Department of Physics and Astronomy

UCL

Retrieval Challenges for the ARIEL Mission

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Thanks to: Giovanna Tinetti, Ingo Waldmann, Marco Rocchetto, Quentin Changeat (UCL)
Pat Irwin, Ryan Garland (University of Oxford)
Mike Line (ASU)

ARIEL

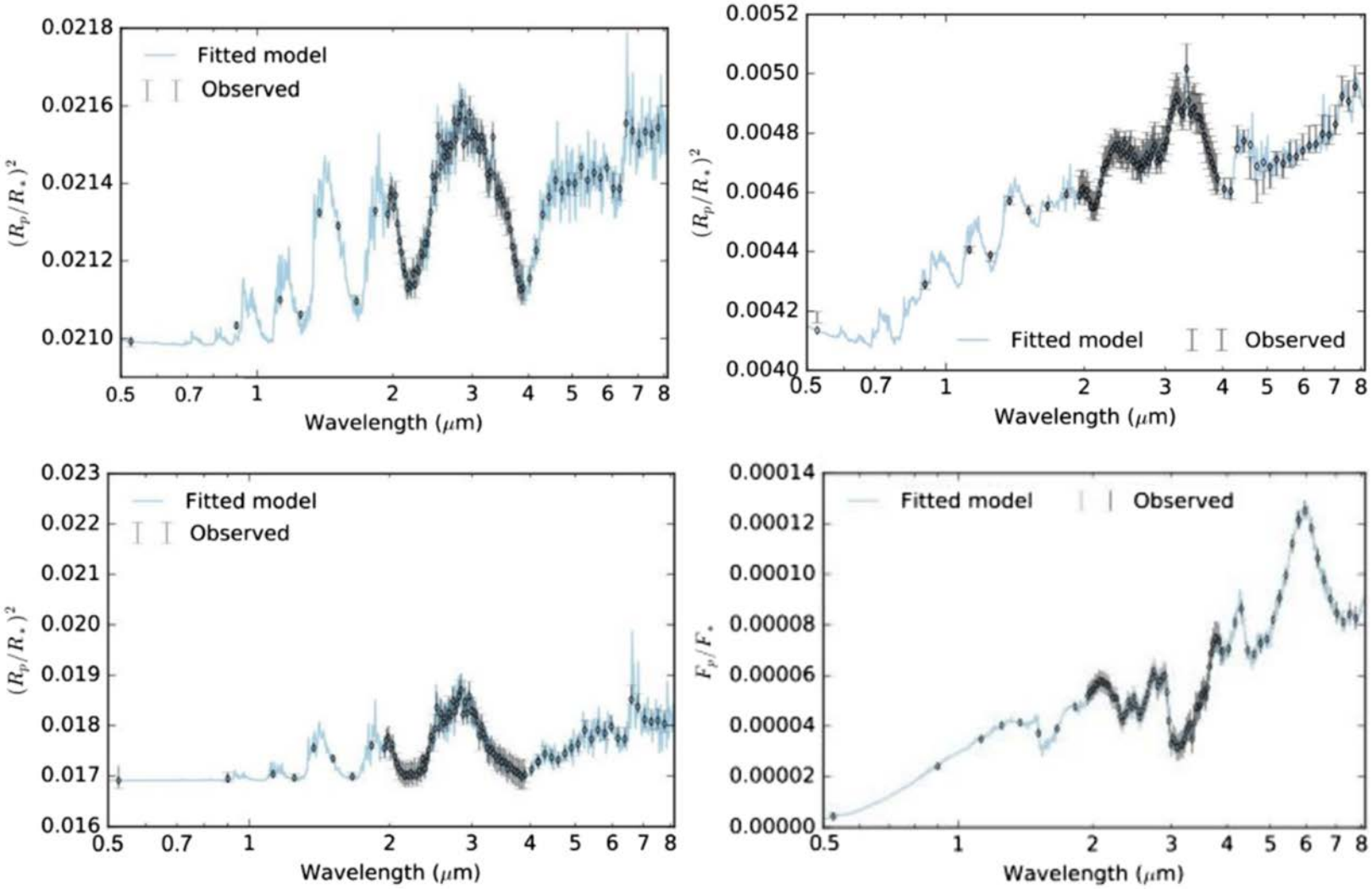


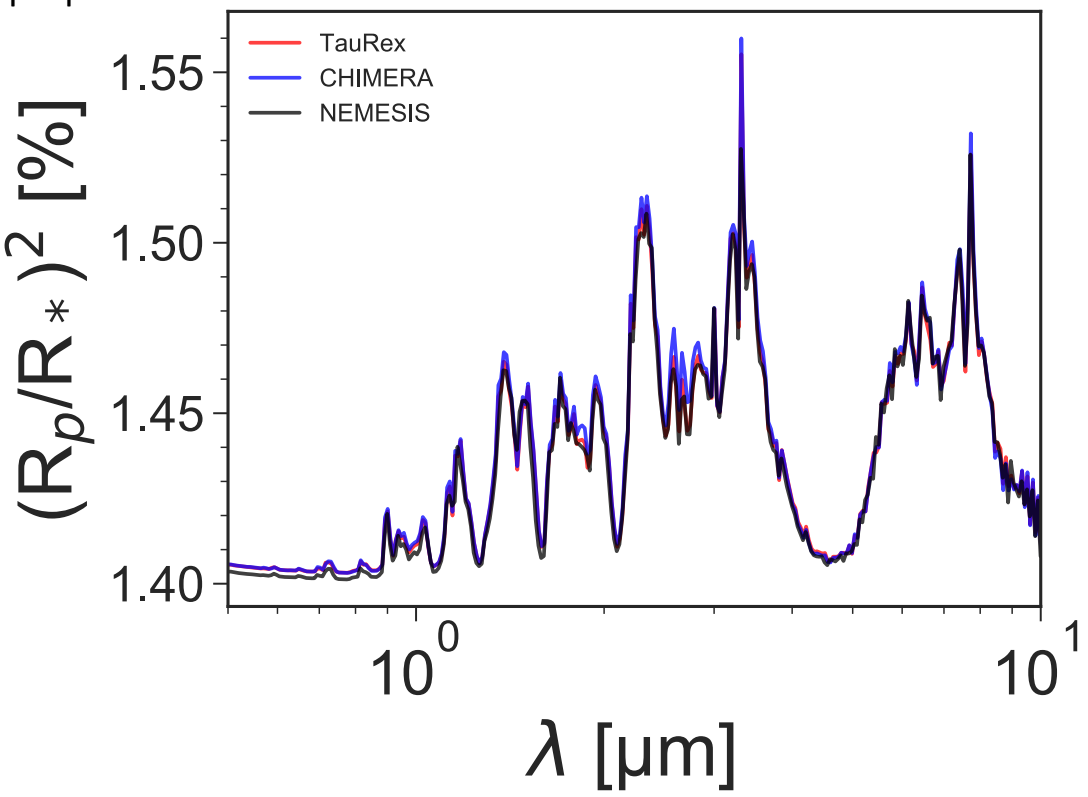
Figure from Tinetti et al, 2016, ExpAst, 46, 135

Quality of ARIEL spectra substantially better than what we can currently achieve

Similar wavelength coverage to JWST

Resolving the challenges: comparative approaches

Barstow, Changeat, Garland, Line, Rocchetto, Waldmann in prep.

