GJ 1214b:
A Challenge for Optimal Estimation Retrieval

Jo Barstow

Suzanne Aigrain, Pat Irwin, Leigh Fletcher,
Jaemin Lee

Outline

1. GJ 1214b – observations and previous modelling

2. Atmospheric property retrieval
   - Solving the inverse problem

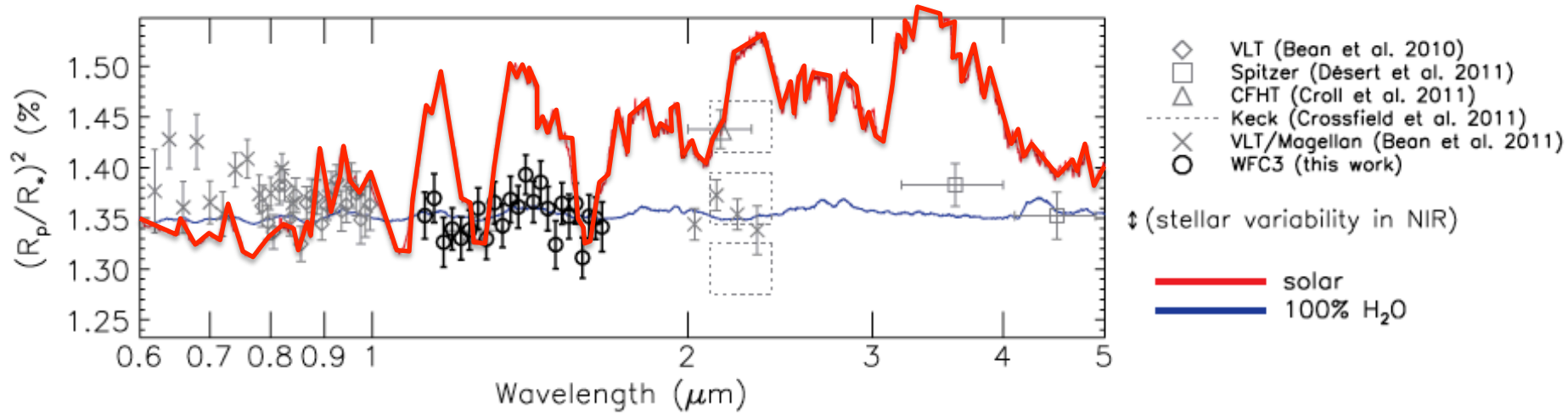
3. Results
   - Best-fit solution and reliability
   - Degeneracies
   - Hope for the future

4. Conclusions

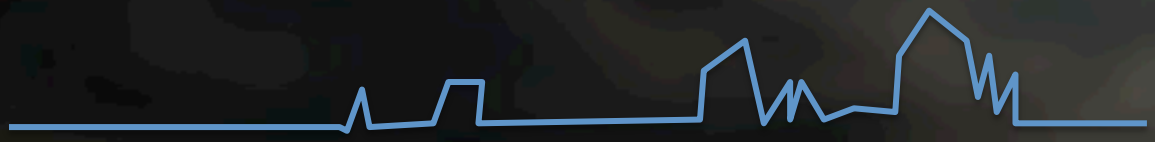
GJ 1214b: The Story So Far

- Discovered as part of the MEarth project
- Super-Earth size (~2.5x) planet orbiting an M4.5 type star
- Orbit 1.6 days
- Mass ~ 6.5 M_E
- Something in between Earth and Neptune, so we have no idea what we expect it to be like (rocky core with thick atmosphere or a miniature gas giant)

