Atmospheric Retrieval Analysis of the Directly Imaged Exoplanet HR 8977b

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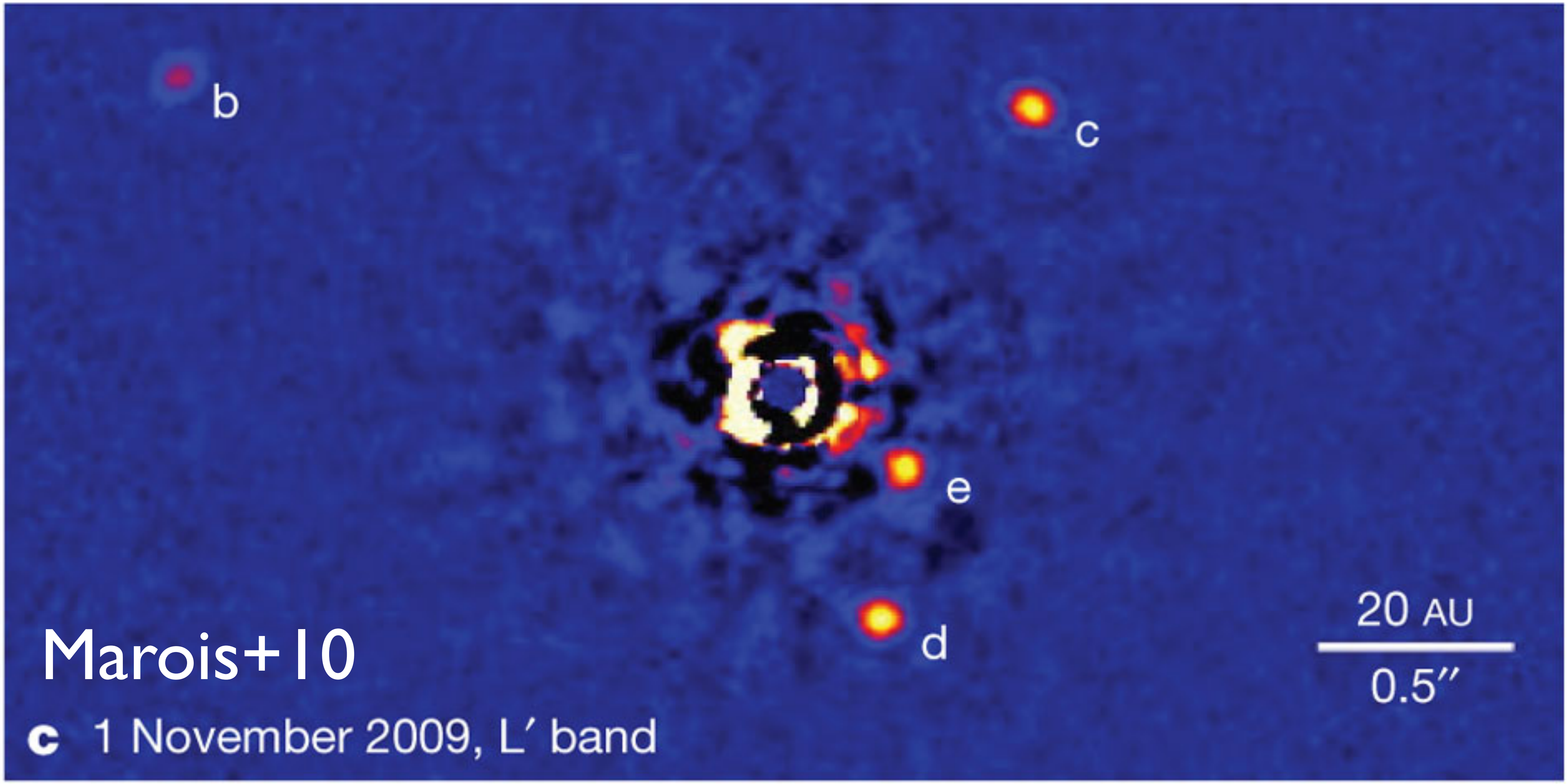
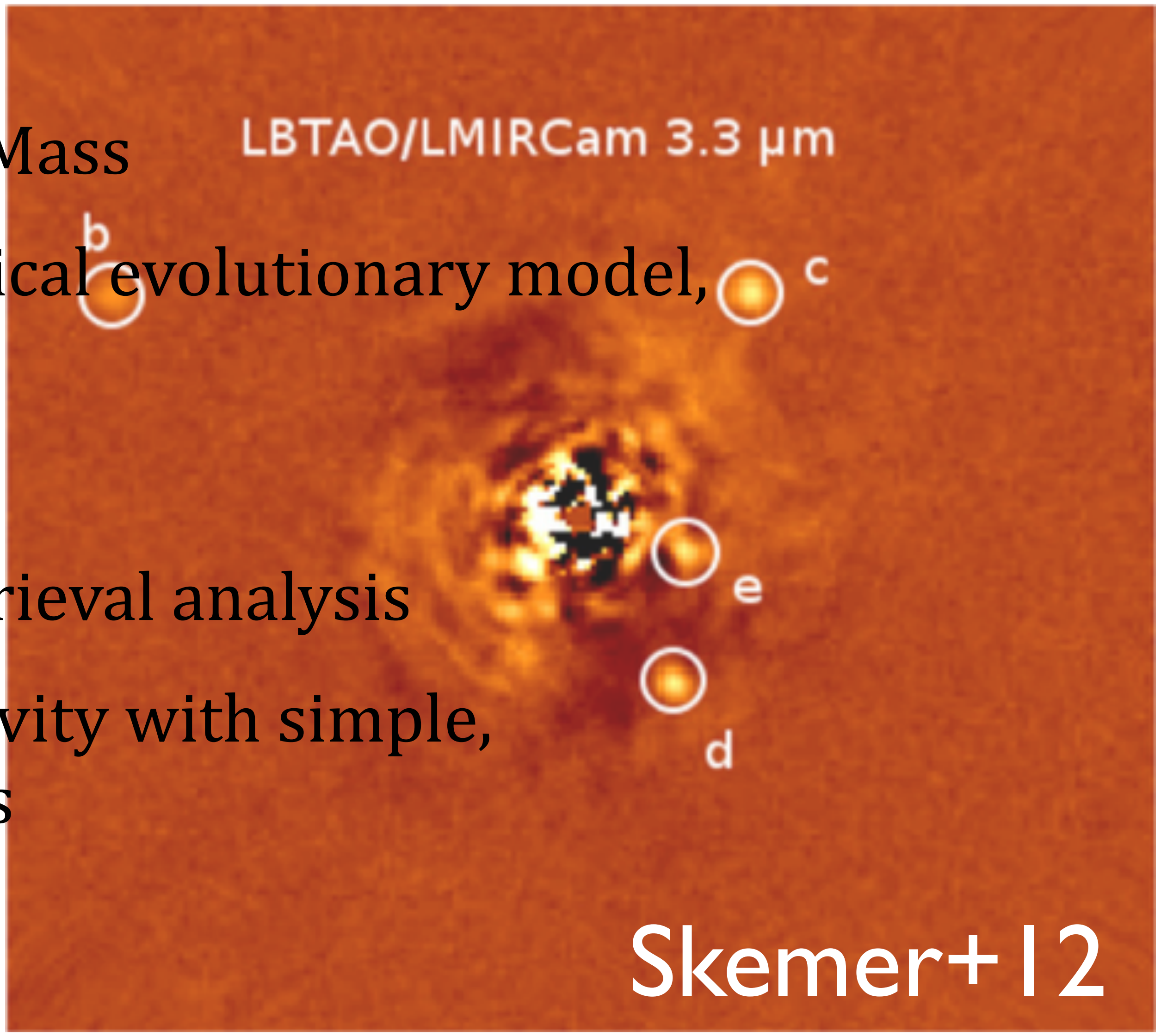


