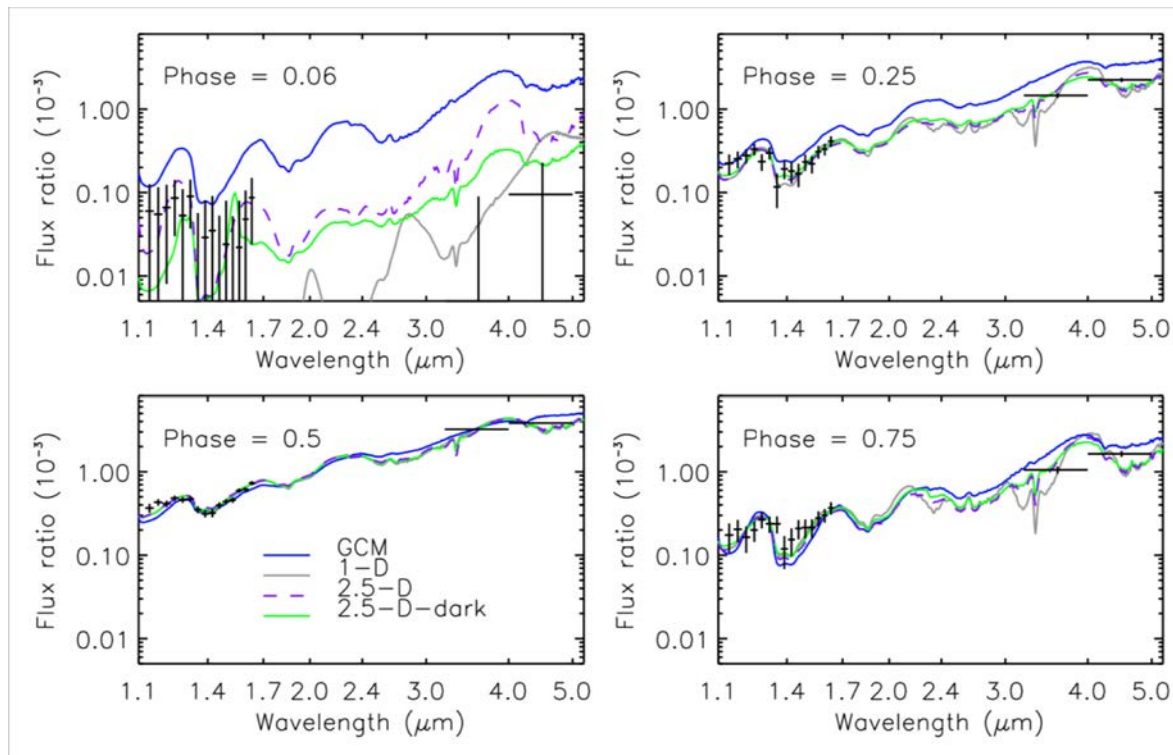
What are the exact physical parameters of the system observed?

TauREx, NEMESIS, ARCiS

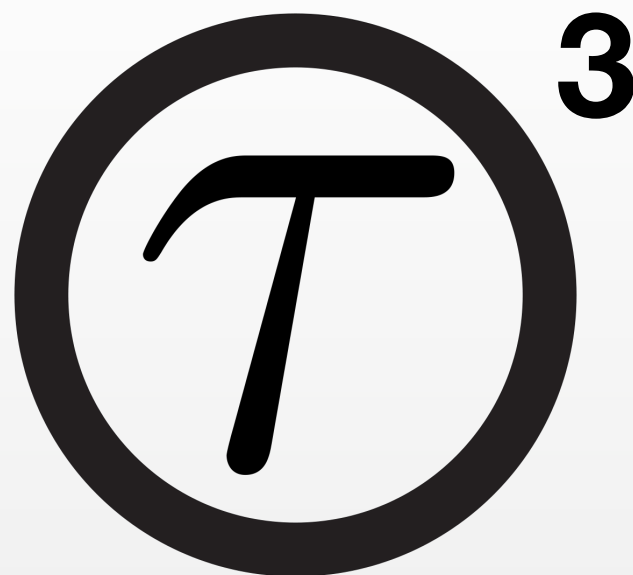
# RETRIEVAL CODES USED

# NEMESIS

- Correlated-k approximation for opacities
- Either nested sampling or optimal estimation
- Not linked to thermal or chemical equilibrium models so free retrieval
- Includes multiple scattering and reflected light
- Suitable for Solar System objects -> brown dwarfs
- 2.5D retrieval mode for simultaneous retrieval of phase curve observations



Irwin et al. (2019)



TauREx 3



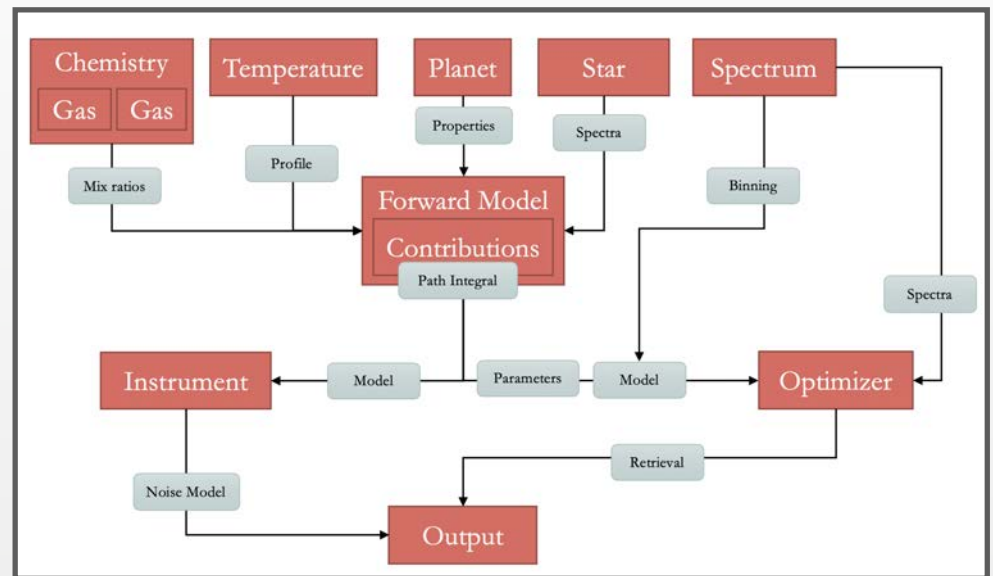
Horizon 2020



Science & Technology  
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# TauREx 3

- Built from the ground up as full python stack
- 10 - 200 times faster than TauREx 2
- Fully tested against TauREx 2 which has been benchmarked against NEMESIS, CHIMERA, ARCIS
- For full installation type: “pip install taurex”
- Plugin features and TauREx extensions
- New and fast cross sections
- Fully open under BSD license



Al-Rafaie et al. arXiv: 1912:07759



# Ultra-Fast retrievals

- TauREx 3 was built for speed. 10 to >100 times faster than TauREx 2.
- Fully Python 3.x but achieves speeds of compiled languages like C
- Uses JIT compilation of forward models with Numba
- Full use of numpy vectorisation and numexpr for faster numpy operations
- TauREx 3.1 includes full GPU support -> No more performance loss for JWST wavelengths and large line-by-line retrievals

	TauREx 2	TauREx 3
R	xsec (s)	xsec (s)
7000	0.57	0.039
10000	0.85	0.062
15000	1.02	0.092

	TauREx 2	TauREx 2	TauREx 3
Molecules	xsec (s)	k-tables (s)	xsec (s)
1	7.23	0.45	0.61
2	8.90	0.78	0.74
4	12.42	1.49	0.92
7	19.02	2.63	1.23
15	263.56	8.21	2.34

	TauREx 2	TauREx 2	TauREx 3
Layers	xsec (s)	k-tables (s)	xsec (s)
50	2.24	0.20	0.24
100	8.60	0.79	0.62
150	19.29	1.81	1.53
200	35.53	3.04	2.29
600	876.24	28.90	15.35