GJ 1214b: The Story So Far

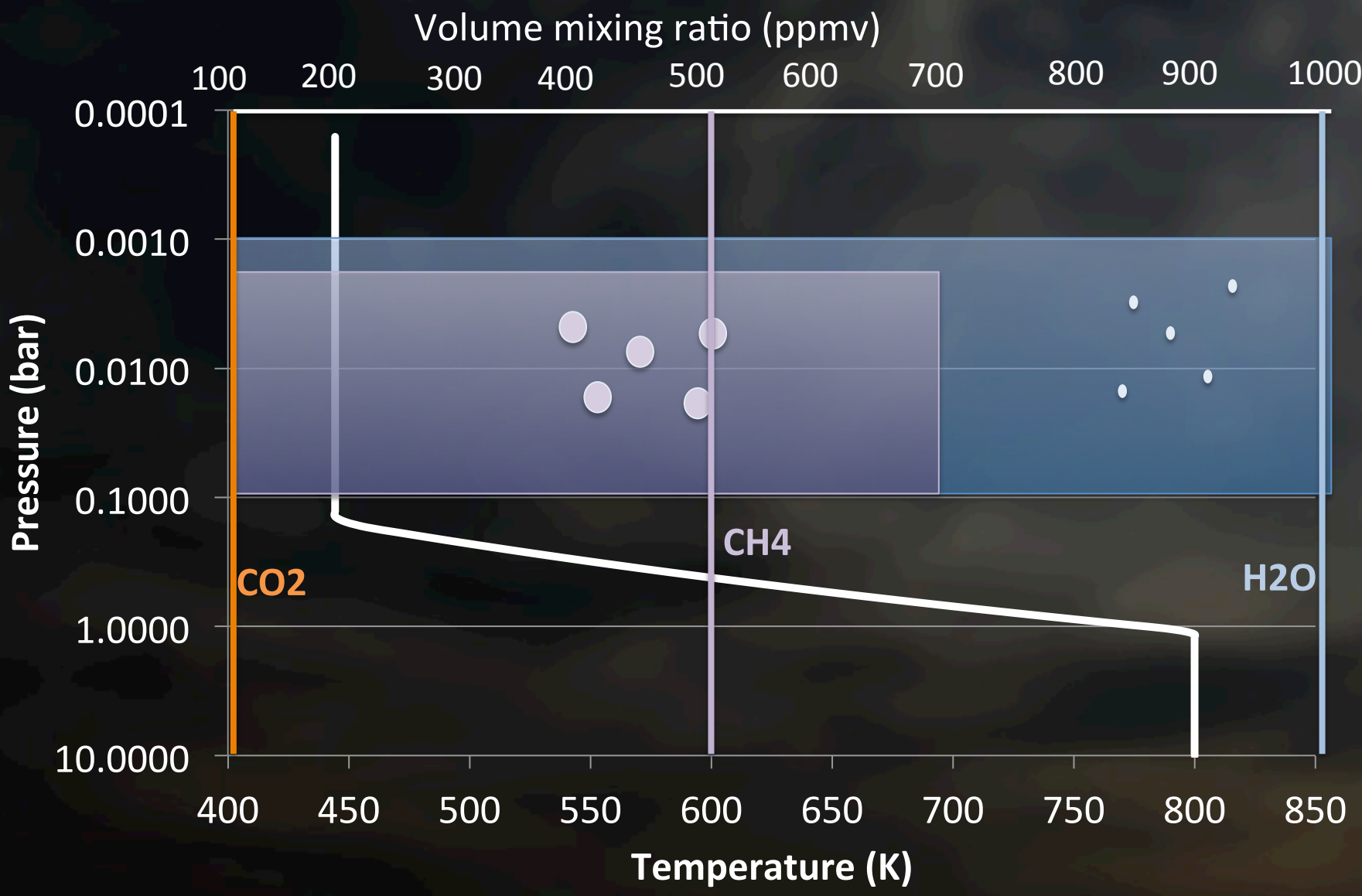


From Berta et al. 2012



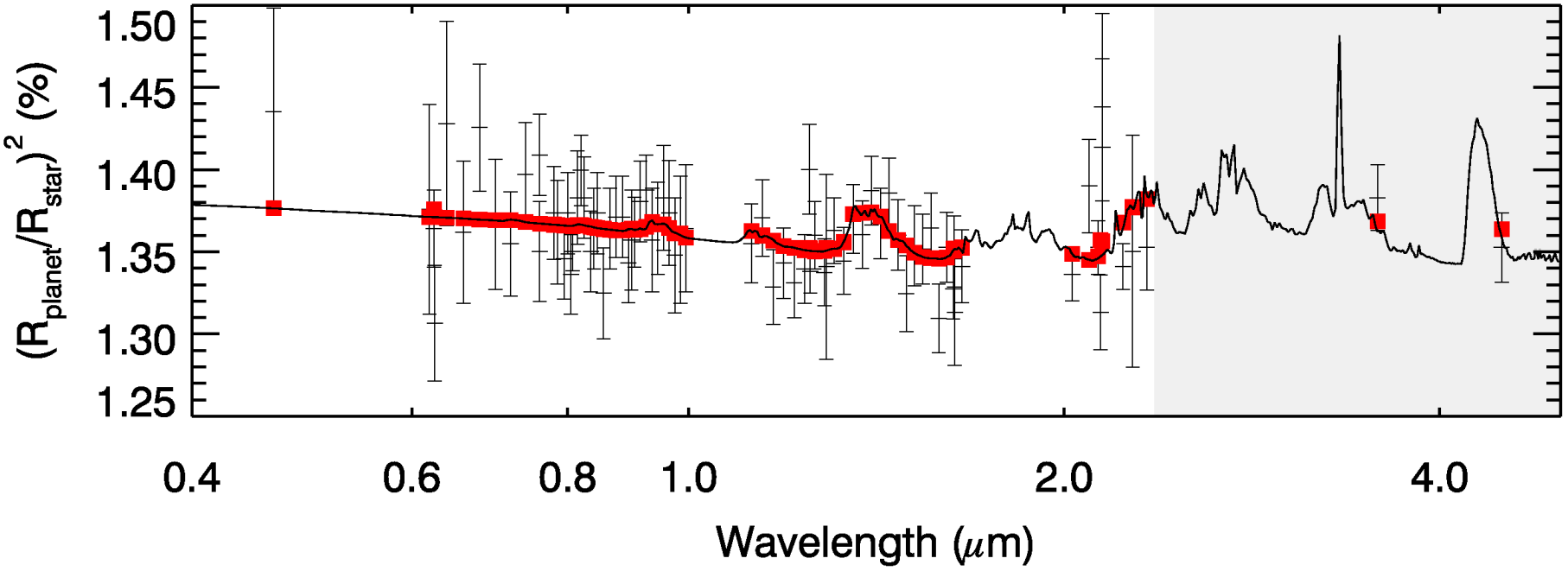
Atmospheric property retrieval

Setting up the problem



Results

Best-fit solution



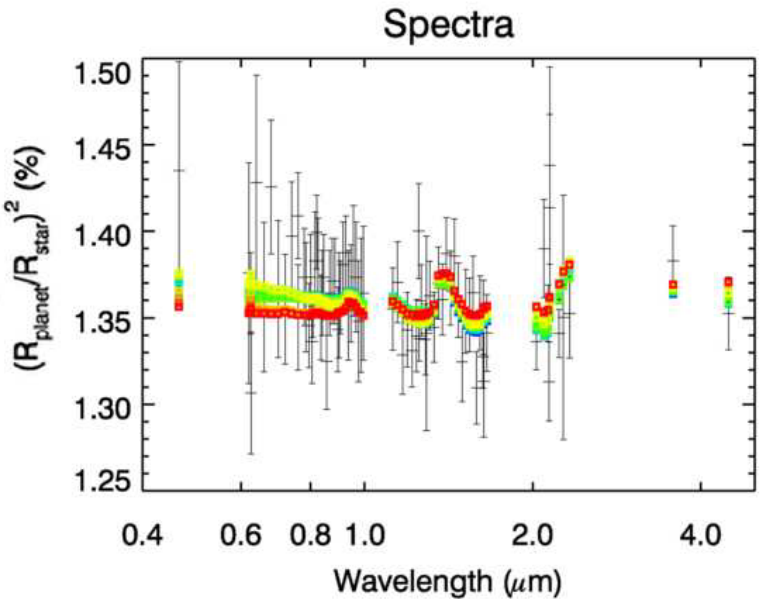