HR 8799b

- Directly imaged exoplanet - Photometrically resolved from the parent star
- No irradiation, Self-luminous planet
- Dark, Low effective temperature (different from other planets)
- Cloudy atmosphere
- Uncertain Radius, Surface gravity, Mass
  - Orbital stability model, Theoretical evolutionary model, Forward model
- What we did
  - Inverse modelling - Spectral retrieval analysis
  - a suite of radius and surface gravity with simple, phenomenological cloud models

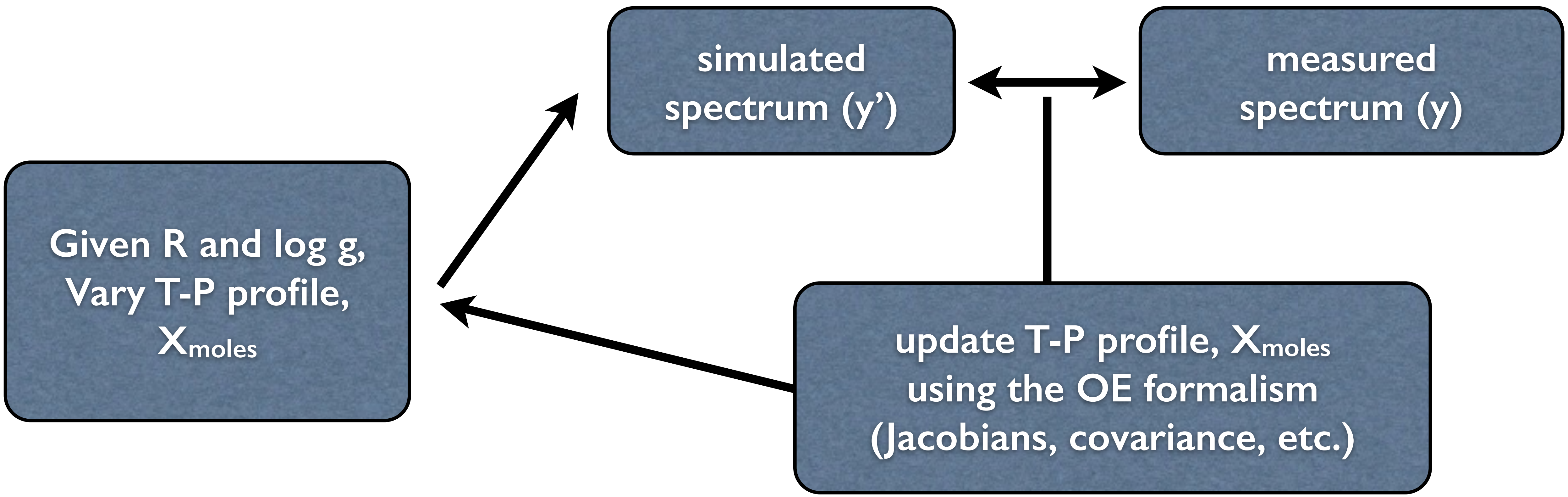


Retrieval - Optimal Estimation

- NEMESIS (Irwin+08, Rodgers 00)
- Find "best-fit" solution by iteratively solving non-linear inverse problem in analytic way
- "What is the atmosphere consistent with data?"
- A common technique to find plausible scenarios for solar system planets and now for transiting exoplanets
- Direct imaged planets (also, brown dwarfs) are much ideal for spectral retrieval than transiting planets

How to set up retrieval

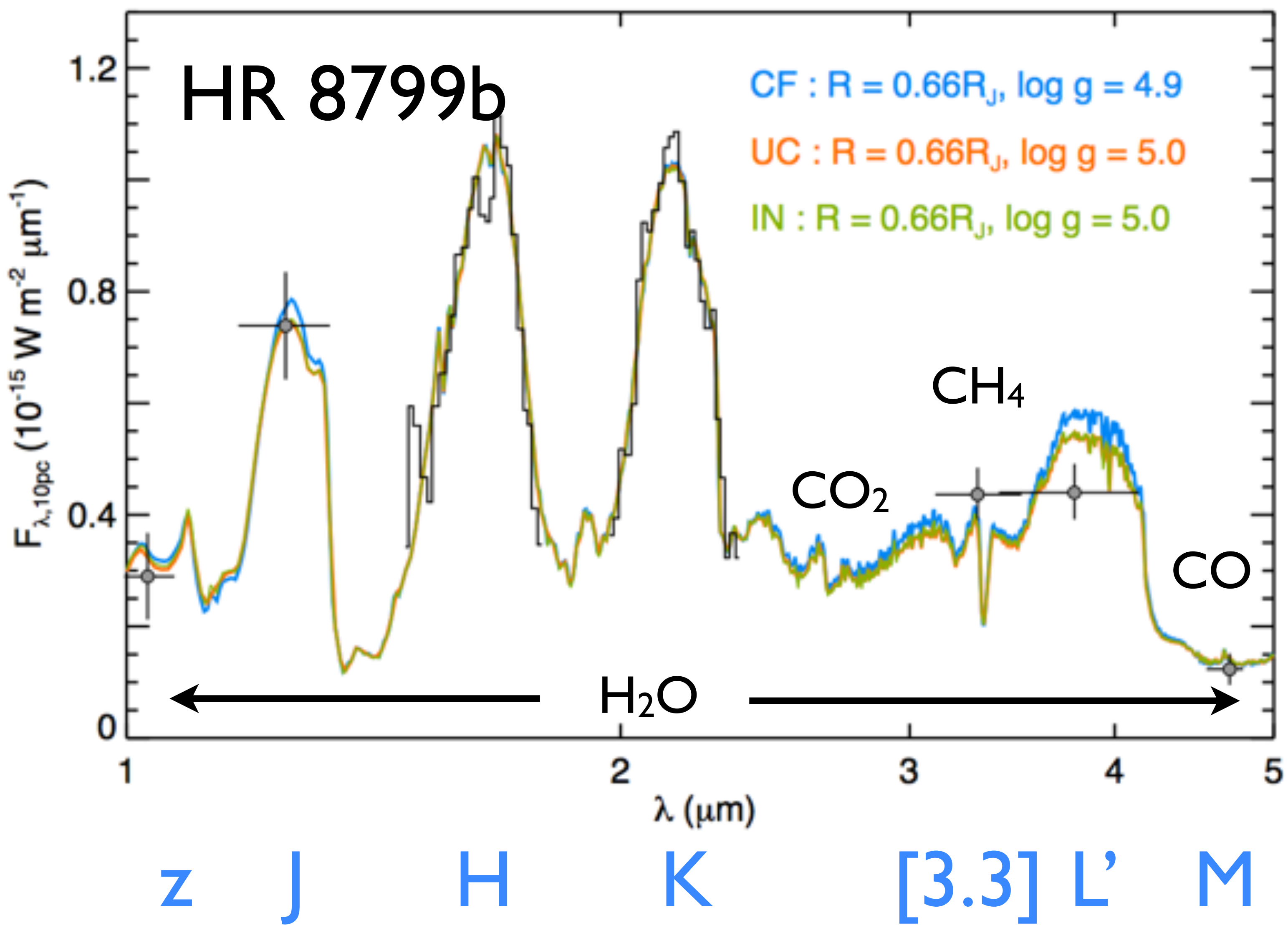
- Free parameters (parameterisation)
  - ✓ $R = 0.6R_J$ - $1.2R_J$ ($R\downarrow \rightarrow \uparrow T_{eff}$ for same F_{TOA} [$W/cm^2/\mu m$])
  - ✓ log g = 3 - 5.5 ($g\uparrow \rightarrow \downarrow$scale height,)
  - ✓ cloud properties, particle size and optical depth (add. opacity)
- Fitting variables : layered T-P profile, X_{moles} for H_2O, CO_2, CO, CH_4