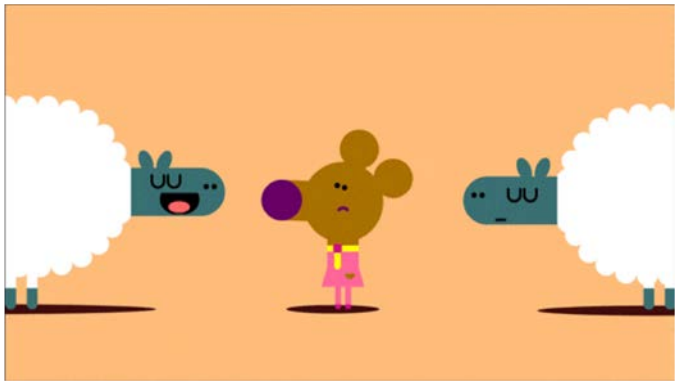


NEMESIS (Irwin et al. 2008), TauREX (Waldmann et al. 2015) and CHIMERA (Line et al. 2013). NEMESIS originally Solar System, TauREX and CHIMERA both developed for exoplanets.

Benchmark models: if you put in the same stuff, do you get the same answer? (Hopefully, yes…)

Image shows synthetic, noise-free JWST spectra for a cloudy, H2-He dominated super Earth/mini Neptune generated using 3 different forward model codes.

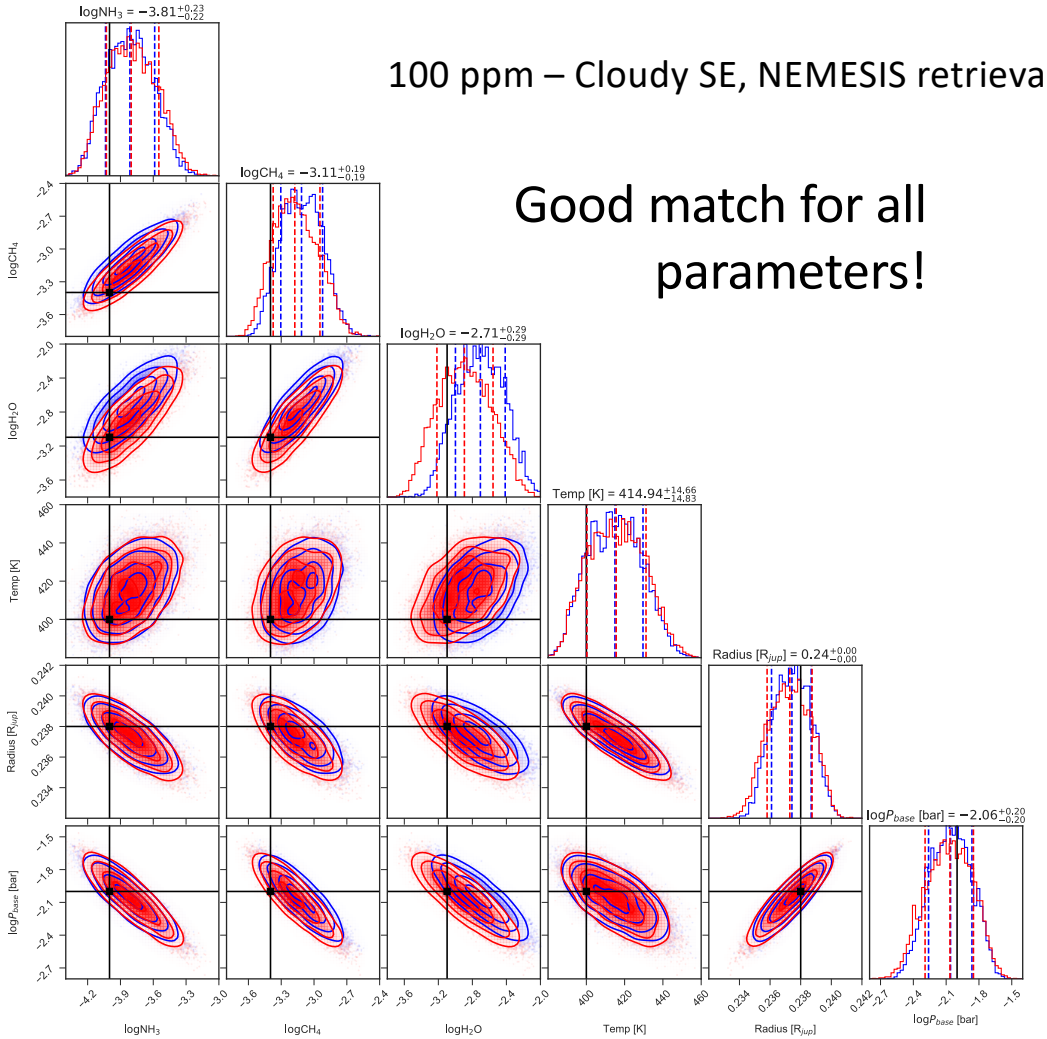
They're the same…. right?