Cloud 1: 1.55 +/- 1.00
Cloud 2: 0.783 +/- 1.13
H2O VMR: 1.16 +/- 1.04
CO2 VMR: 0.876+/- 1.16
CH4 VMR: 0.169 +/- 0.732
Radius: 15320 +/-58 km

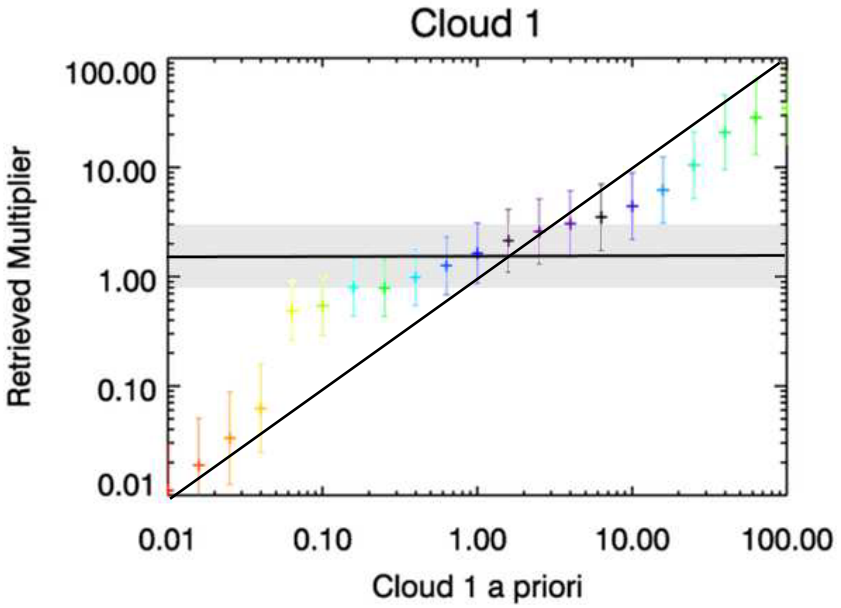
How dependent is this solution on the *a priori*?