Al-Rafaie et al. arXiv: 1912:07759




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ExoClouds - ARCiS

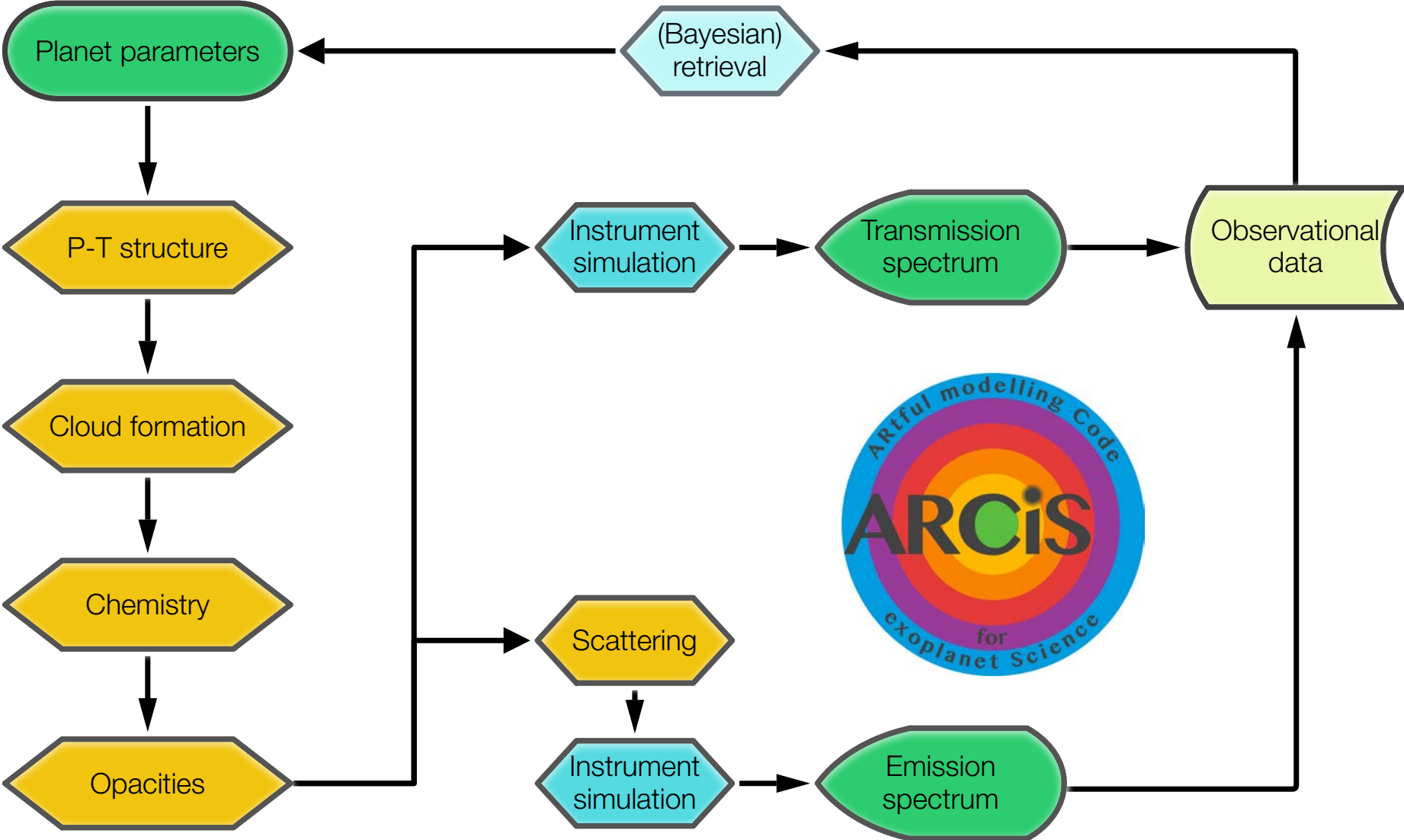
HOME SOFTWARE PUBLICATIONS CONTRIBUTORS

artful modelling of cloudy exoplanet atmospheres

### ARCiS tools

-  **Cloud Transport model**  
Python module for computing cloud structures [More](#)
-  **OpacityTool**  
Compute DIANA standard opacities [More](#)
-  **ARCiS**  
The ARTful modelling Code for exoplanet Science [More](#)

# ARCiS scheme



## Opacities for exoplanet atmospheres

Cross-sections ( $R=15,000$ )  
and k-tables ( $R=1000$ )

All molecules in ExoMol database  
+ HITEMP + MOLLIST (80+ molecules)

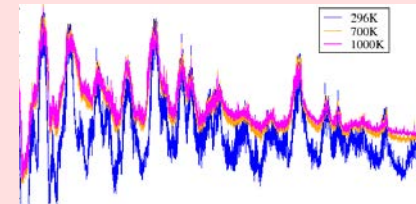
Retrieval codes:  
ARCIS (k-tables), TauREx (xsecs),  
NEMESIS (k-tables,  
petitRADTRANS (k-tables)

Available soon on [www.exomol.com](http://www.exomol.com)

22 pressures

27 temperatures

594 T/P points / molecule



Chubb, · Rocchetto, · Yurchenko, · Min, Waldmann, · Barstow, · Mollière, Al-Refaie,  
· Tennyson (In prep)

# ARIEL retrieval challenge

ariel-datachallenge.azurewebsites.net

DrayTek Save to Mendeley Exoplanet data ■ ARIEL Livelink Sing 2016 data Intranet PLATO-Office Refractive index GroupWise ERC login OurGroceries › Inloggen ADS Google >> +

Ariel Atmospheric Retrieval Challenge About Download Upload Retrievals Current Results Documentation Login Sign Up

**ARIEL SPACE MISSION**  
European Space Agency M4 Mission

**Ariel Atmospheric Retrieval Challenge**

Welcome to the Ariel Atmospheric Retrieval Challenge. The Ariel Space mission is a European Space Agency mission to be launched in 2028. Ariel will observe the atmospheres of 1000 extrasolar planets - planets around other stars - to determine how they are made, how they evolve and how to put our own Solar System in the galactic context.

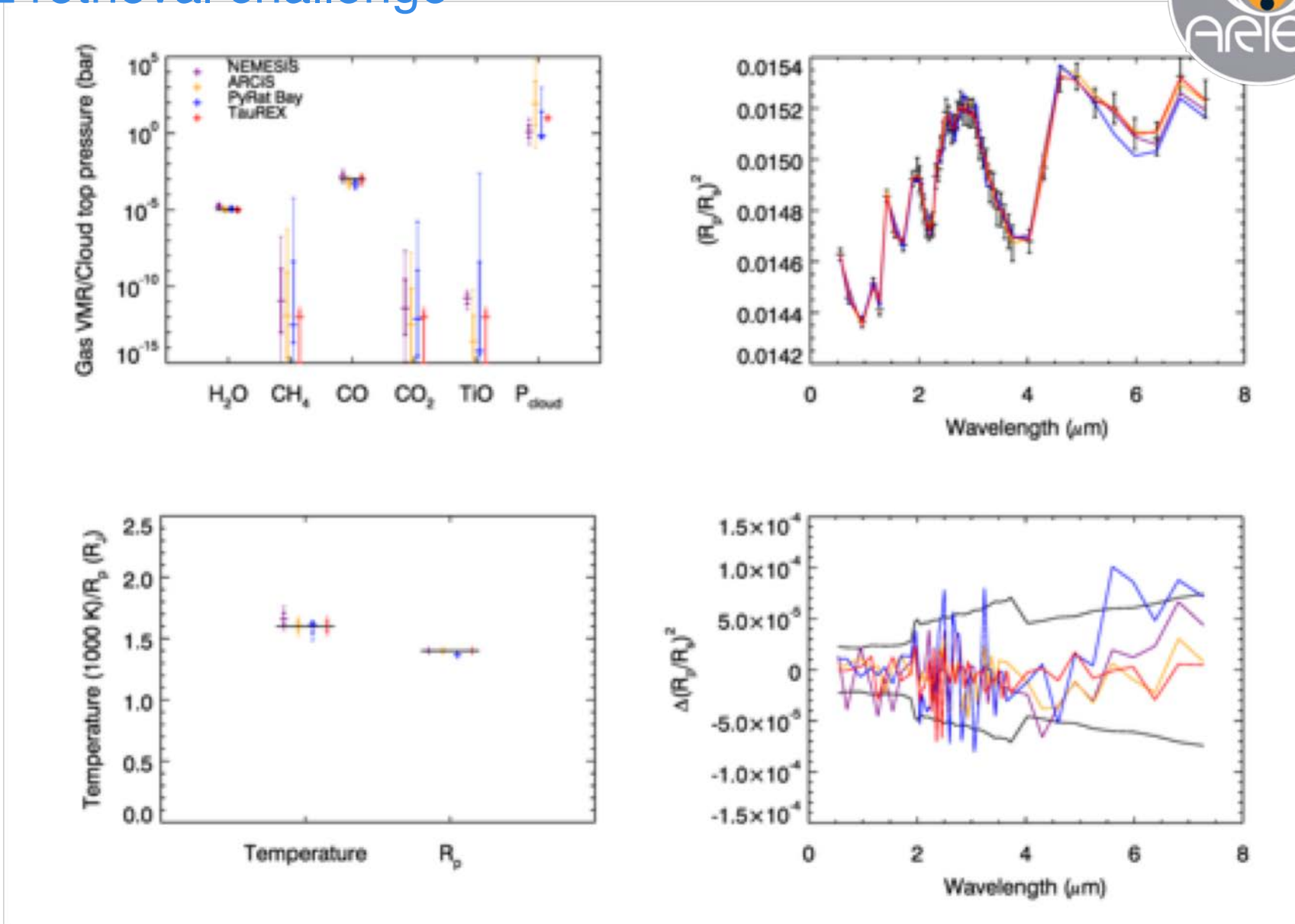
### Atmospheric Retrievals

In preparation to the Ariel Red Book, we run this atmospheric retrieval challenge as a conduit to conduct forward model comparison as well as full retrieval comparison. The retrieval challenge will be run in 2 stages. The first stage will entail relatively simple model/retrieval comparisons. Stage 2 will entail a range of forward models in varying complexity. Each participant will be scored on the accuracy of their retrievals and their forward models. For more