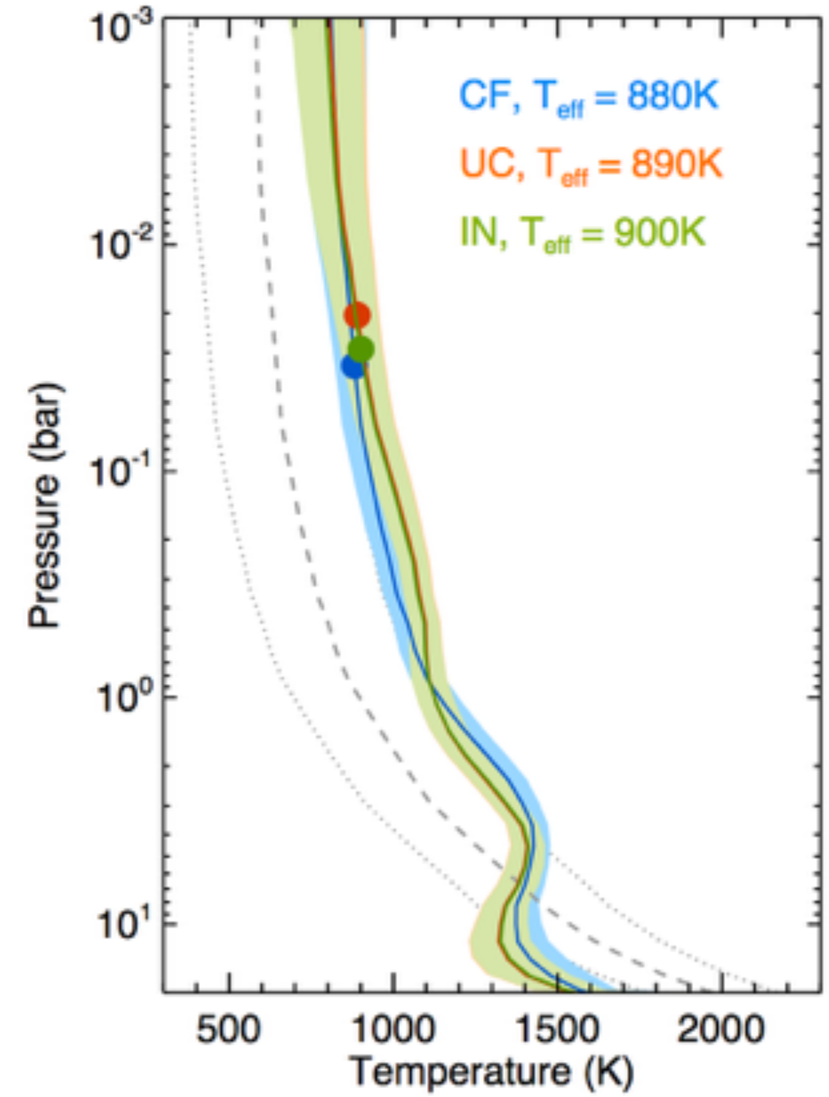


Spectrum fitting

- Fitting variables : Species (H_2O, CO_2, CO, CH_4, H_2, He), temperature profile (43 layers) → disk-averaged flux, F_λ