Test – vary each of 2x cloud optical depth, H2O, CO2 and CH4 VMR *a priori* values over 0.01x-100x, 21 steps

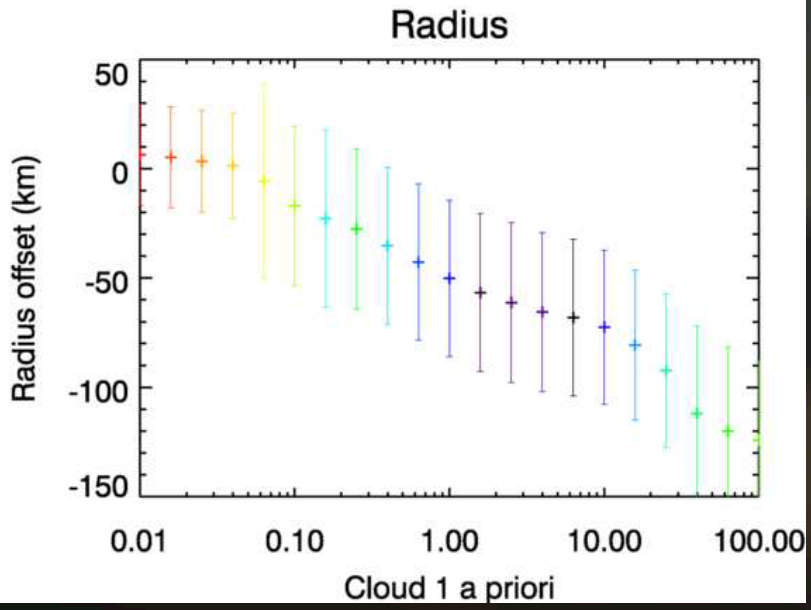
Monitor effect on results

Varying cloud 1 *a priori*



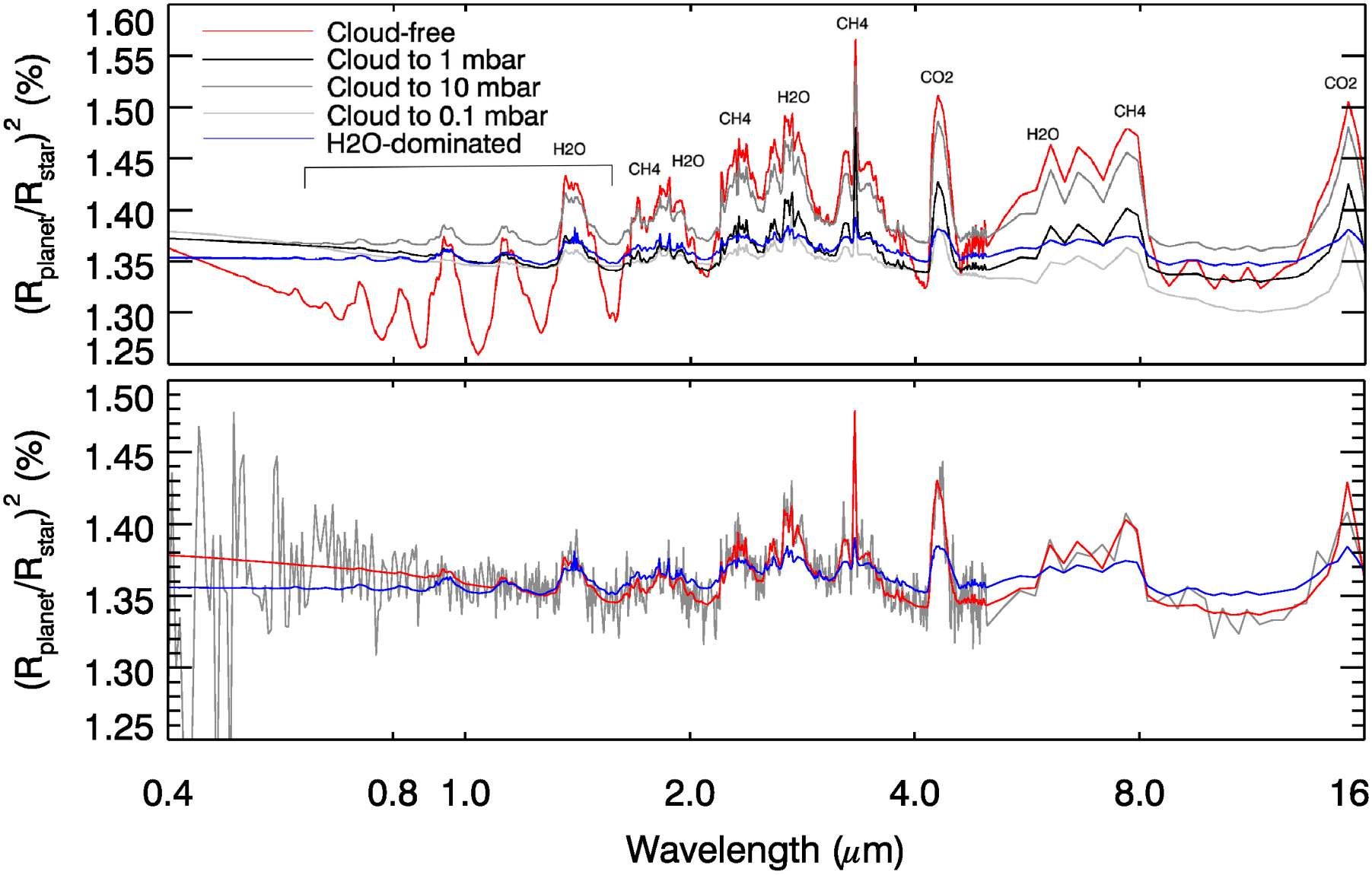


- Currently available spectroscopic/ photometric data are not constraining
- Range of H2-He models with cloud fit the spectrum well – a priori for small particulate haze has been varied over 4 orders of magnitude, which drives the retrieved property as other variables compensate
- 50% H2O atmosphere produces an equally good fit (not shown)