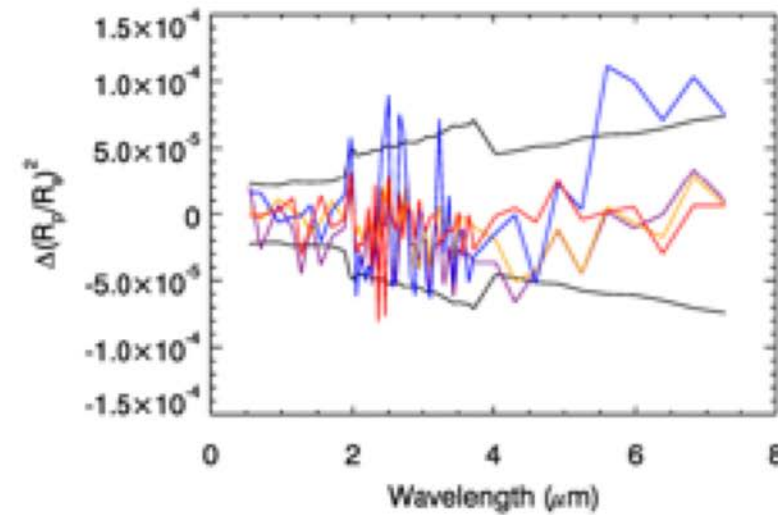
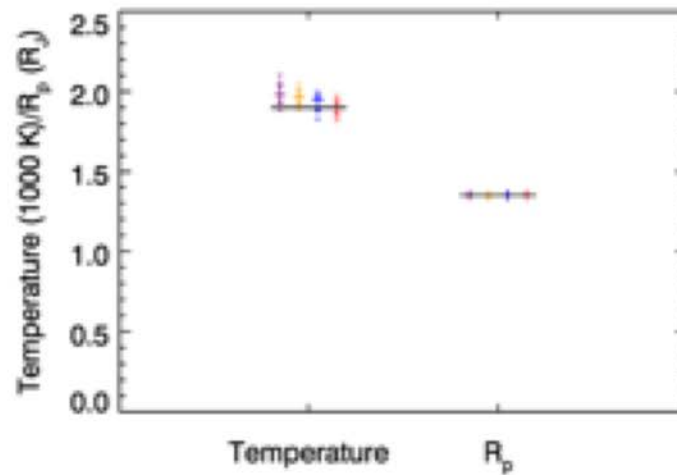
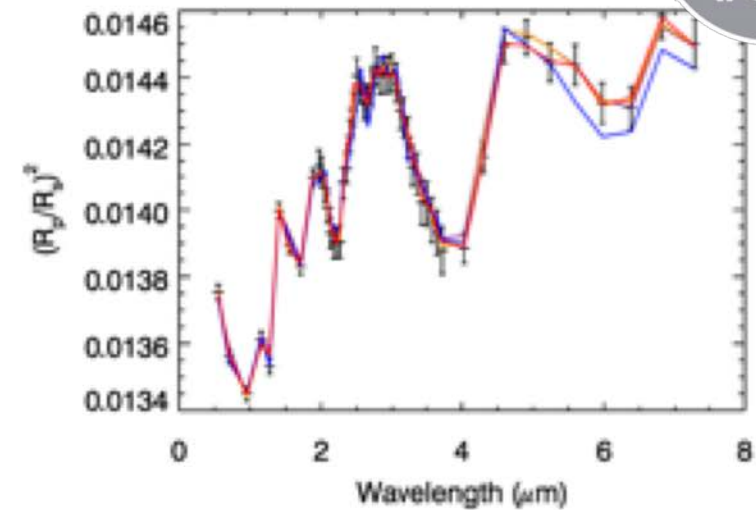
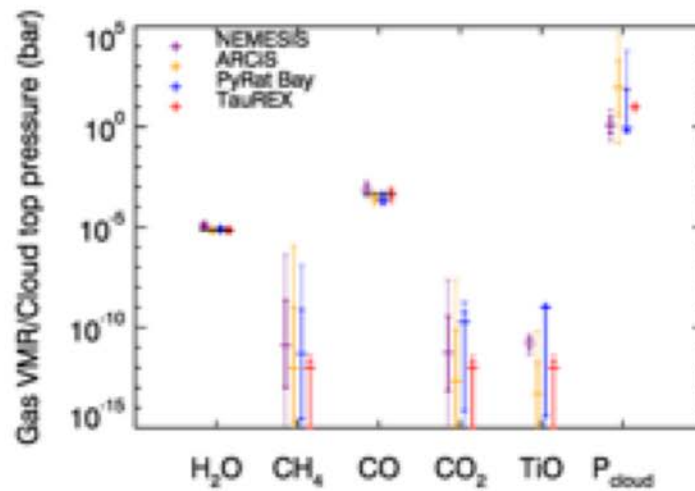