- Triangular shapes of H and K : H_2O + C species

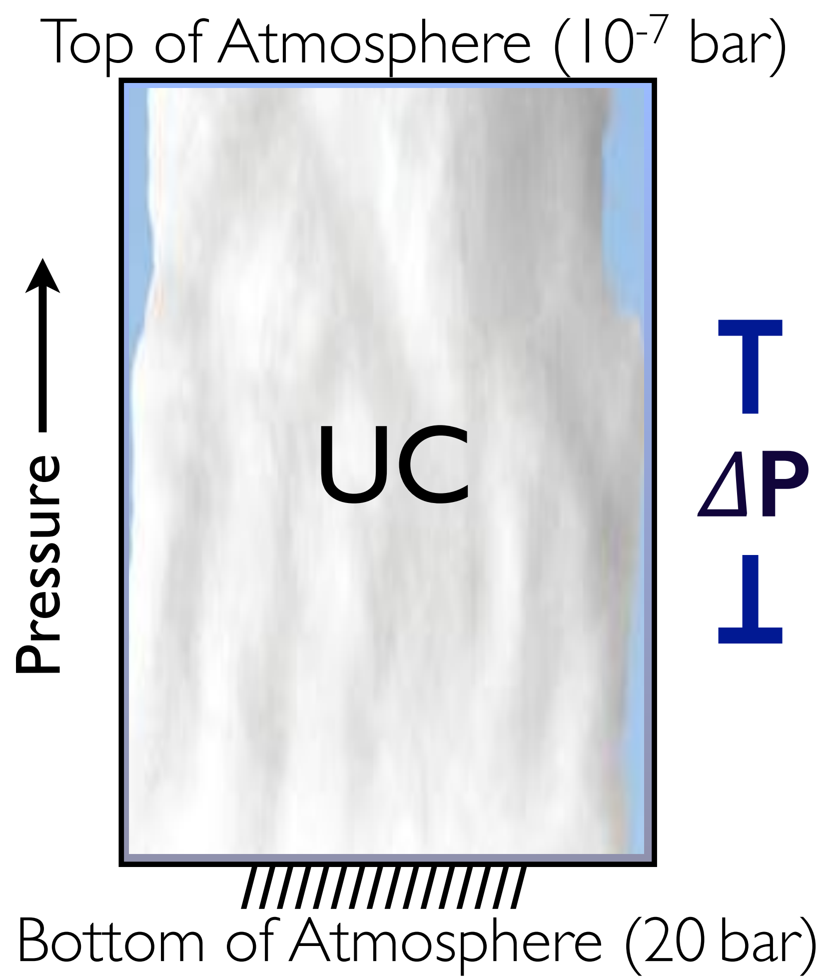


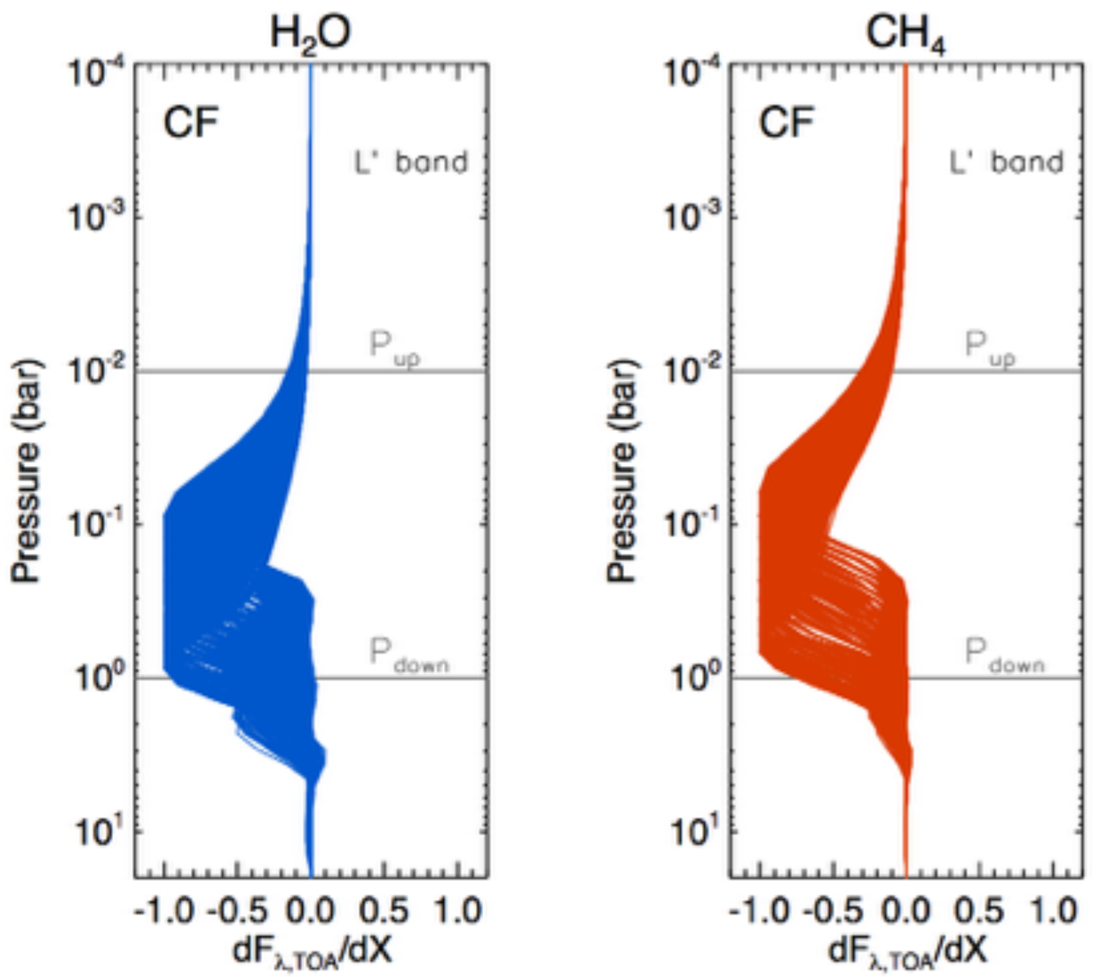


z, J, L' : Currie+11 H, K : Barman+11 [3.3] : Skemer+12 M : Galicher+11

Cloud Model

- Simple and Phenomenological Cloud
  - horizontally and vertically uniform and spherical, mono-disperse $MgSiO_3$ particles
  - two parameterised model, optical depth and particle size (free parameters), additional two parameters for geometry
  - CF (cloud-free), IN (intermediate), UC model (uniform)