NEMESIS-TauREX-CHIMERA retrieval comparison

100 ppm – Cloudy SE, NEMESIS retrieval

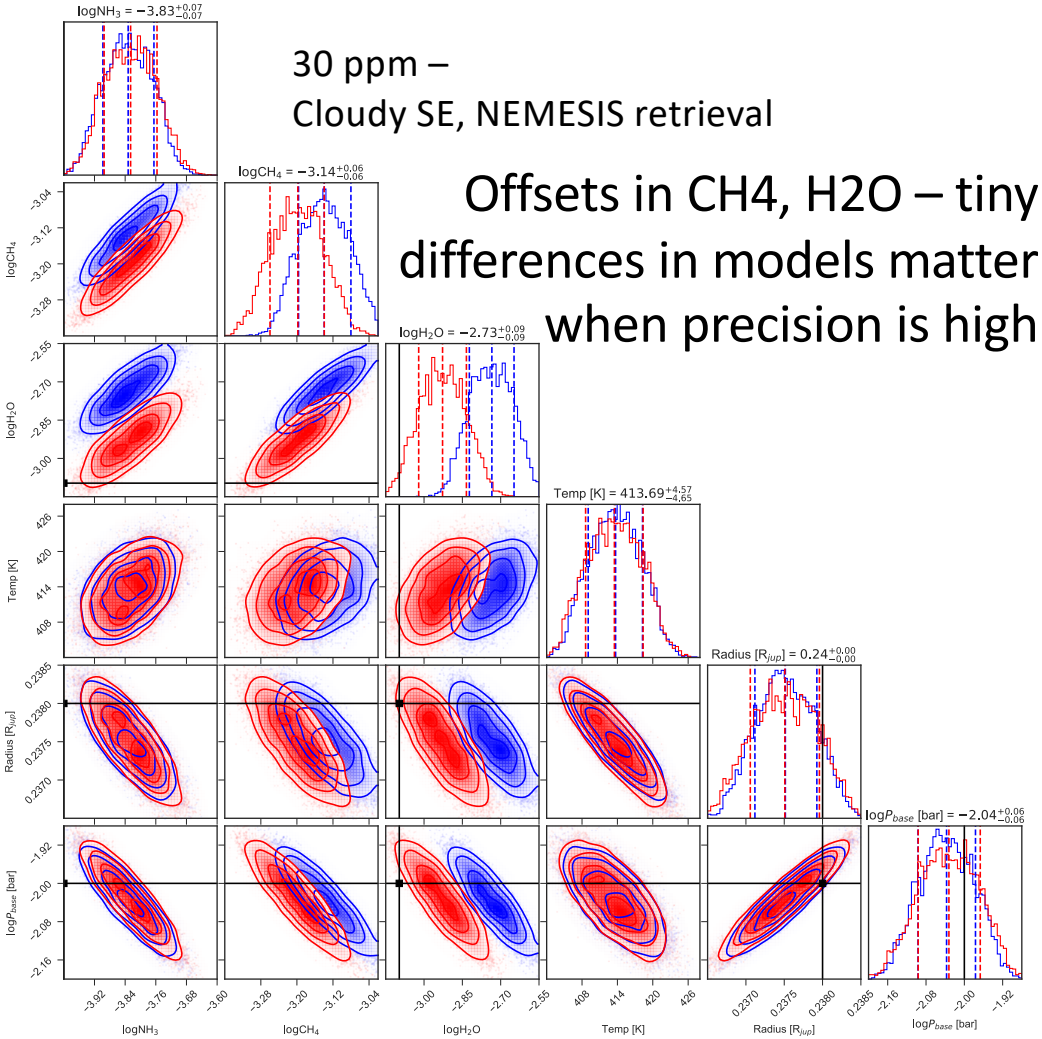
Good match for all parameters!