# ARIEL retrieval challenge



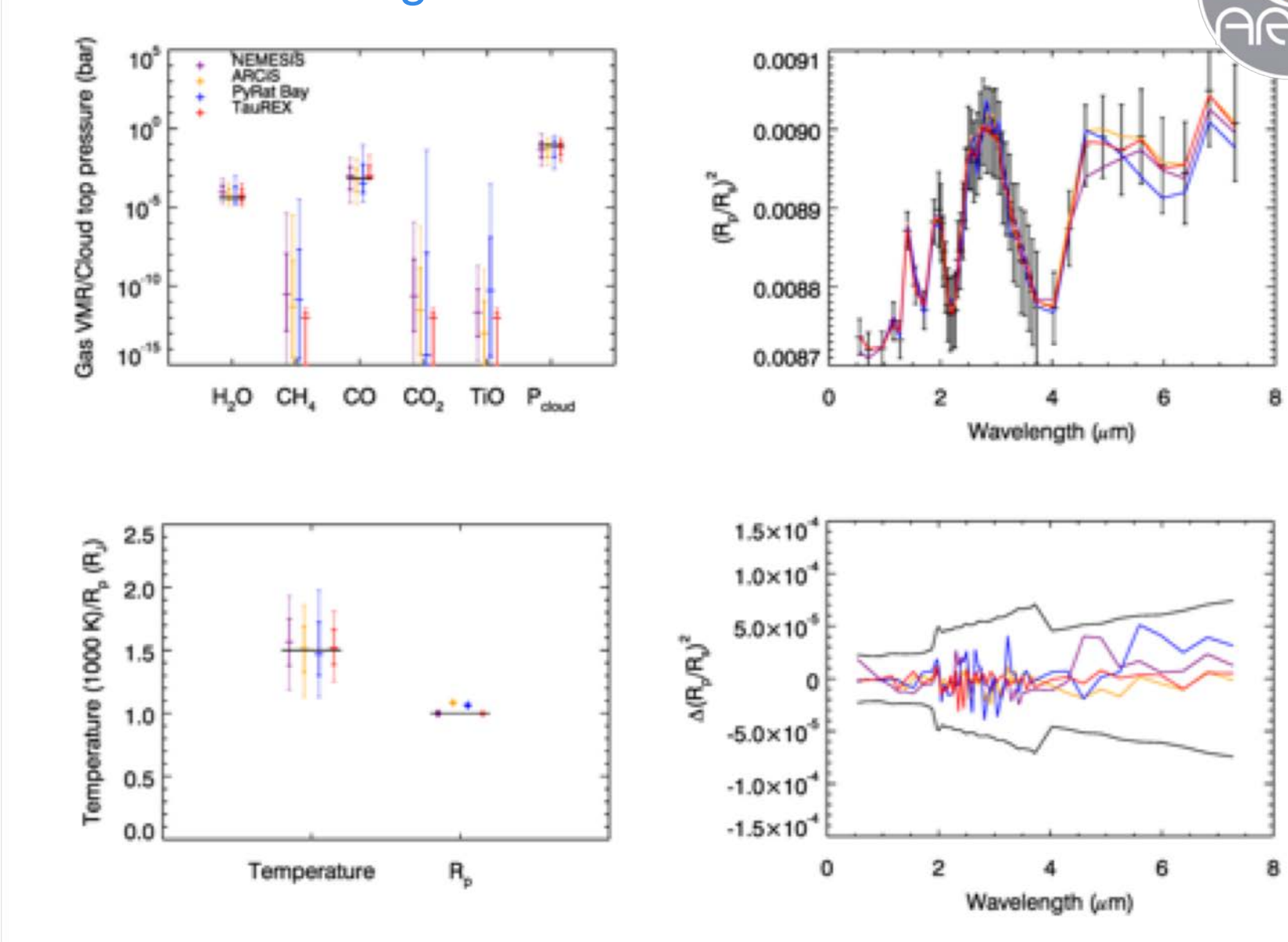


# ARIEL retrieval challenge





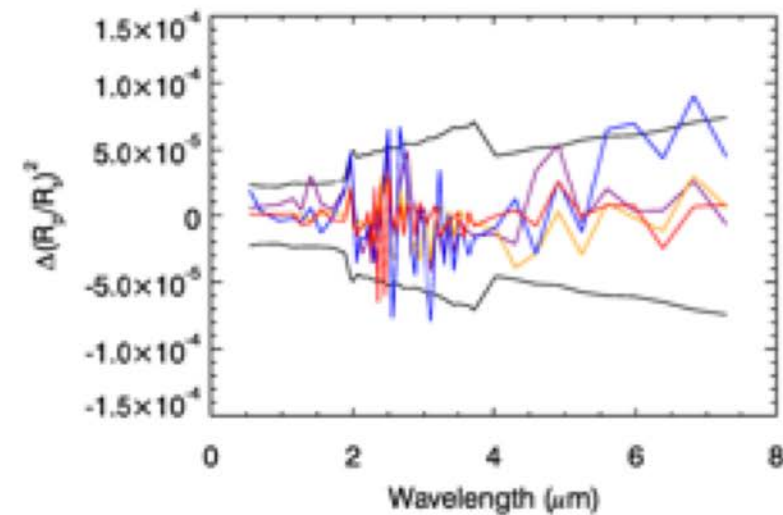
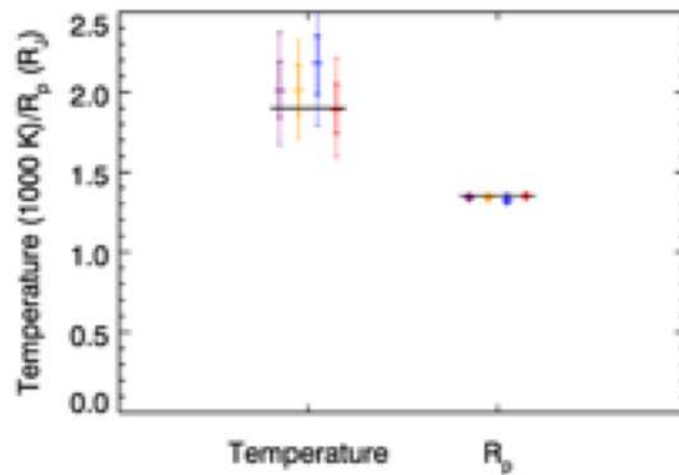
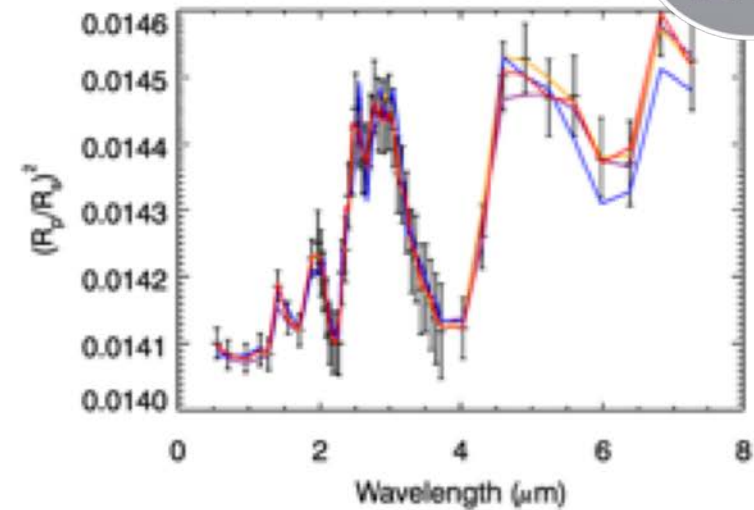
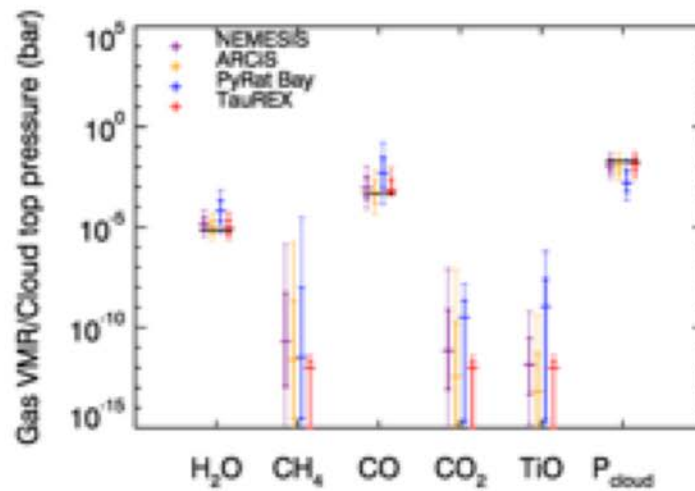
# ARIEL retrieval challenge





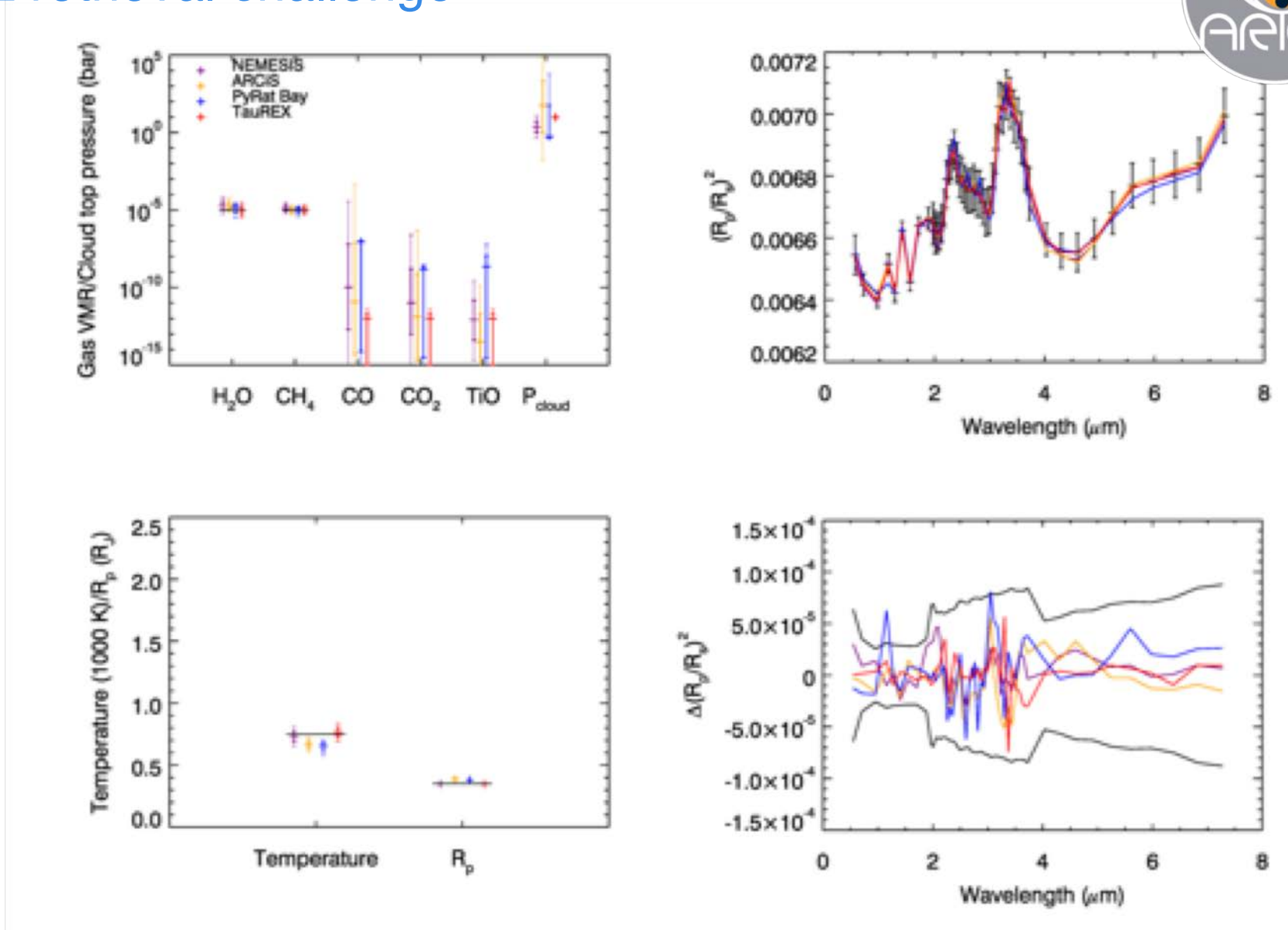


# ARIEL retrieval challenge



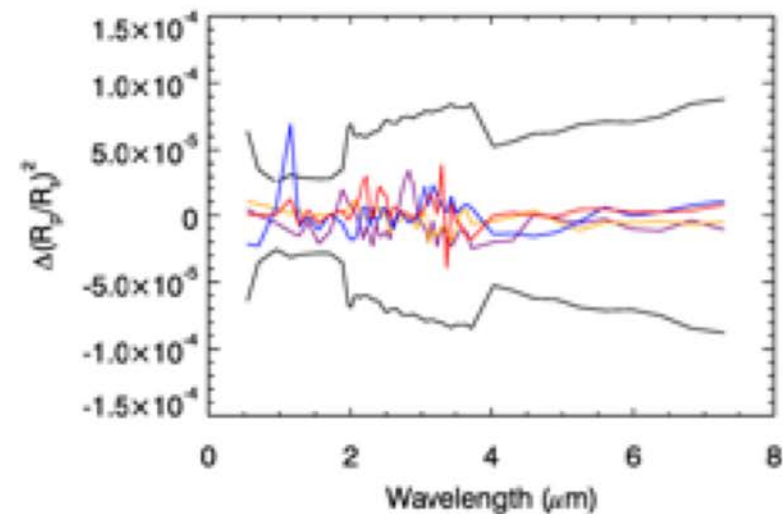
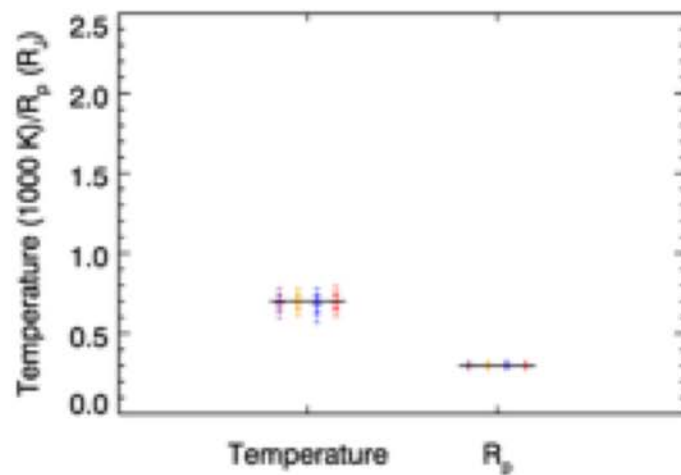
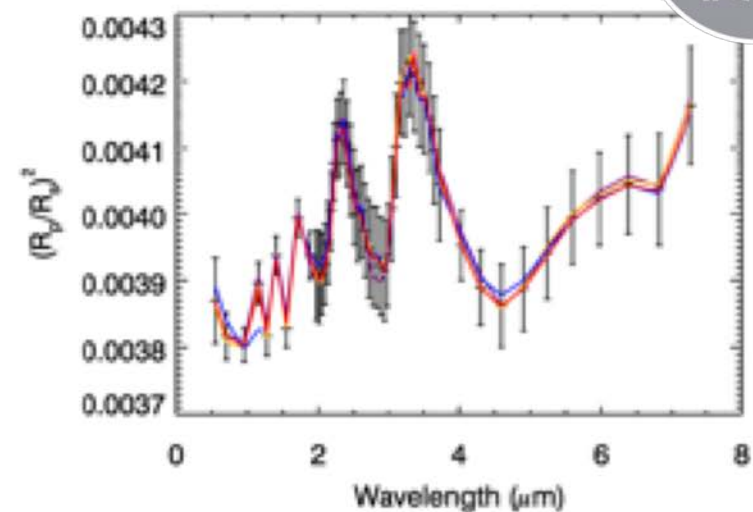
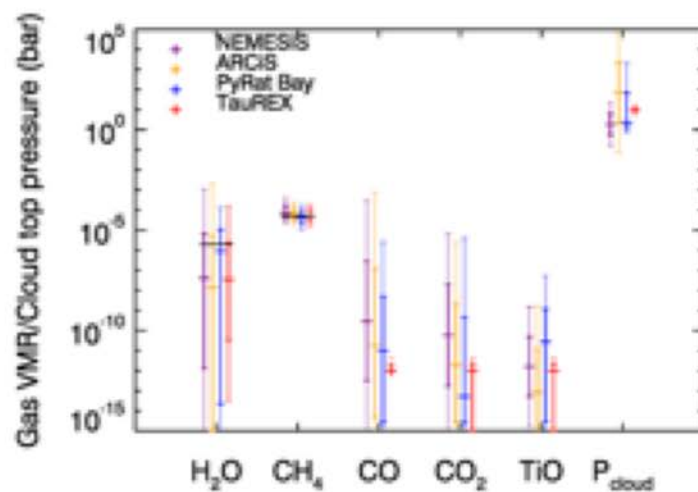