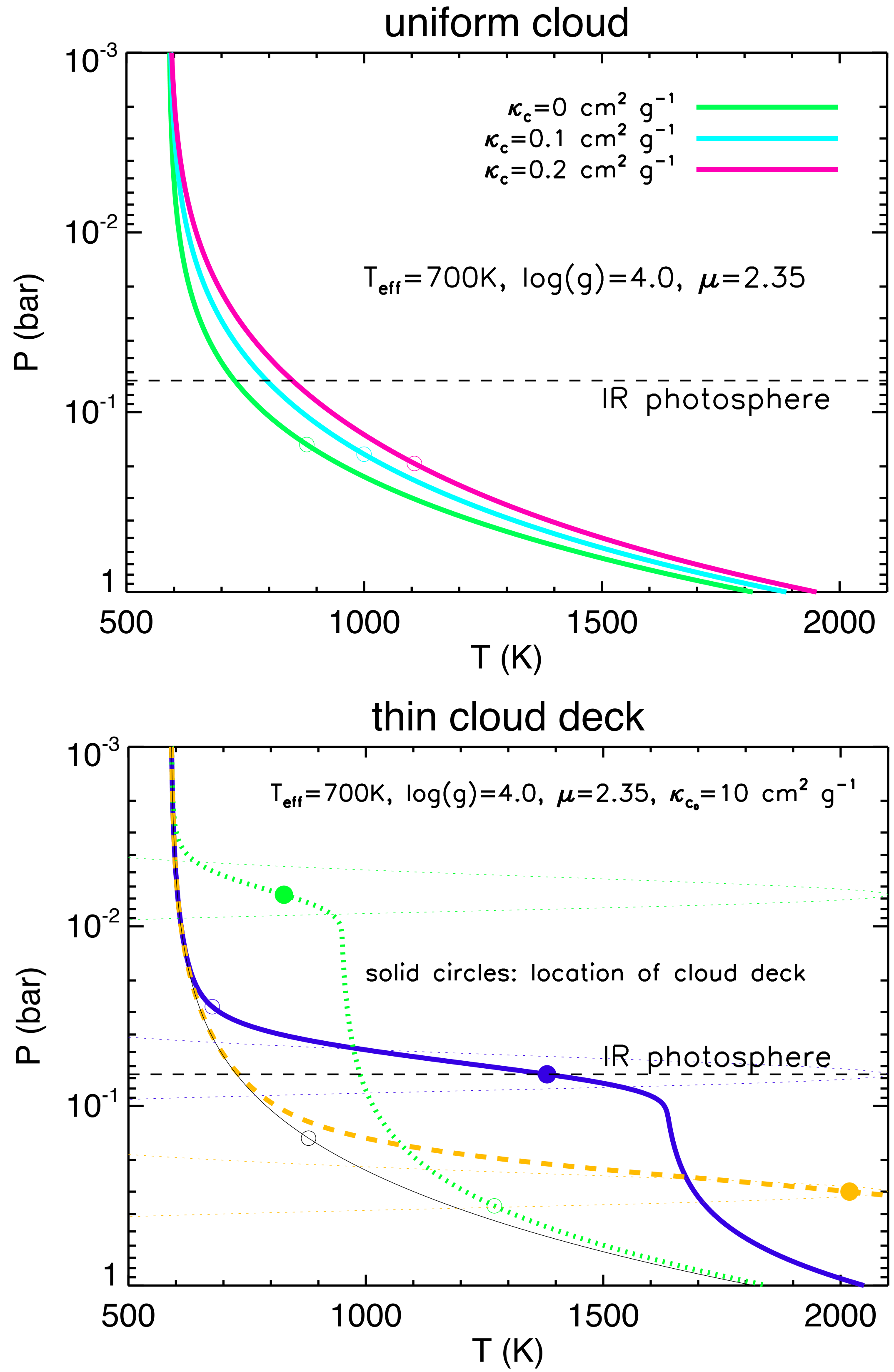




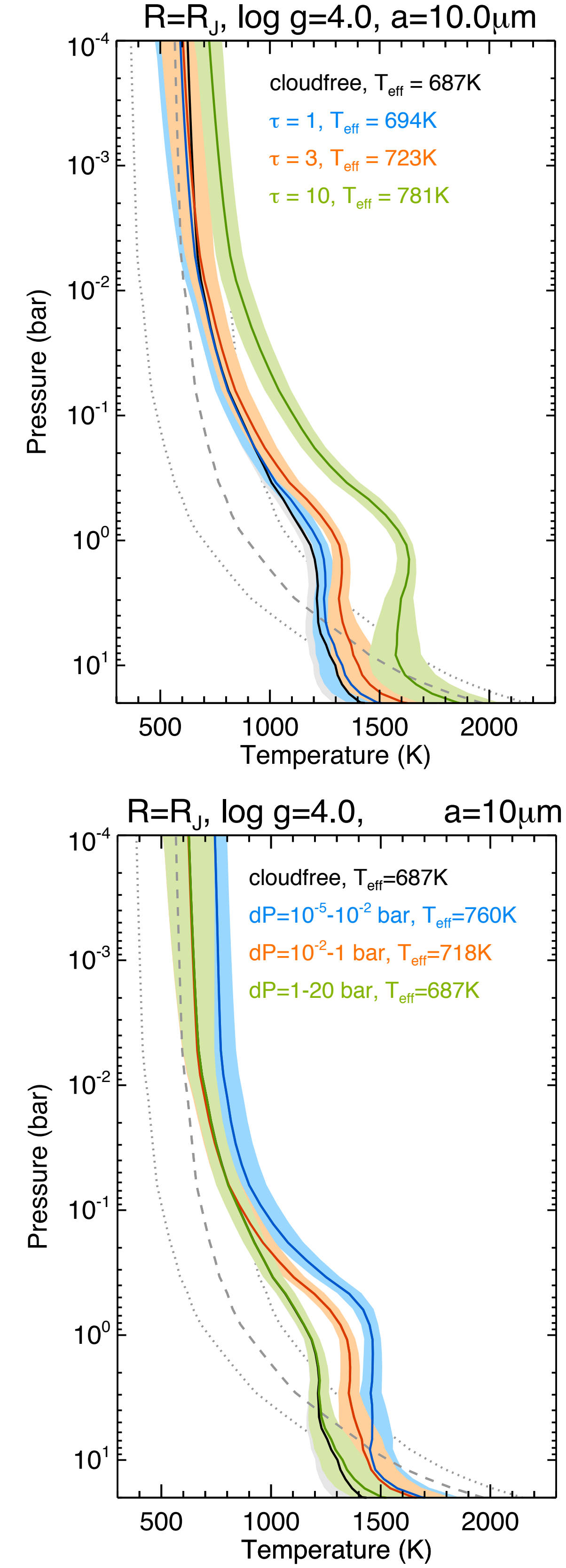
Effect of cloud to temperature profile

- ✓ Maximum scattering extinction (Q_{sca}) → maximum greenhouse effect
- ✓ pure absorbers
- ✓ T-P profile : retrieved from measurement constraints
- ✓ Cloud → increase temperature at certain pressures