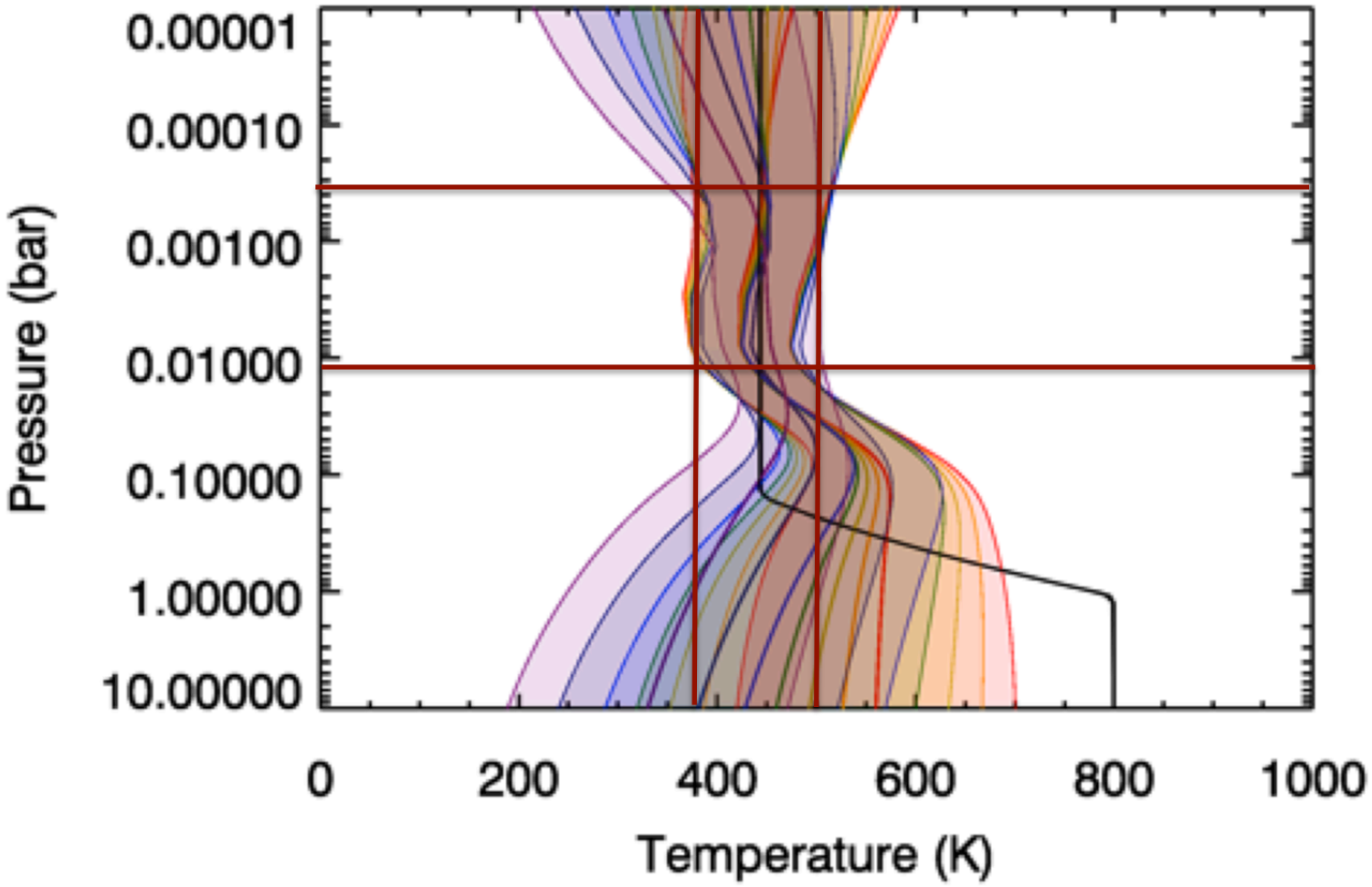


Hope for the future

- Can we solve this problem with EChO?
- GJ 1214b has one of the best transit signals
- Benchmark case for EChO's ability to constrain properties of super-Earth atmospheres.
- EChO has huge advantages over current ground + space capability – spectrum from visible to 16 microns obtained simultaneously, no stitching problems
- Also might be able to detect secondary eclipse for the first time – crucial for breaking degeneracies



- Different model atmospheres for GJ 1214b as seen by EChO
- At EChO resolution/sensitivity, should be able to distinguish between scenarios