# ARIEL retrieval challenge



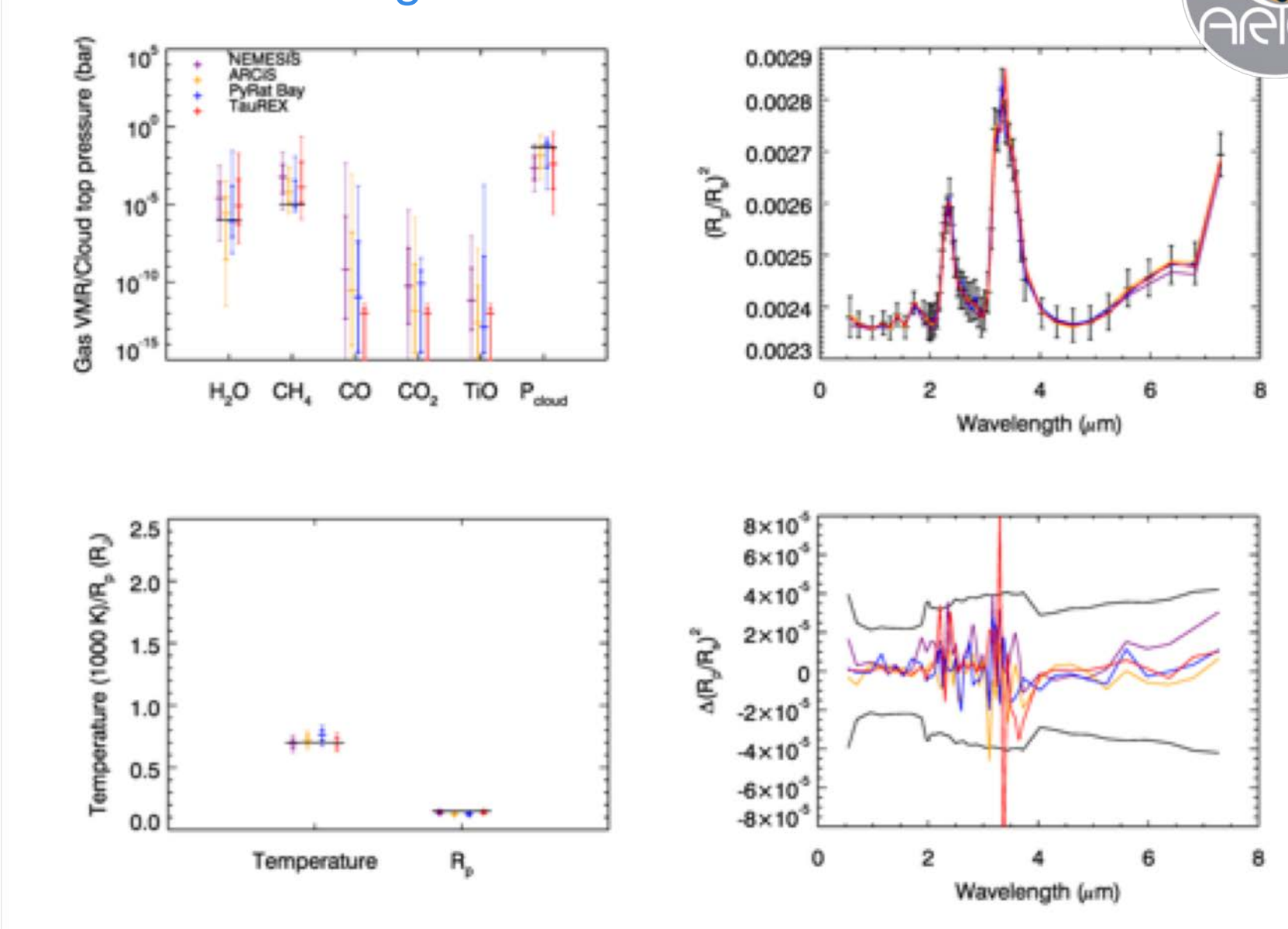


# ARIEL retrieval challenge



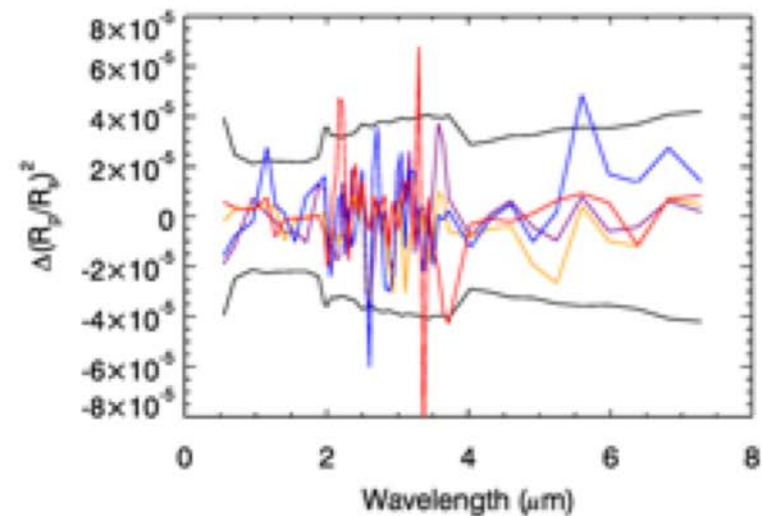
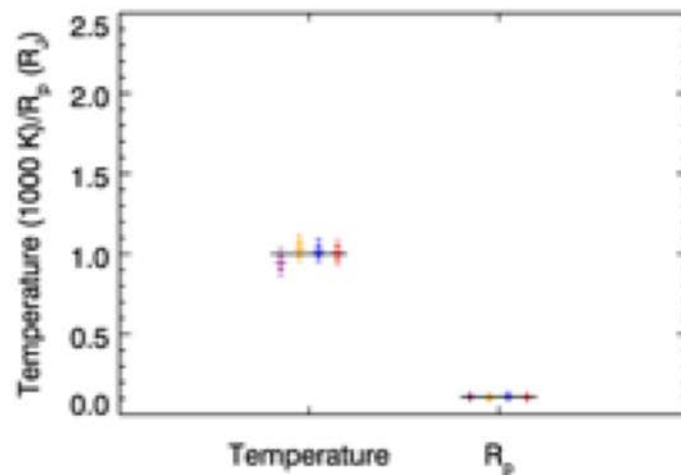
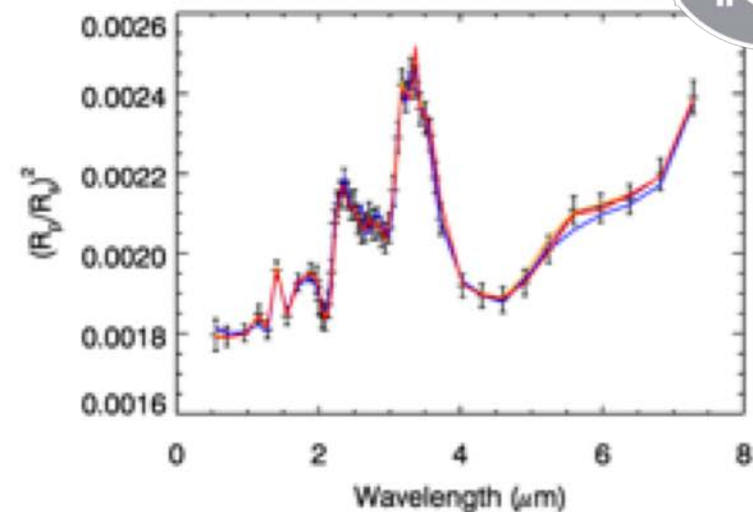
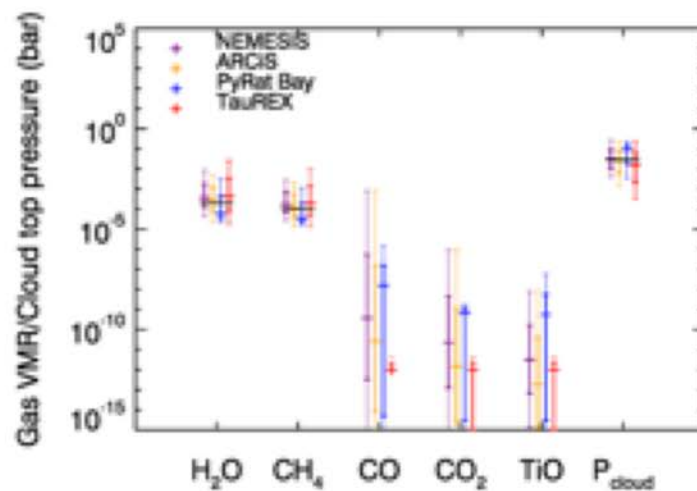