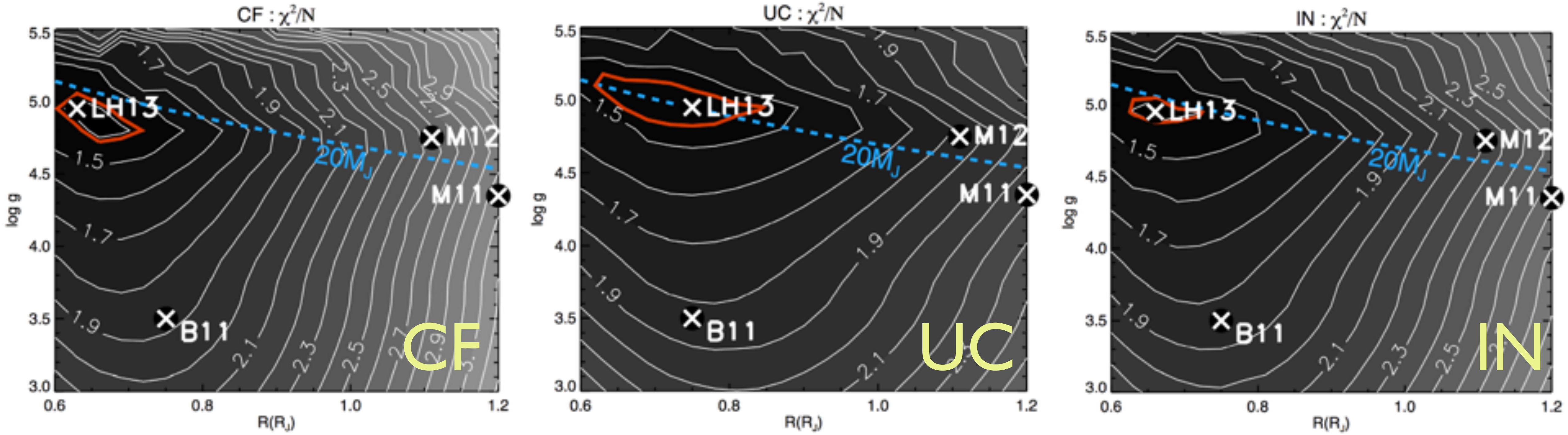
Analytical model



Retrieval

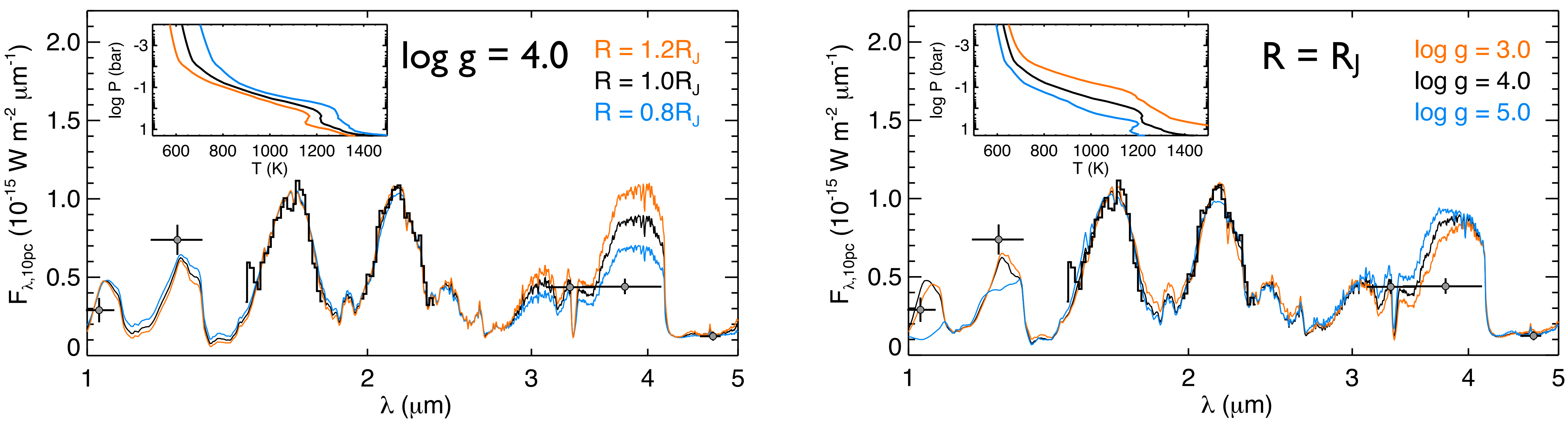


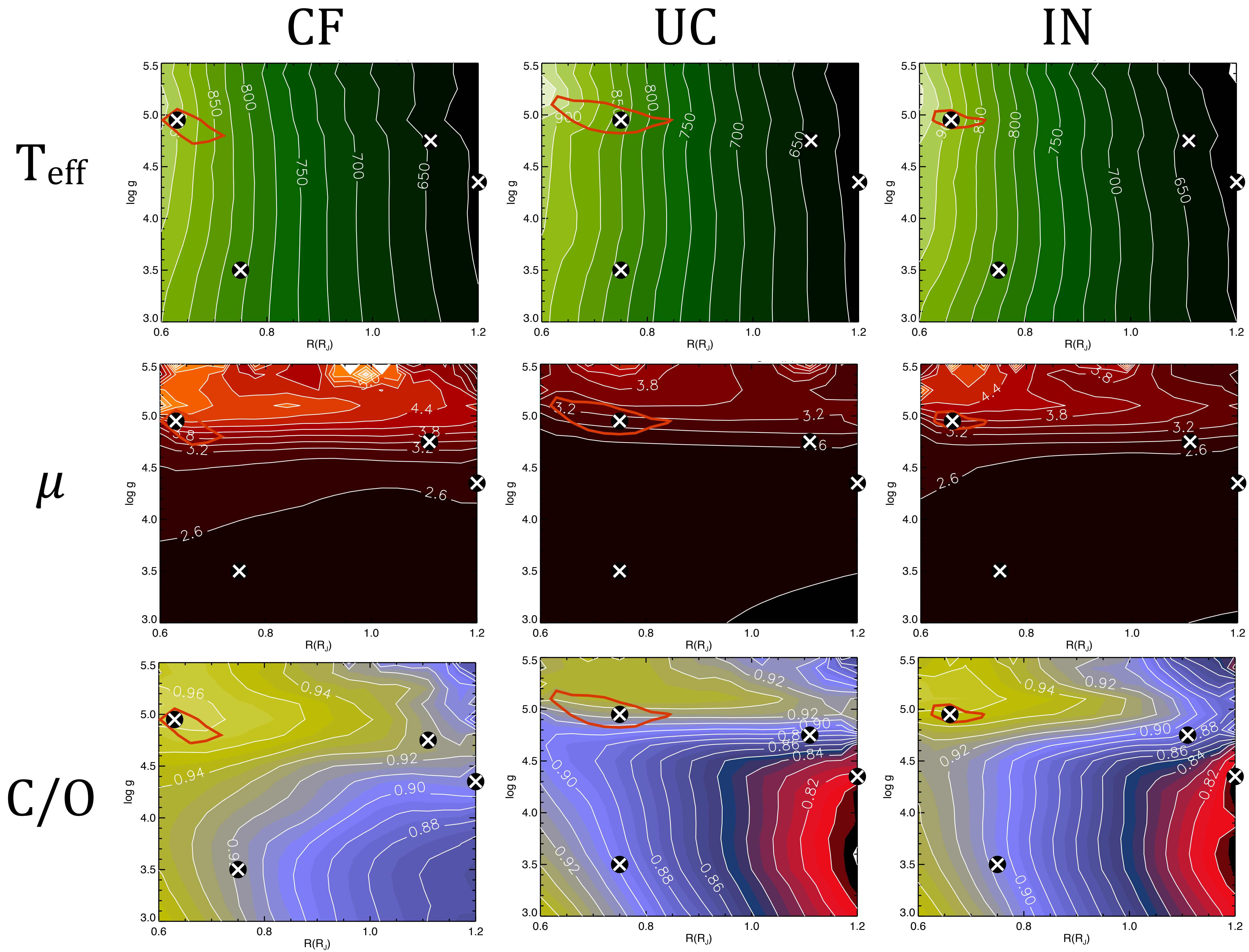
Small R (R~0.6-0.7RJ) and large log g (log g~5)