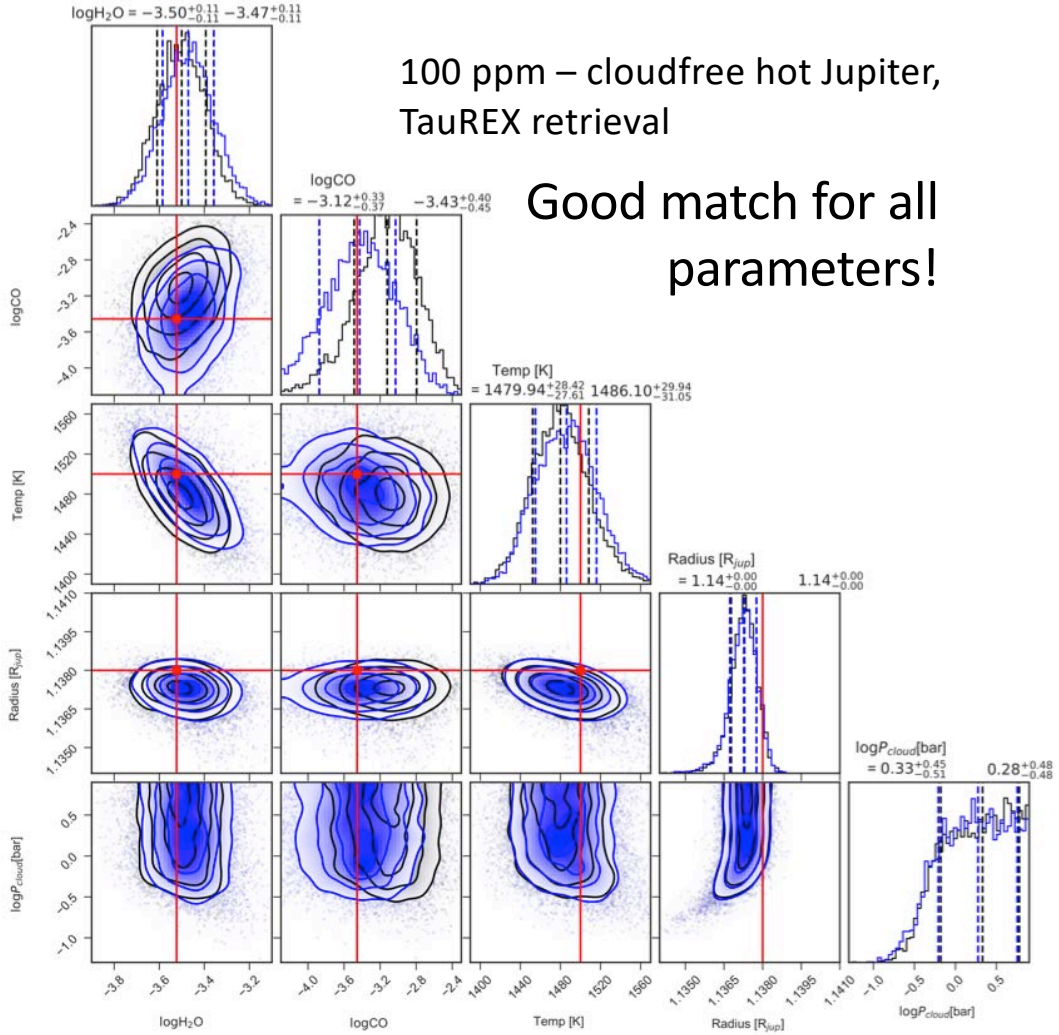
Blue = CHIMERA, Red = TauREX

30 ppm –
Cloudy SE, NEMESIS retrieval

Offsets in CH4, H2O – tiny differences in models matter when precision is high

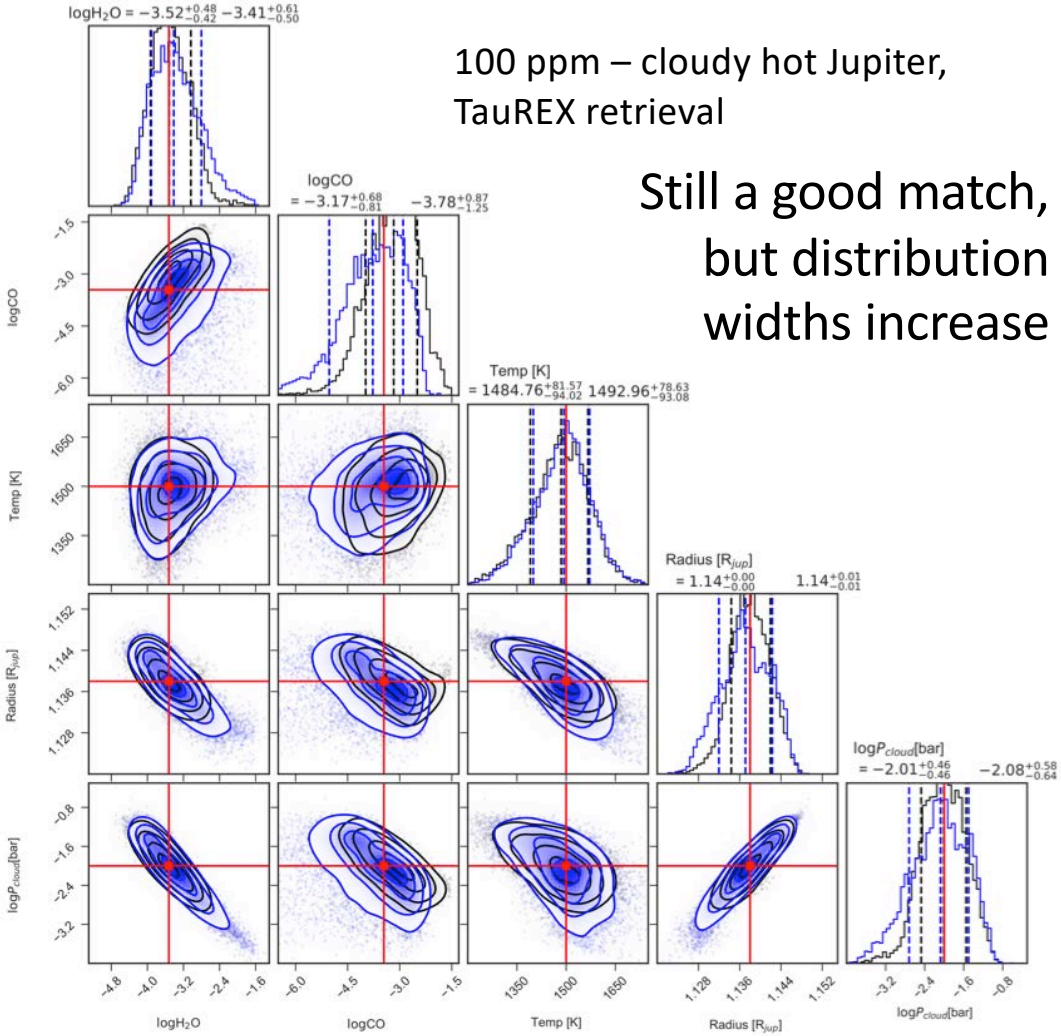


NEMESIS-TauREX-CHIMERA retrieval comparison



100 ppm – cloudfree hot Jupiter, TauREX retrieval

Good match for all parameters!