# ARIEL retrieval challenge





# ARIEL retrieval challenge



# Sensitivity study - molecules

Targets to include for this:

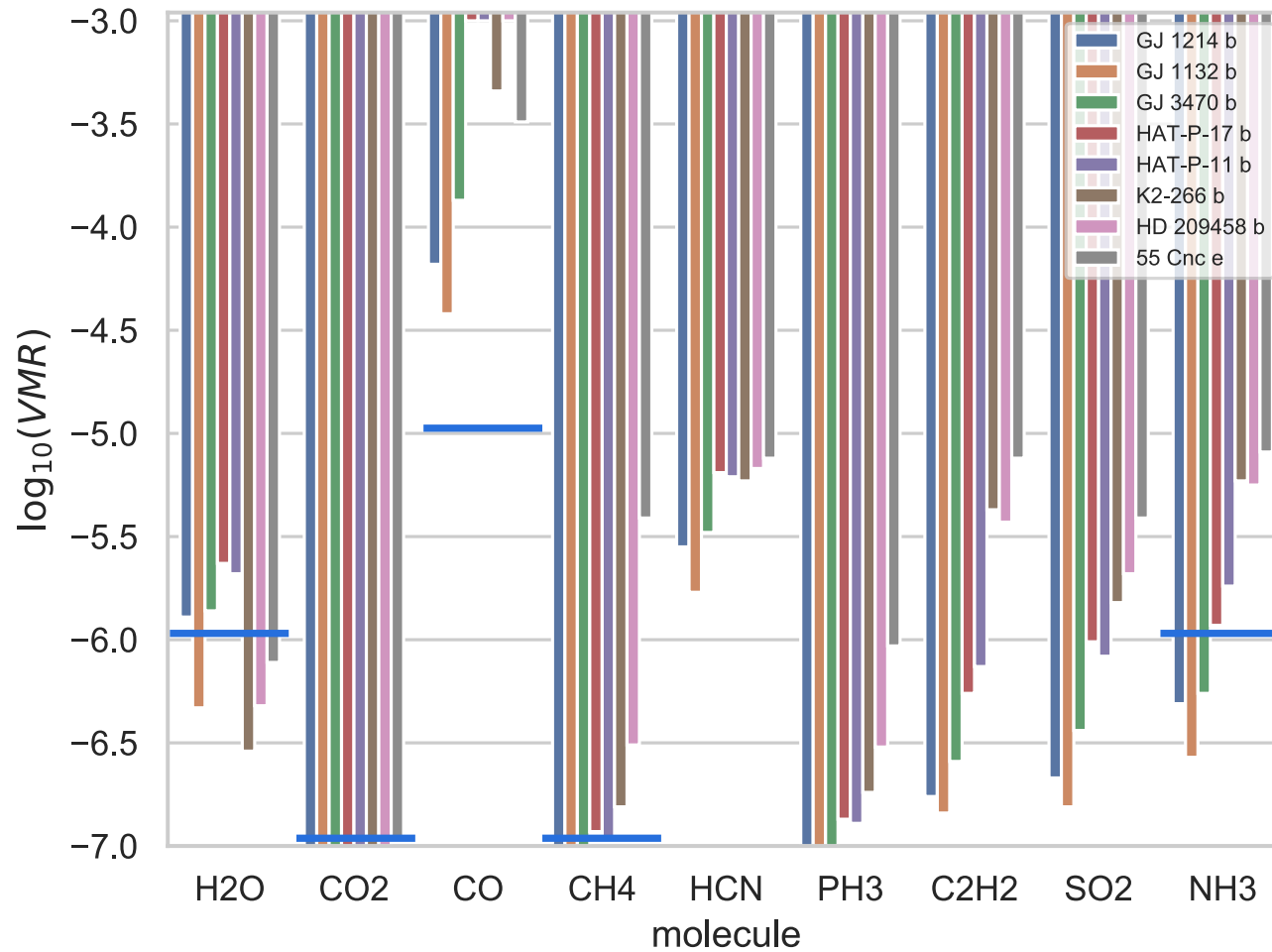
- 55 Cnc e
- GJ 1132 b
- GJ 1214 b
- K2-266 b
- GJ 3470 b
- HD 209458 b
- HAT-P-11 b
- HAT-P-17 b

Standard model contains:

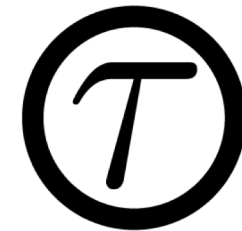
- H<sub>2</sub>O (1e-4 level)
- CH<sub>4</sub> (1e-5 level)
- CO (1e-5 level)
- CO<sub>2</sub> (1e-4 level)

**Doing these tests came down to doing ~700 full retrievals**

# Sensitivity study - molecules

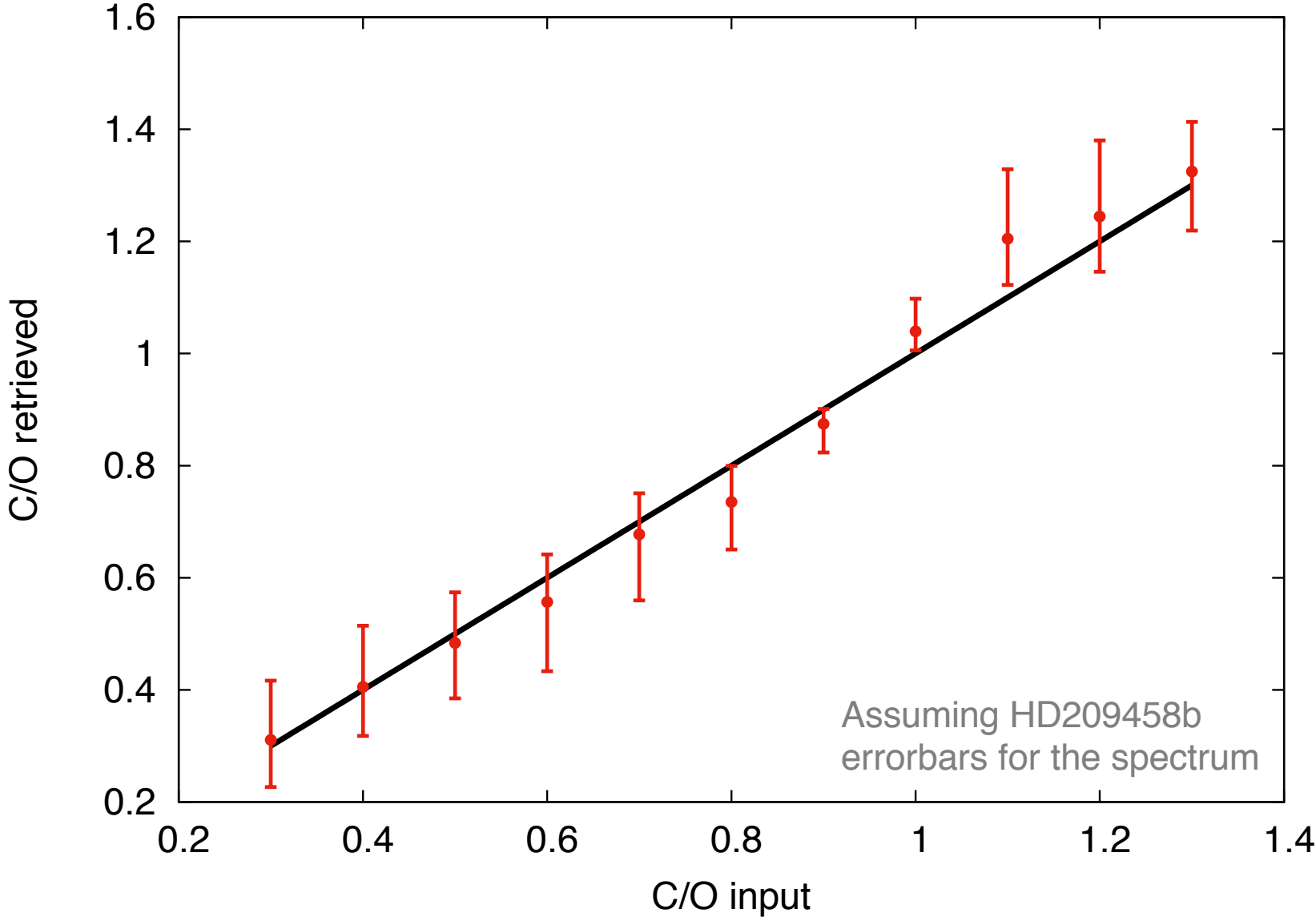


Alfnoor results  
(talk by Lorenzo Mugnai)