B11 : Barman+11 M11 : Madhusudhan+11 M12 : Marley+12

fix Xs and vary T-P profile



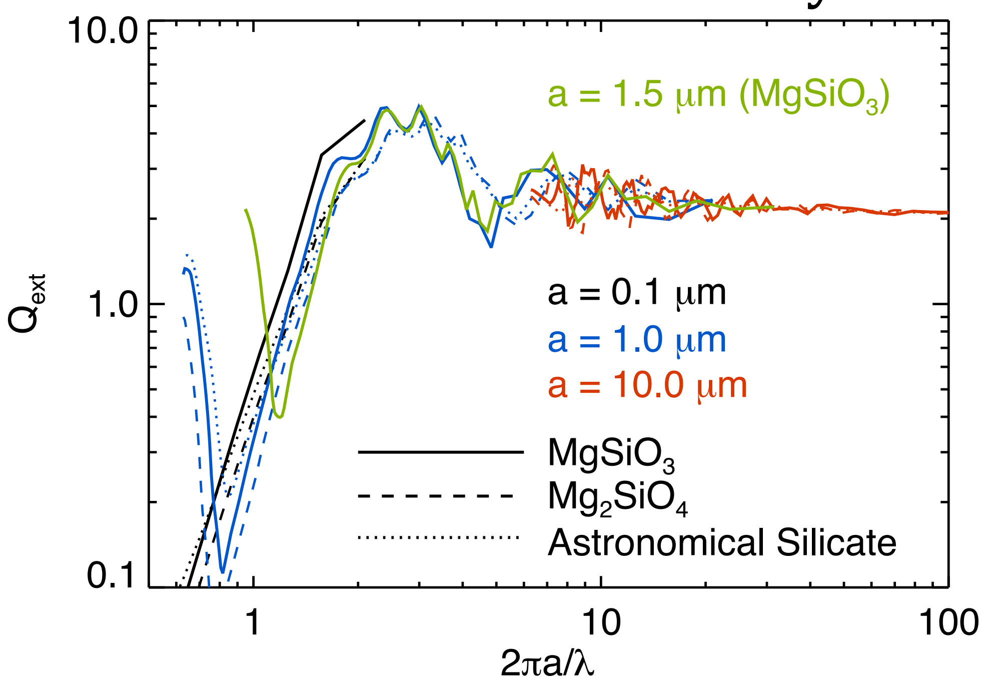


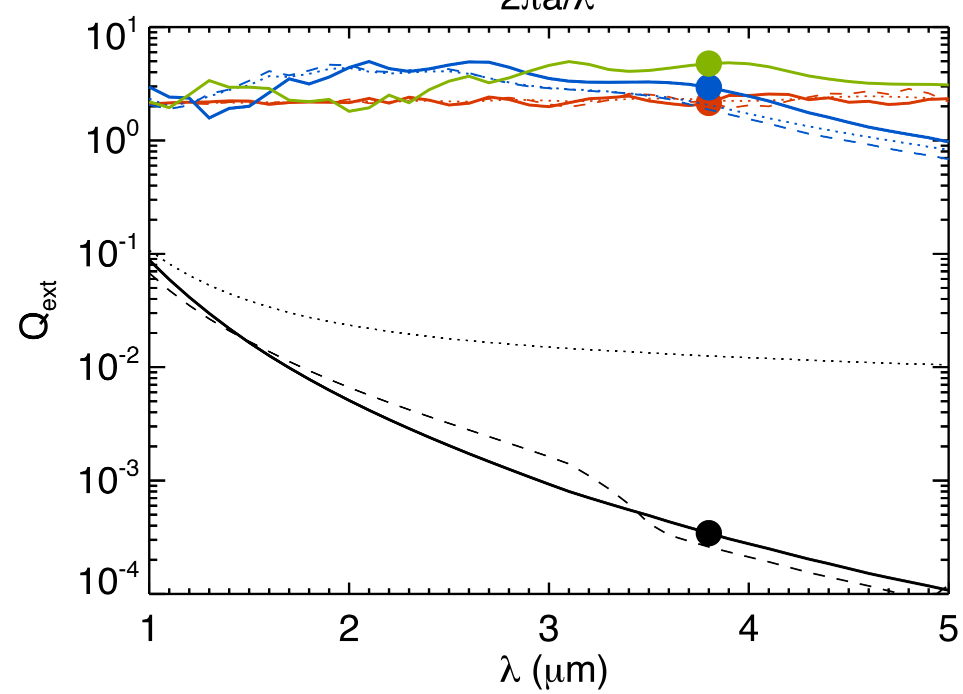
CF
UC
IN
T_{eff}
μ
C/O
log g
R(R_J)
850
800
750
700
650
900
3.8
3.2
2.6
4.4
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.82

Particle size effect

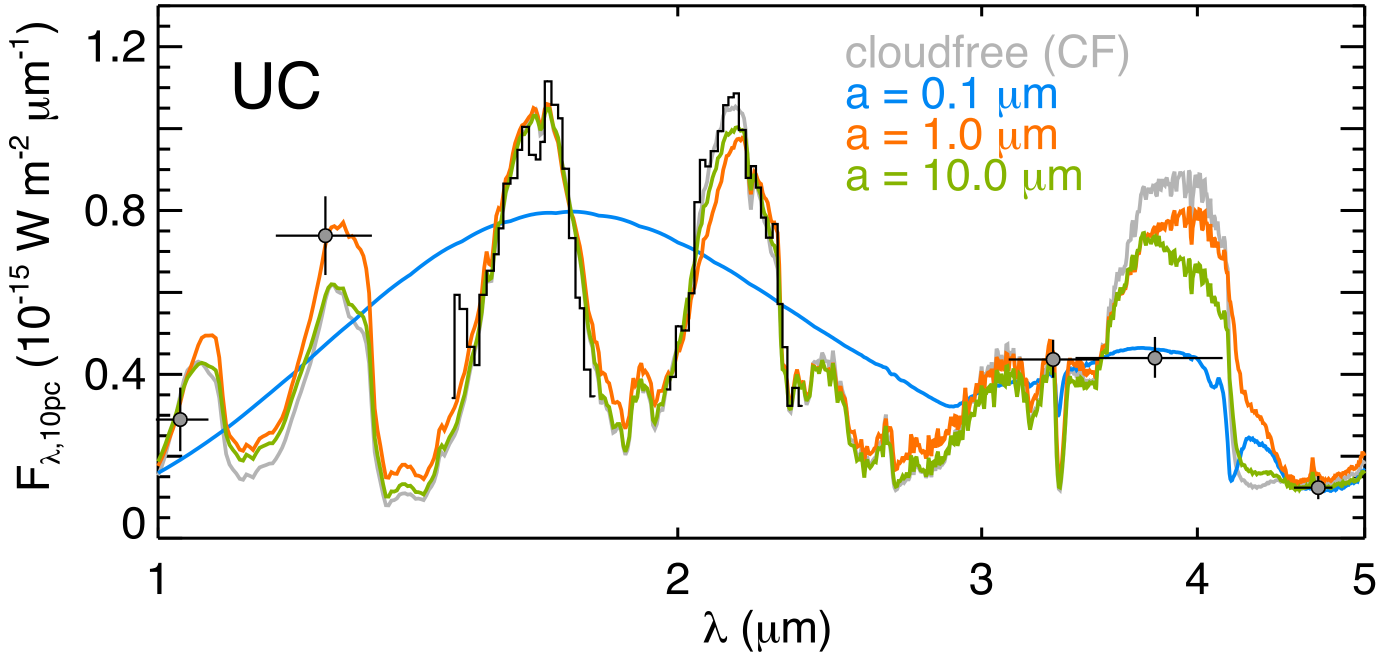
- A specific particle size gives a better fit by reducing a flux at a specific band, e.g., L' band