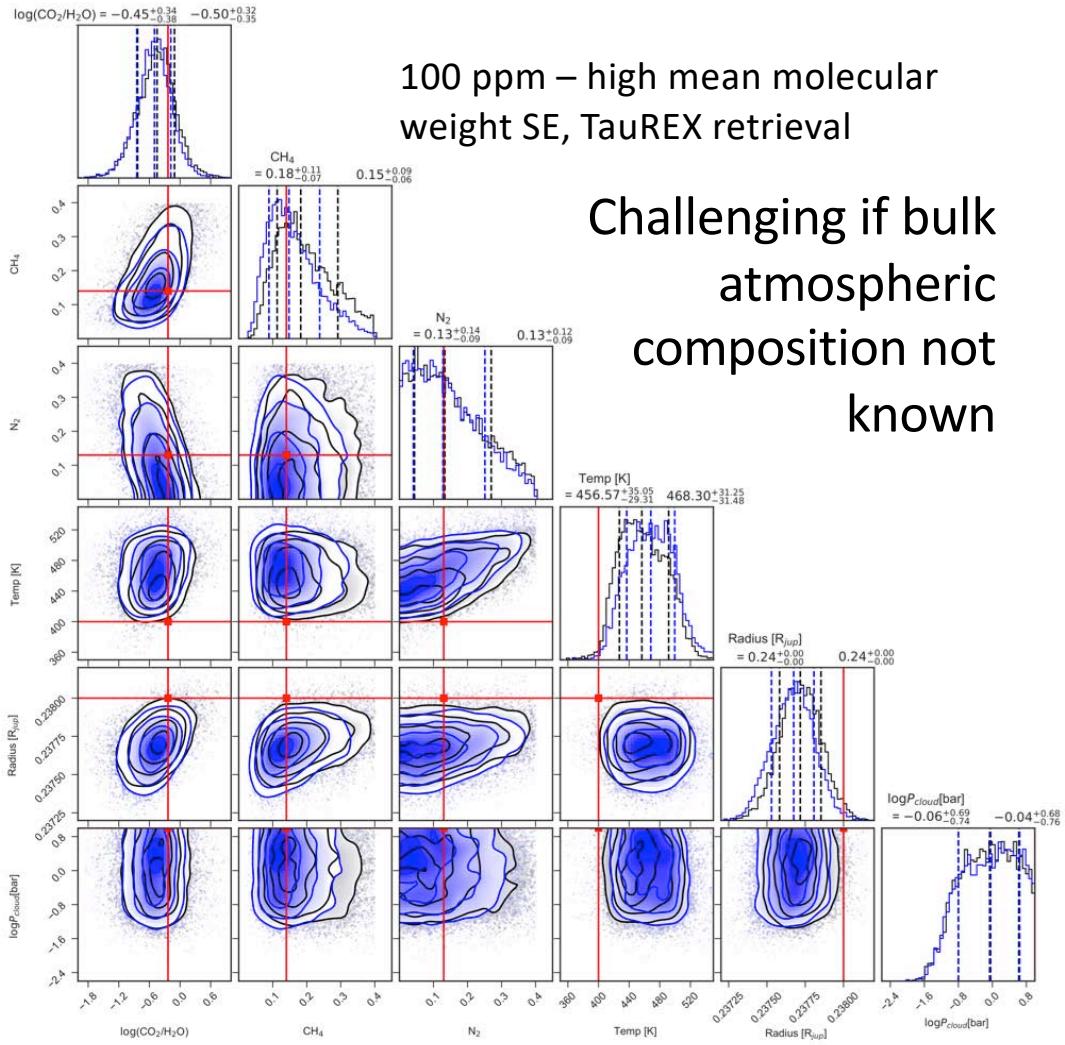


100 ppm – cloudy hot Jupiter, TauREX retrieval

Still a good match, but distribution widths increase

Blue = CHIMERA, Black = NEMESIS

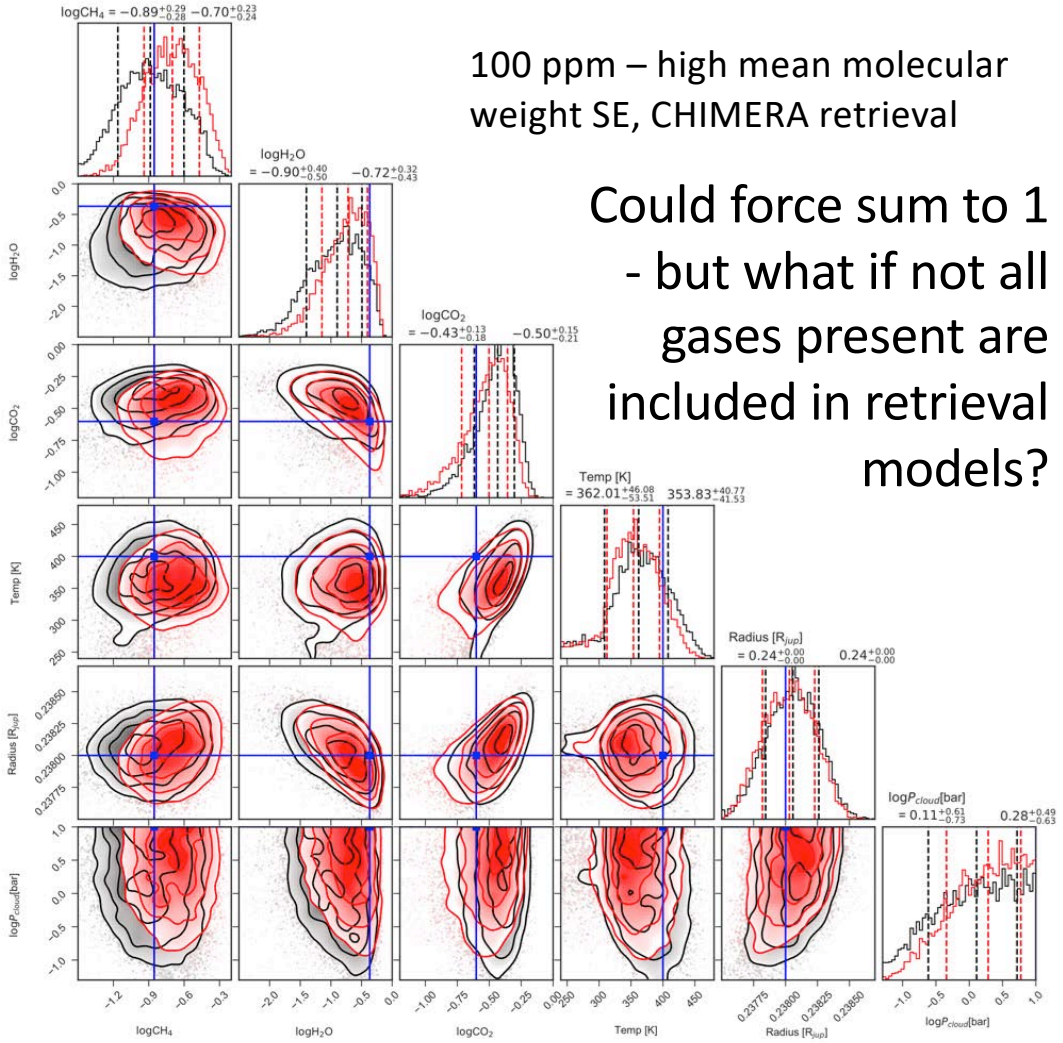
NEMESIS-TauREX-CHIMERA retrieval comparison



100 ppm – high mean molecular weight SE, TauREX retrieval

Challenging if bulk atmospheric composition not known

Blue = CHIMERA, Black = NEMESIS



100 ppm – high mean molecular weight SE, CHIMERA retrieval

Could force sum to 1 - but what if not all gases present are included in retrieval models?

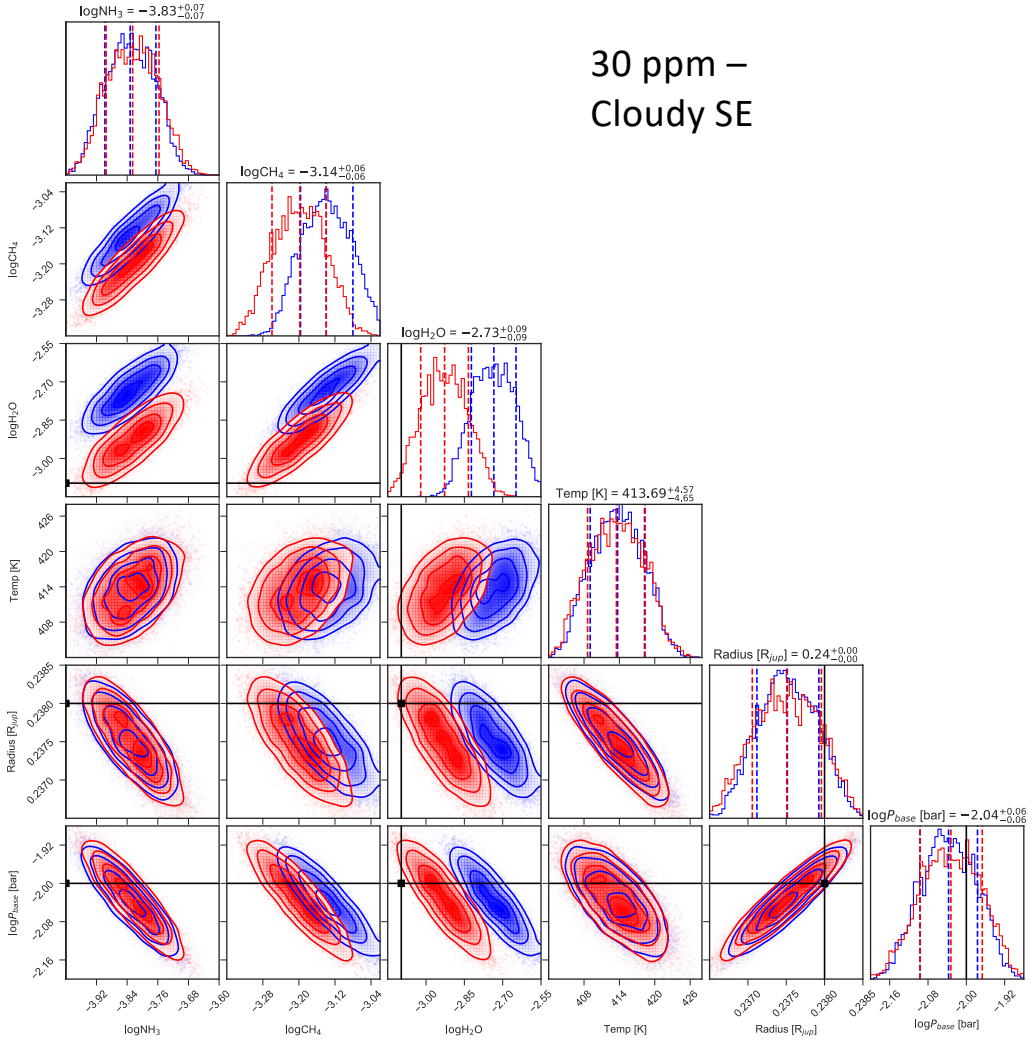
Red = TauREX, Black = NEMESIS

NEMESIS-TauREX-CHIMERA retrieval comparison

Observed differences are a good analogy for instrument systematics + astrophysical systematics.

Plus: there is no such thing as a ‘right’ model, all approximations.

Testing a variety of approximations and approaches is probably what will get us closest to the truth.