# Sensitivity study - chemistry

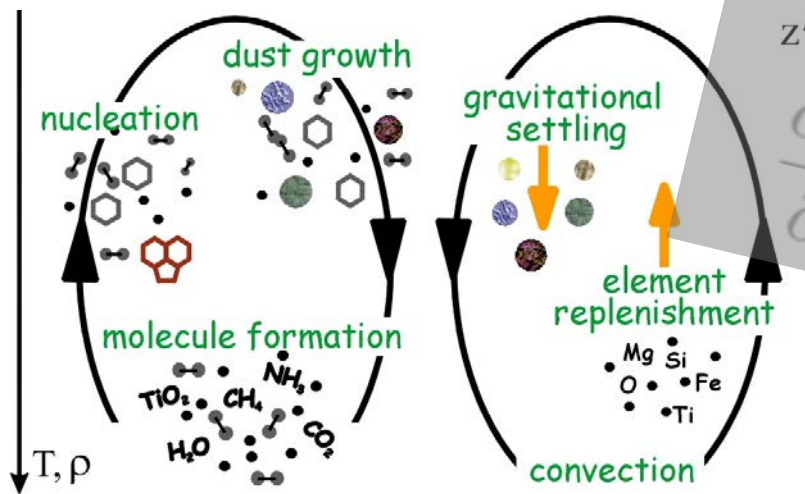




# Cloud formation model

- Condensation of MgSiO<sub>3</sub> (pyroxene) using vapour pressure equations
- Particle settling (rain)
- Particle coagulation
- **Diffusion** parameterized using diffusion strength
- **Nucleation rate** is a free parameter

Fundamental physics is captured while unknowns are parameterized

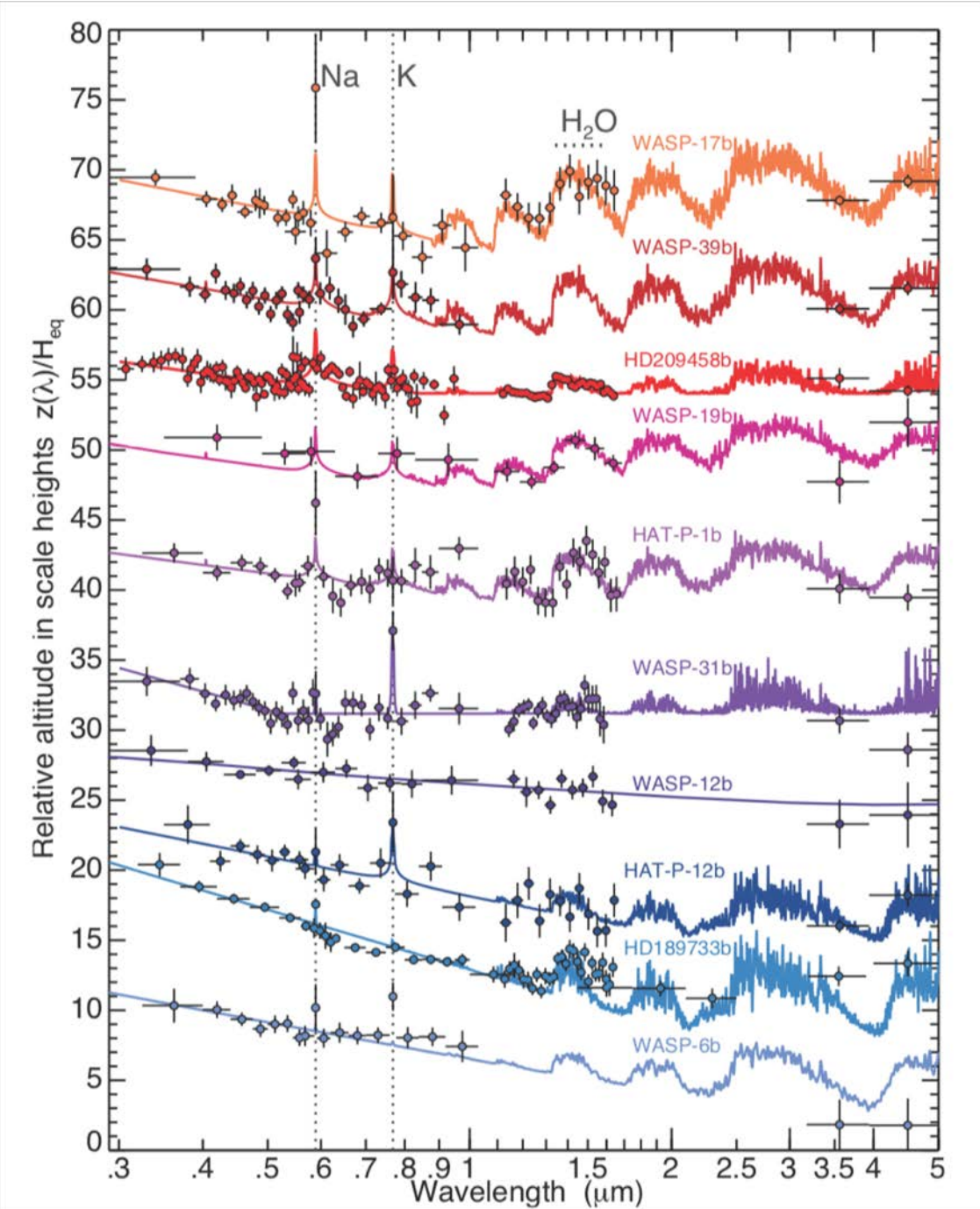


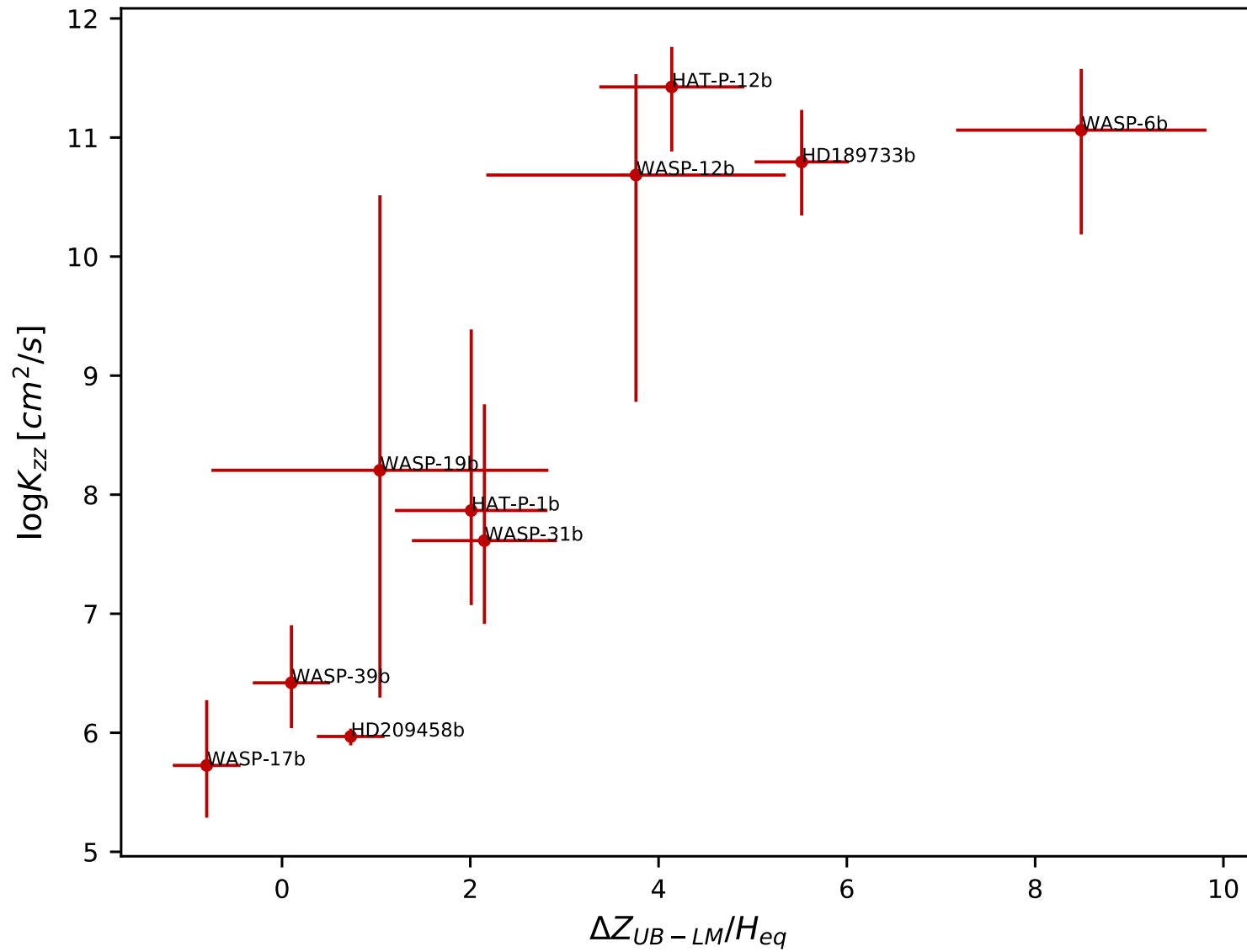
$$\frac{\partial \mathcal{M}_c}{\partial z} = \mathcal{S}_c$$
$$\frac{\partial \mathcal{M}_n}{\partial z} = \mathcal{S}_n$$
$$\frac{\partial x_c}{\partial z} = x_c v_{\text{sed},p} / K_p - \mathcal{M}_c / K_p \rho_{\text{gas}}$$
$$\frac{\partial x_n}{\partial z} = x_n v_{\text{sed},p} / K_p - \mathcal{M}_n / K_p \rho_{\text{gas}}$$
$$\frac{\partial x_v}{\partial z} = -\mathcal{M}_v / K_v \rho_{\text{gas}}$$

Ormel & Min (2019)