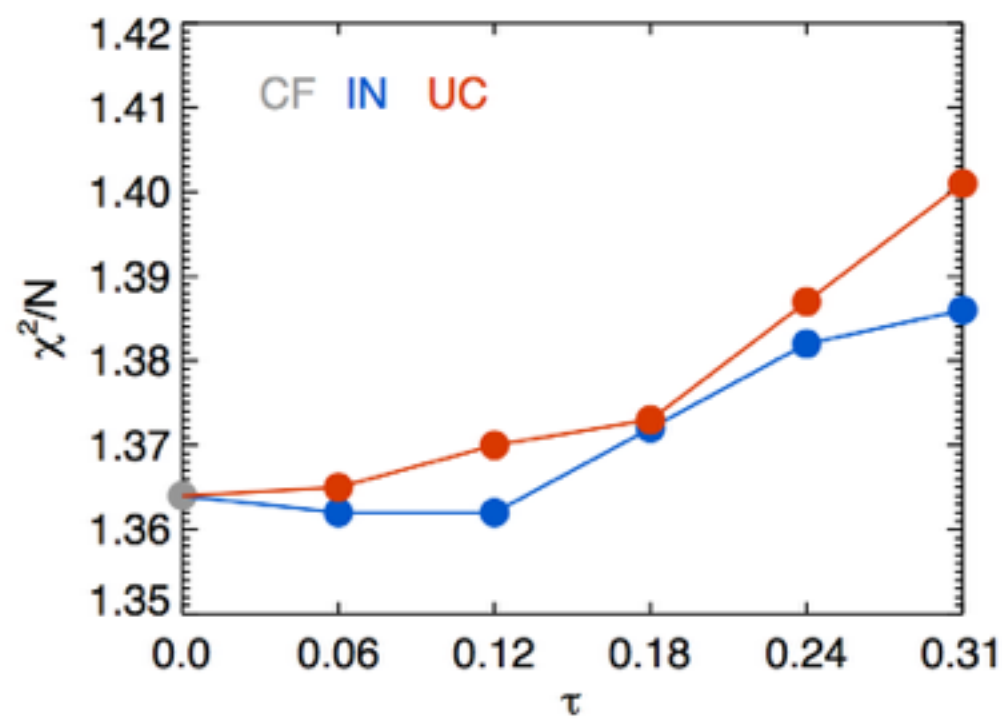
Extinction efficiency





Optical depth = 0.58





IN model
a = 1.5 um

Findings...

from the first retrieval approach for direct imaged planet HR 8799b

- small radius ($R \sim 0.6$-$0.7\ R_J$) and high surface gravity ($\log g \sim 5$) for all cloud models

- $R=0.6$, $\log g=5.0$ give $M \sim 15$-$20\ M_J$, (high density)

- High mean molecular weight ($\mu \sim 3$-4) due to a high CO retrieved

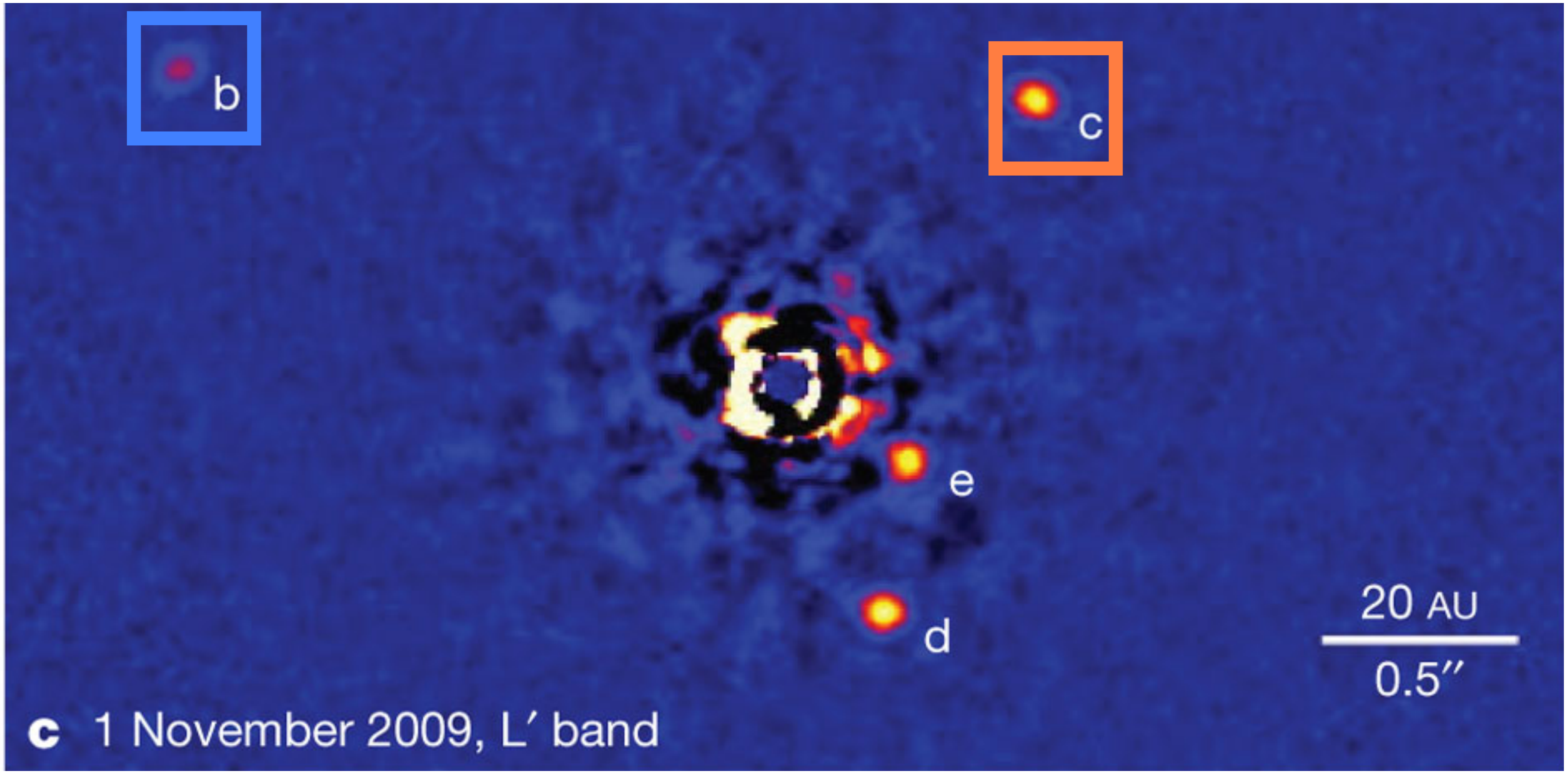
- L' band is constrained and some photometric points are less useful

- "Magic" monodisperse particle size a=1.5 um provides the best-fit model

- Limitations - no prior information, incomplete line-lists, degeneracy between all parameters

Beyond HR 8799b...

- ✓ HR 8799b vs. HR 8799c
  - Can we provide any information for planet formation?



- ✓ Surely, brown dwarfs will be our next targets!