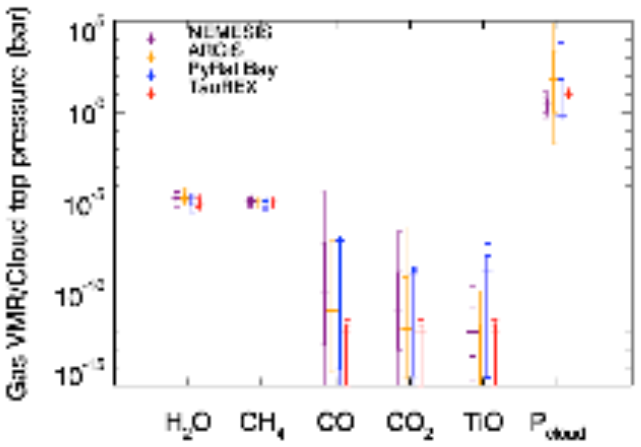
30 ppm –
Cloudy SE

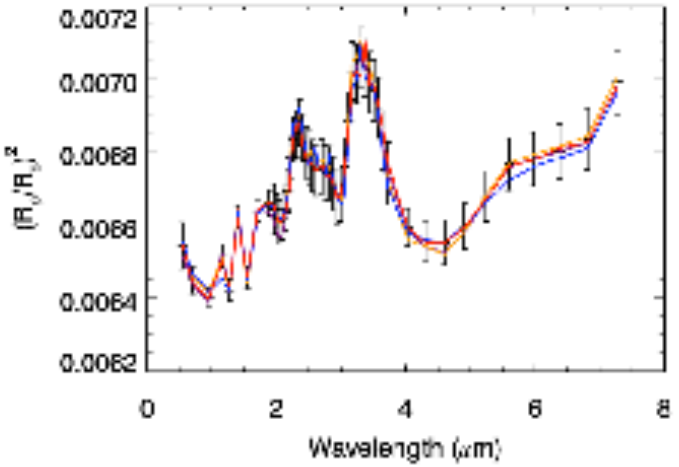
ARIEL Retrieval Challenge

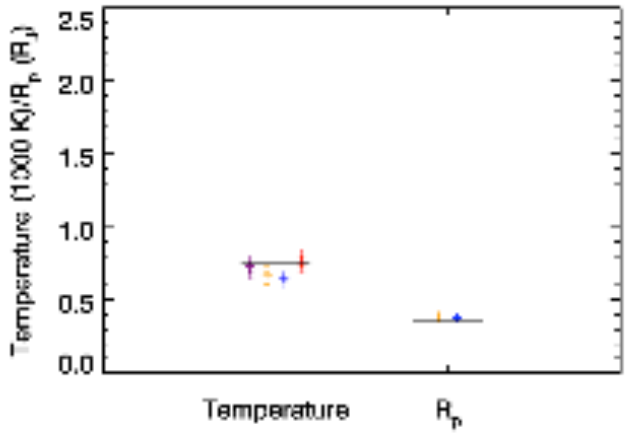
Simple models generated using TauREX

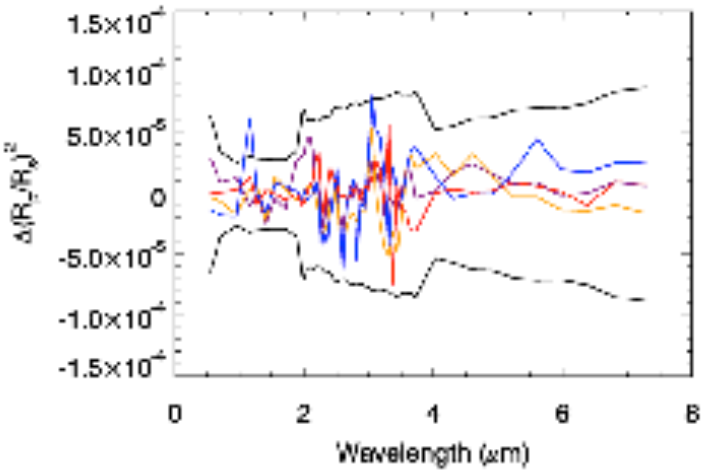
4x known input models, 4x fully blind models

Good match for true values, good consistency between different models, good spectral matches