# Clouds and hazes

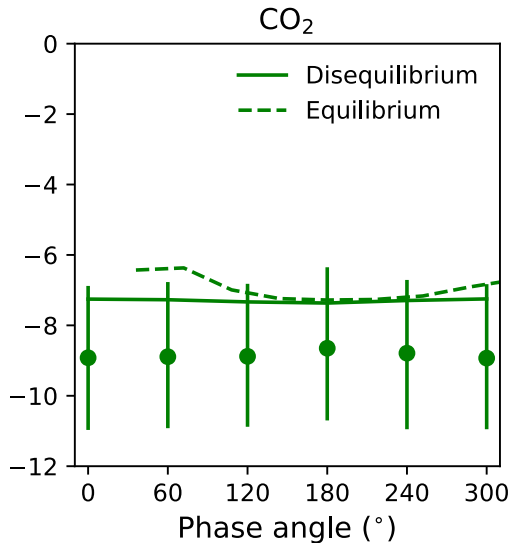
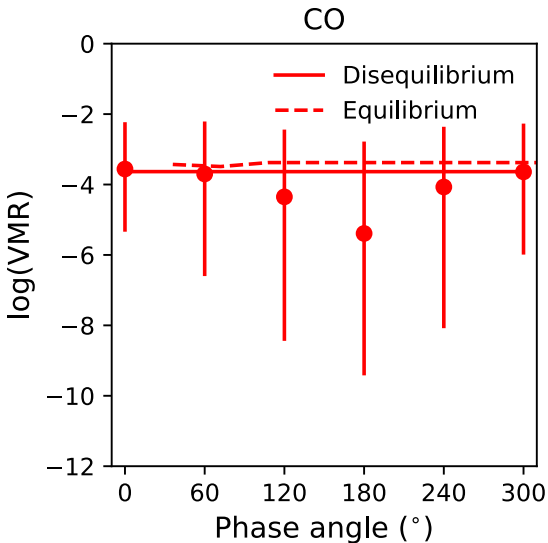
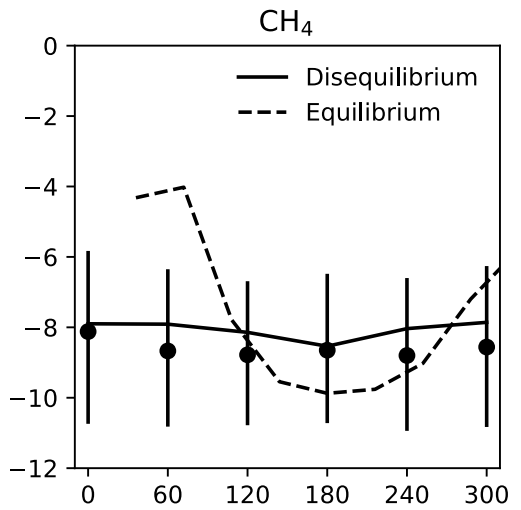
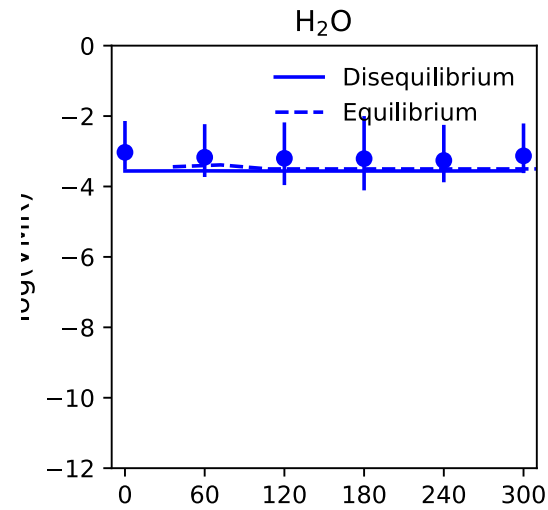
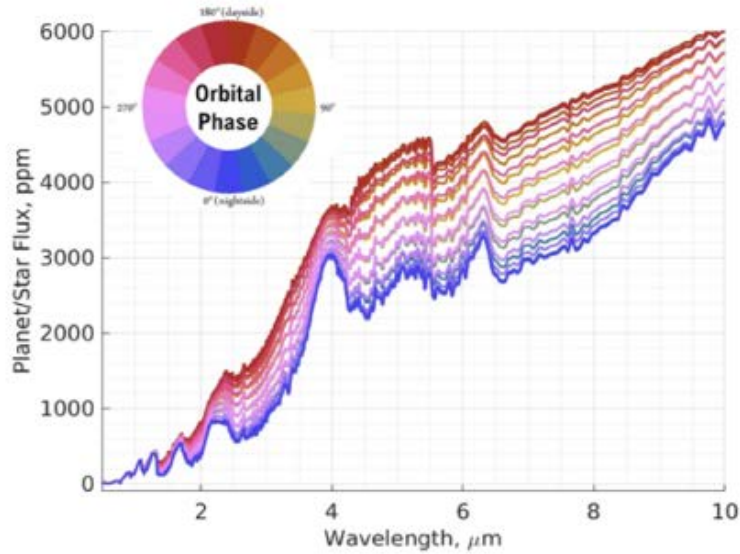
Sing et al. 2016, Nature





# Phase curve retrieval

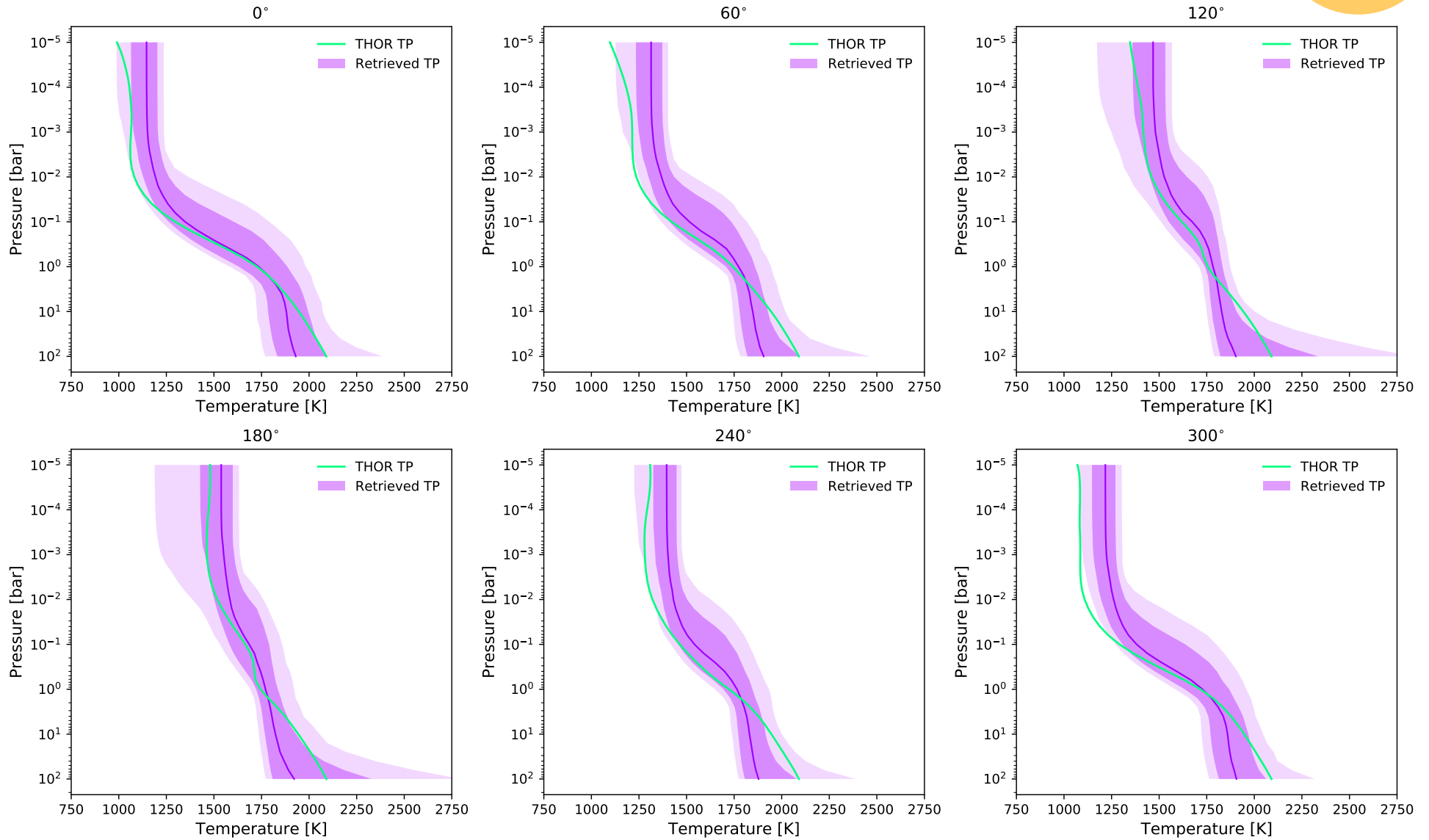
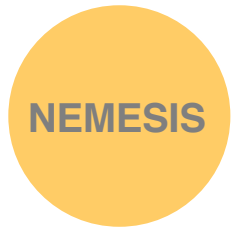
no clouds



Work from Jake Taylor for the phase curve WG report

GCM model for WASP43b using THOR (Mendonca et al (2018))

# Phase curve retrieval

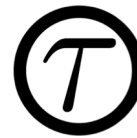


# Summary/takeaway message

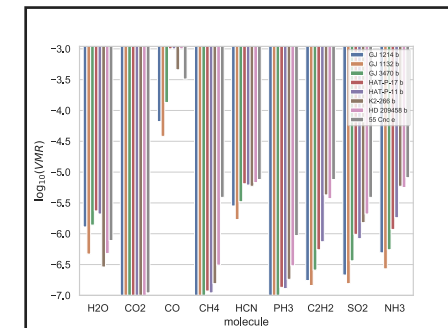
- Your retrieval is only as good as the underlying forward model. Always remember the question you asked.



- We have many tools available



- ARIEL will be able to measure accurate molecular abundances for many molecules



- Adding complexity is possible, can be advantageous and sometimes even needed

- (diseq.) Chemistry
- Clouds
- 3D structures