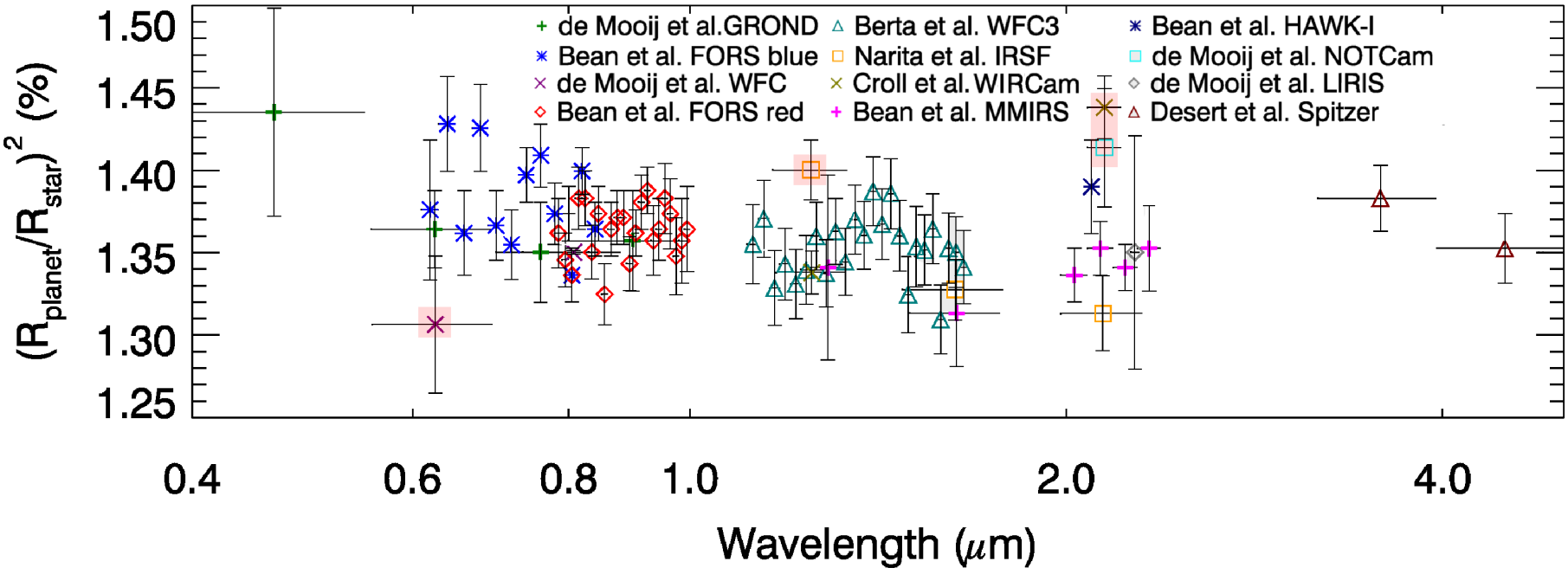

Pressure (bar)
0.00001
0.00010
0.00100
0.01000
0.10000
1.00000
10.00000
0
200
400
600
800
1000
Temperature (K)