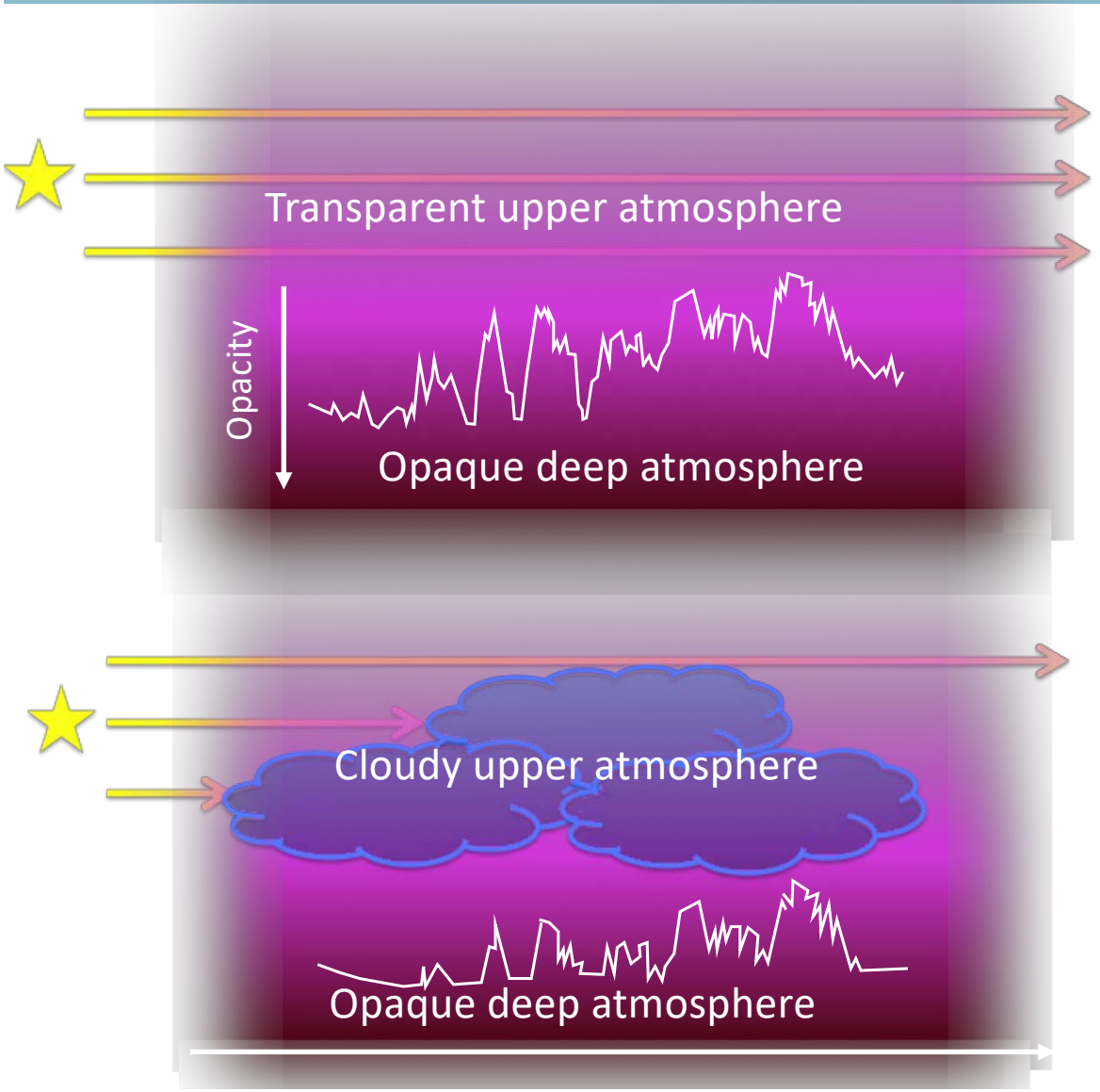


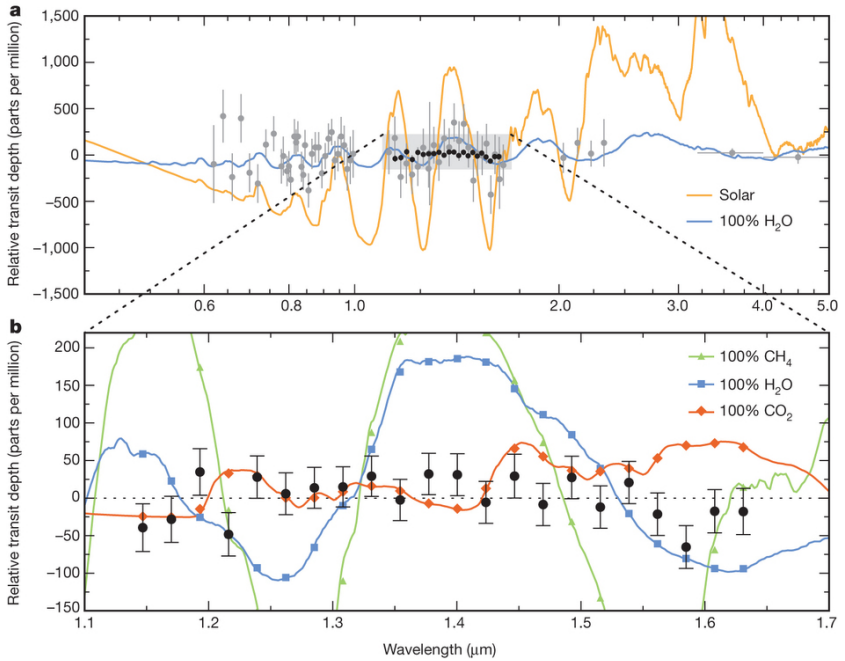






Effect of clouds on transmission spectrum



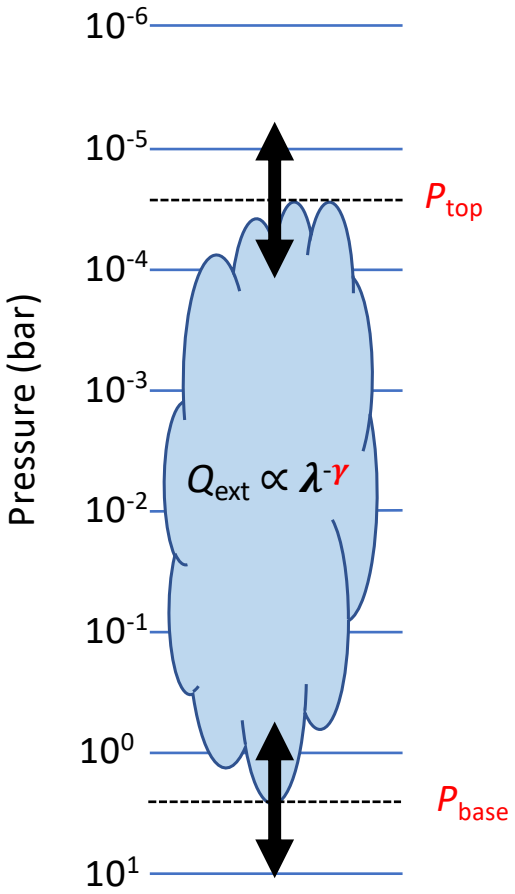


Cloudy GJ 1214b's flat spectrum – taken from Kreidberg et al. 2014, Nature, 505, 69

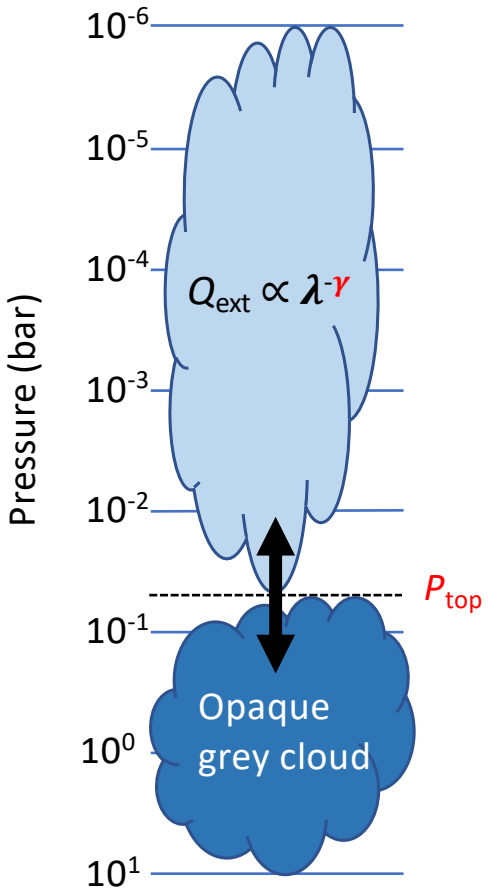
How should cloud be represented? Limited information content of spectra requires something simple, but many different approaches.

Parameterisations: a selection

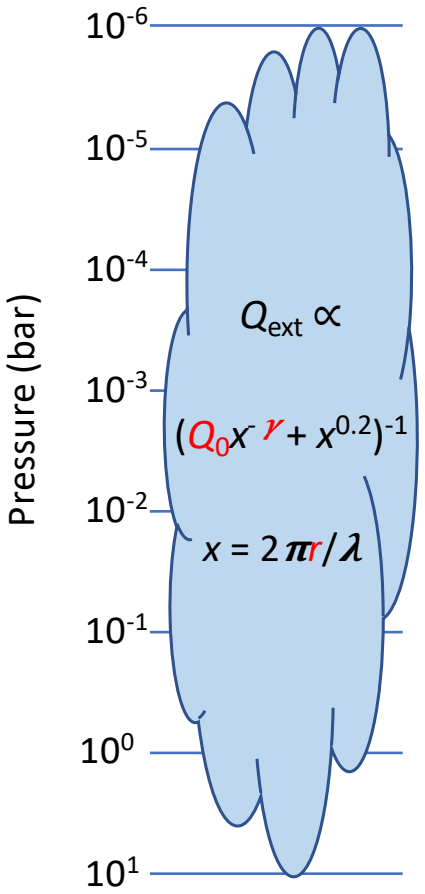
Barstow et al 2017 (B17).



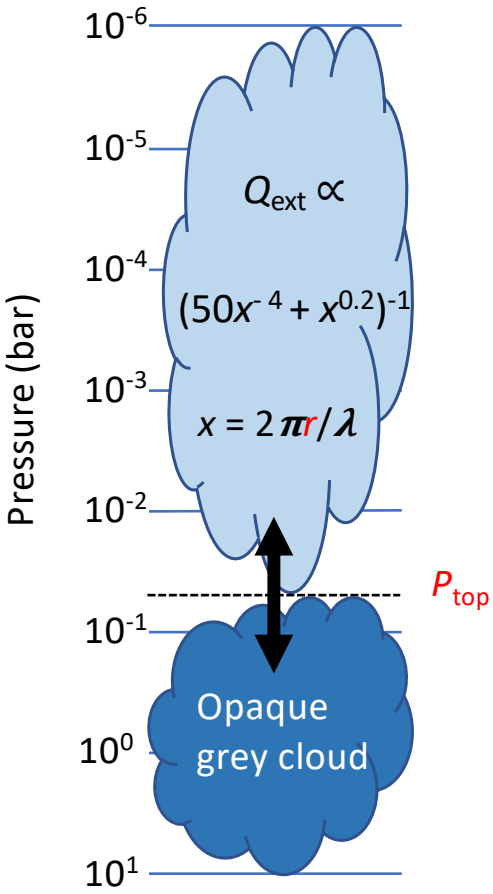
Pinhas et al. 2019 (P19)



Fisher & Heng 2018 (F18)



Tsiaras et al 2018 (T18).



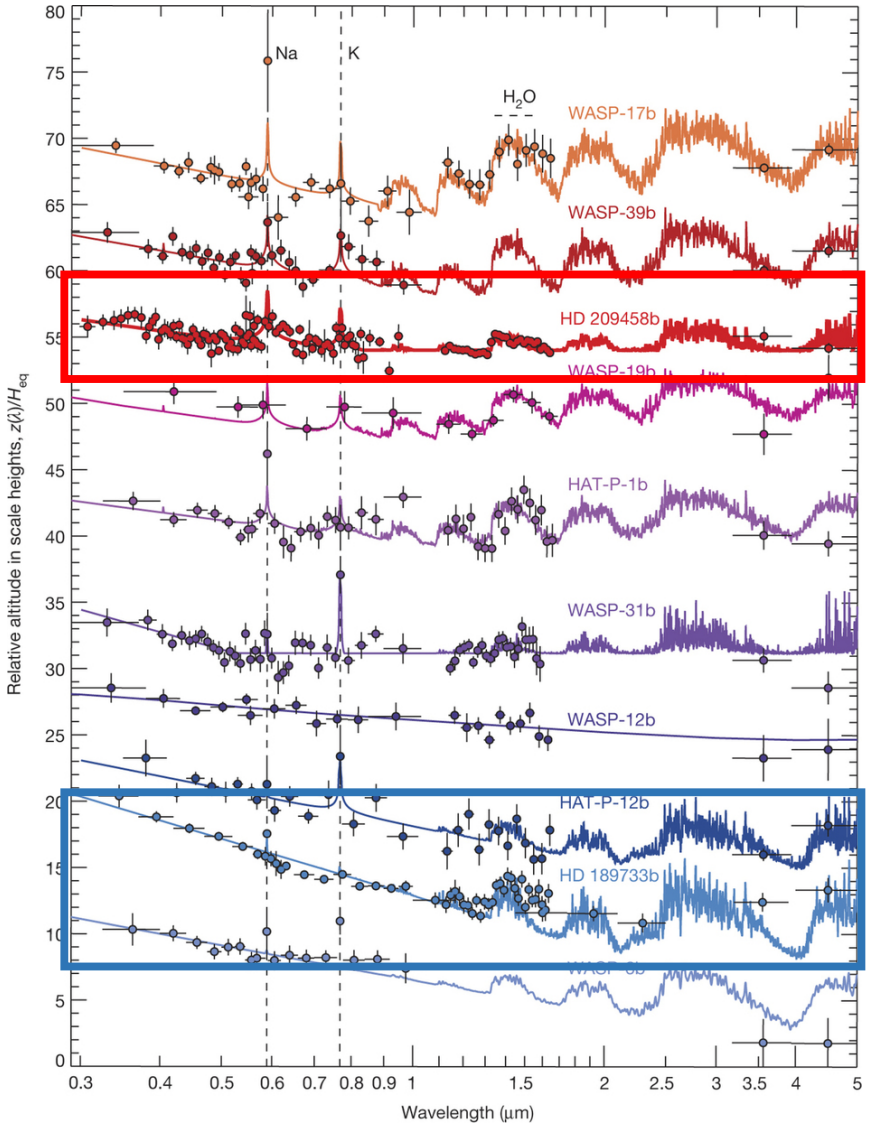
Test case planets:

HD 209458b:

- R=1.38 R_J
- M=0.69 M_J
- T_{eff} =~1400 K
- Previously claimed to be cloudy (muted features)

HD 189733b:

- R=1.138 R_J
- M=1.162 M_J
- T_{eff} =~1200 K
- Previously claimed to be hazy (muted H_2O feature, large scattering slope in the visible)



Results

HD 209458b:

- R=1.38 R_J
- M=0.69 M_J
- T_{eff} =~1400 K
- Previously claimed to be cloudy (muted features)

Parameter	Barstow17	Pinhas19	Fisher18	Tsiaras18
Log(H2O VMR)	-4.89	-4.95	-5.11	-5.02
Log(nadir optical depth)	5.37	-2.72	-0.13	-4.4
Scattering index	3.69	8.79	5.08	N/A
Log(top pressure (bar))	-0.65	-0.61	N/A	-0.79
ΔLn evidence	-3.6	-2.1	0.0	-1.7

HD 189733b:

- R=1.138 R_J
- M=1.162 M_J
- T_{eff} =~1200 K
- Previously claimed to be hazy (muted H_2O feature, large scattering slope in the visible)

Parameter	Barstow17	Pinhas19	Fisher18	Tsiaras18
Log(H2O VMR)	-4.94	-4.98	-5.02	-5.56
Log(nadir optical depth)	3.37	4.35	4.49	2.55
Scattering index	6.34	6.47	6.37	N/A
Log(top pressure (bar))	-6.56	0.34	N/A	0.28
ΔLn evidence	-0.7	-0.2	0.0	-35.8

Conclusions: cloud modelling

All cloud parameterisations in the literature do a reasonable job of fitting the data

H_2O abundances are very robust to different cloud models.

Combination of fits with different models elucidates key points about the cloud:

- For HD 189733b: cloud with steep scattering slope is present at low pressures, no evidence for grey cloud
- For HD 209458b, no evidence for small particle haze but evidence for deep cloud deck.

Conclusions

- After 10 years of exoplanet atmospheres, quality of spectra has improved enormously but problem still degenerate. ARIEL represents a significant advance on what is currently possible.
- Model dependence is an inescapable fact – but we can use it
- No model is ‘right’ – but some may be wrong!
- 3D effects will become increasingly important, must be accounted for
- Comparative work using different codes/approaches helpful for getting close to ‘truth’