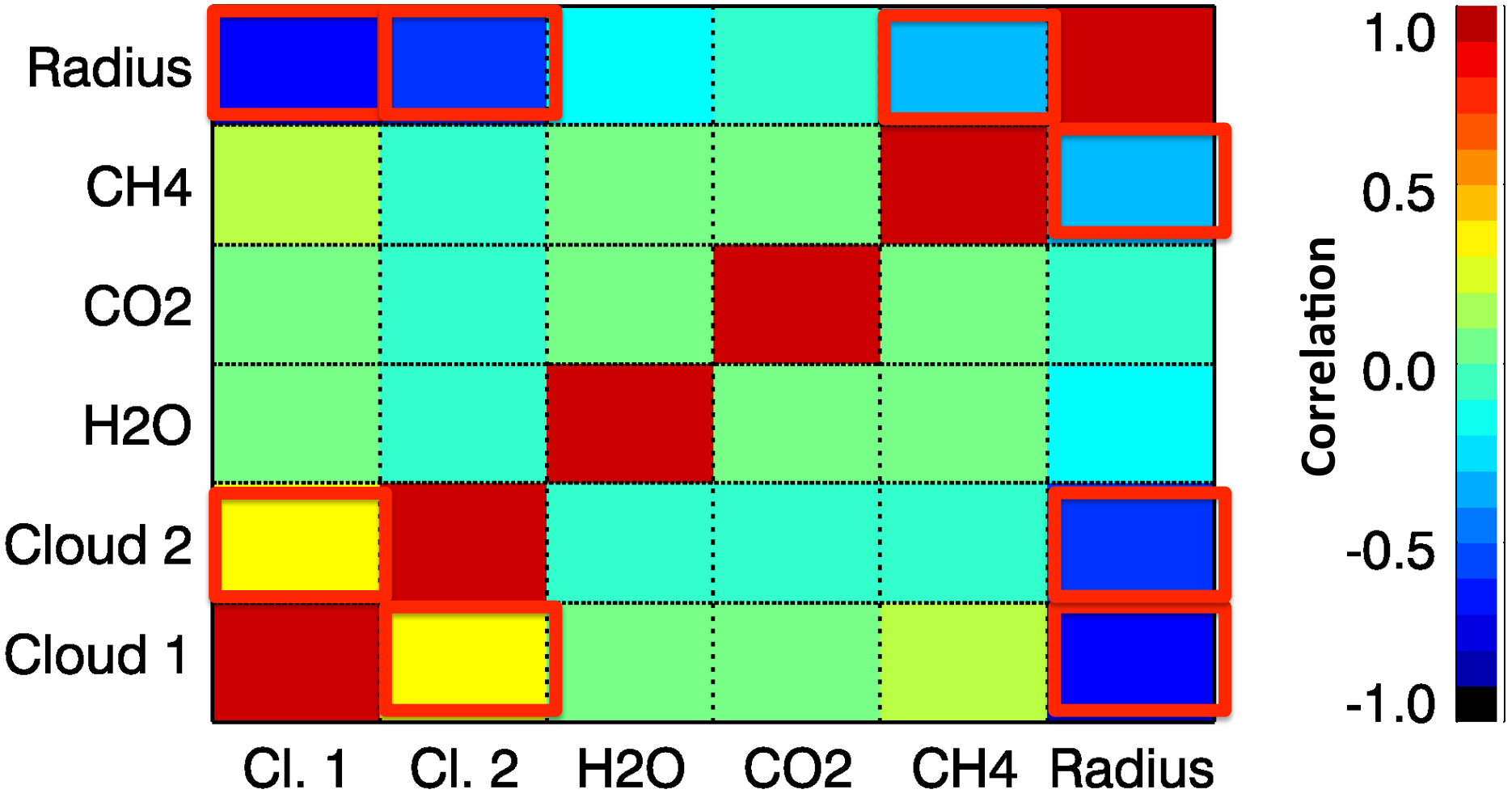
Conclusions

- Possible to fit GJ 1214b spectra with a cloudy H2-He atmosphere model
- However, getting any meaningful constraint on cloud/gas abundances is impossible with current data – many degenerate solutions
- Still a useful exercise though because
  a) Degeneracy problems highlighted – cautionary
  b) Indicates region of the spectrum that require observation in order to differentiate between scenarios
  c) Complementary method to *ab initio* modelling (e.g. techniques generally used for brown dwarfs etc) and reassuring when results are similar
- Will be able to do better with future missions like EChO.

Atmospheric property retrieval

Data




Radius
CH4
CO2
H2O
Cloud 2
Cloud 1
Cl. 1
Cl. 2
H2O
CO2
CH4
Radius
Correlation
1.0
0.5
0.0
-0.5
-1.0

Solving the inverse problem

- How do we get from a spectrum to an atmospheric structure composition?
  - Much of the spectrum is sensitive to many atmospheric properties
  - Need some method to disentangle these effects

- NEMESIS – uses non-linear optimal estimation algorithm
  - Calculates a synthetic spectrum based on an initial guess
  - Calculates a cost function that represents the difference between the synthetic and measured spectra
  - Simultaneously varies temperature structure, trace gases, cloud etc. in model and computes the 'functional derivative' (radiance gradient with respect to each model parameter at each wavelength)
  - Iterates towards solution with minimised cost function
  - Uses correlated-k approximation to rapidly compute absorption due to gases – very fast forward models
  - *A priori* constraints can be placed to prevent convergence on an unphysical solution. These constraints are normally based on information from previous observations; this is obviously more difficult for extrasolar planets!

Atmospheric property retrieval

Setting up the problem

- In transmission, not much information about temperature structure - assume simple T-P profile based on equilibrium temperature .

- Best-fits so far seem to be based on Titan tholins (complex hydrocarbons) – see Howe & Burrows.

- Start with a combination of 0.1 and 1 micron tholin particles – 0.1 micron particles with very narrow log-normal distribution (width 0.01, haze) micron log-normal distribution of width 0.25 (more like a cloud), 10-1 mbar (Problem: I could assume pretty much anything about this…)

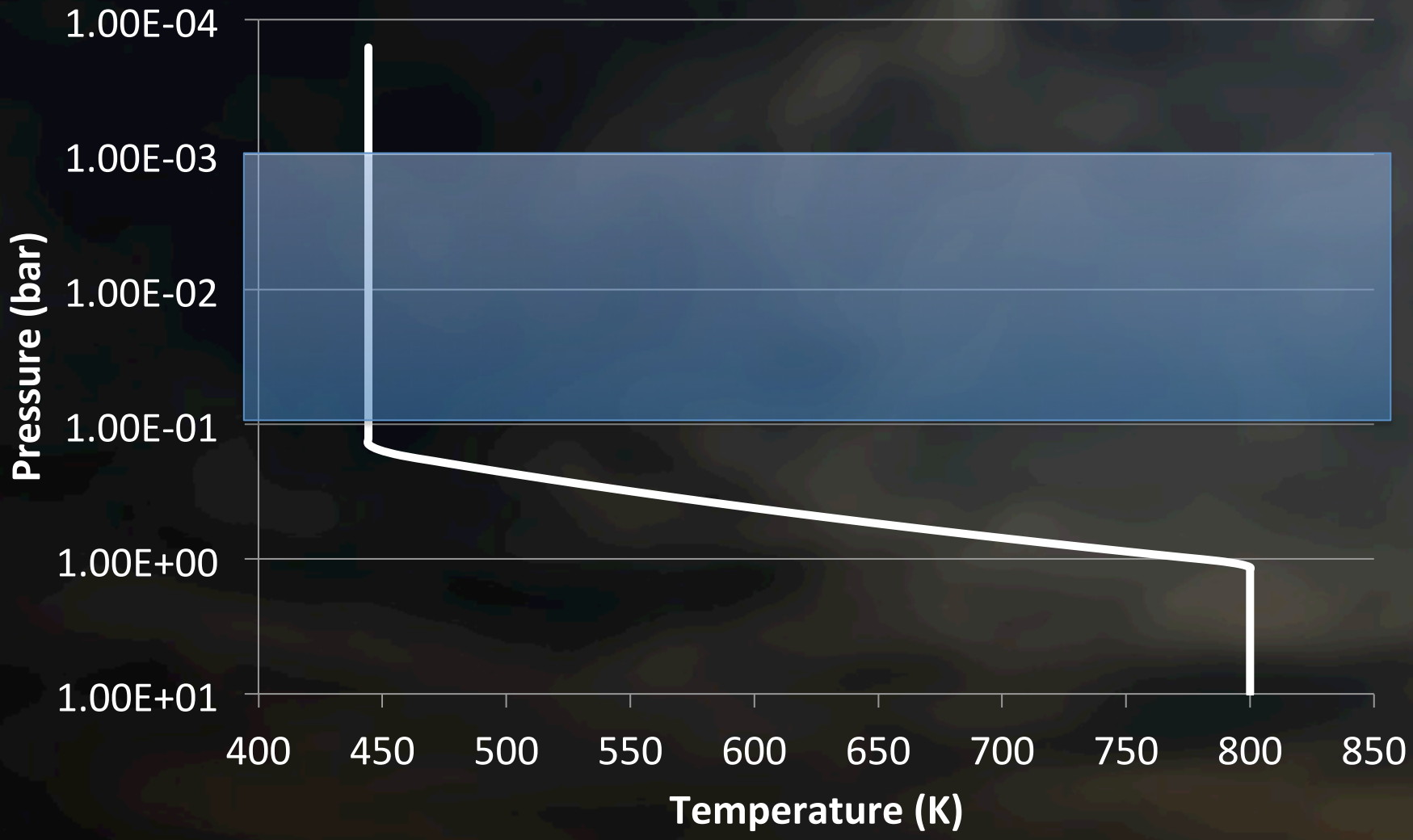
- *A priori*: 1000 cm-3 haze, 1 cm-3 cloud at 100 mbar, F.S.H.=1

- Variables:
  - 2x cloud population optical depth
  - H2O, CO2, CH4 VMR (assumed constant with altitude)
  - Planetary radius

- Rest of atmosphere assumed to be 9:1 H2:He

Atmospheric property retrieval

Setting up the problem



Atmospheric property retrieval

Setting up the problem

- In transmission, not much information about temperature structure - assume simple T-P profile based on equilibrium temperature .

- Best-fits so far seem to be based on Titan tholins (complex hydrocarbons) – see Howe & Burrows.

- Start with a combination of 0.1 and 1 micron tholin particles – 0.1 micron particles with very narrow log-normal distribution (width 0.01, haze) micron log-normal distribution of width 0.25 (more like a cloud), 100-10 mbar (Problem: I could assume pretty much anything about this…)

- *A priori*: 1000 cm-3 haze, 1 cm-3 cloud at 100 mbar, F.S.H.=1

- Variables:
  - 2x cloud population optical depth
  - H2O, CO2, CH4 VMR (assumed constant with altitude)
  - Planetary radius

- Rest of atmosphere assumed to be 9:1 H2:He

Atmospheric property retrieval

Data

- Grond (g,r,i,z), WFC (r,I,z), NOTCAM (Ks), LIRIS (Kc) - deMooij et al. 2012
- VLT FORS Blue, MMIRS (J,H,K), HAWKI 209 - Bean et al. 2011
- VLT FORS Red – Bean et al. 2010
- Hubble WFC3 – Berta et al. 2012
- IRSF (J,H,K) – Narita et al. 2012
- WIRCAM (J,Ks) – Croll et al. 2011
- Spitzer (3.6,4.5) – Desert et al. 2011