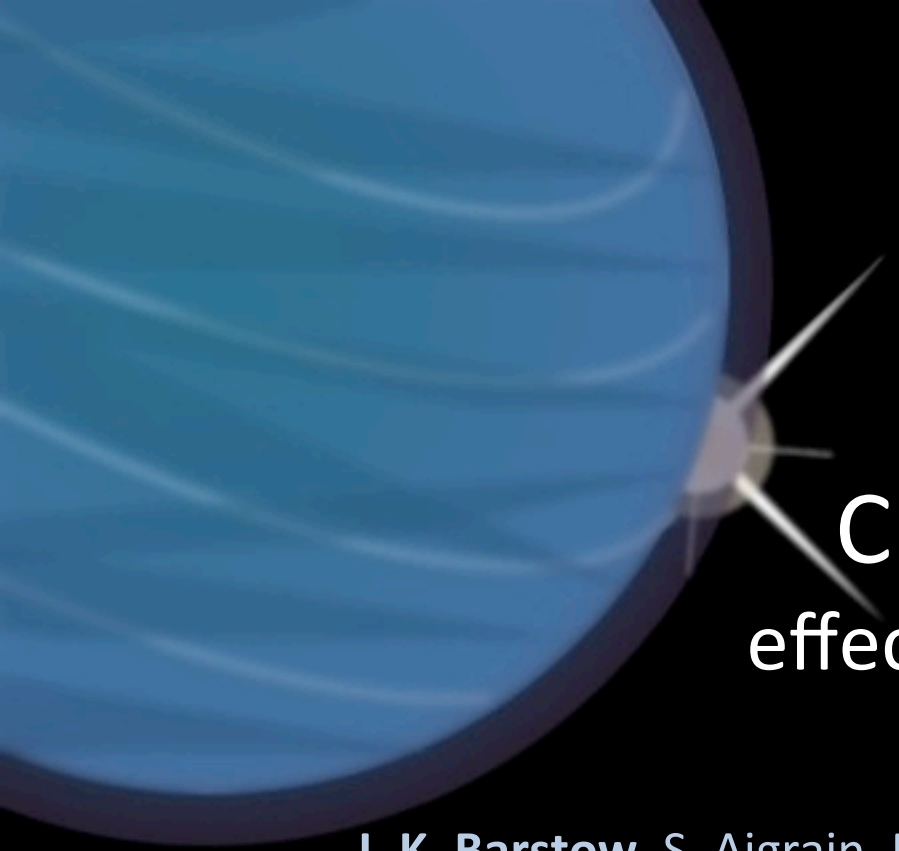

UNIVERSITY OF OXFORD

# Clouds on HD 189733b:
## effects on atmospheric retrieval

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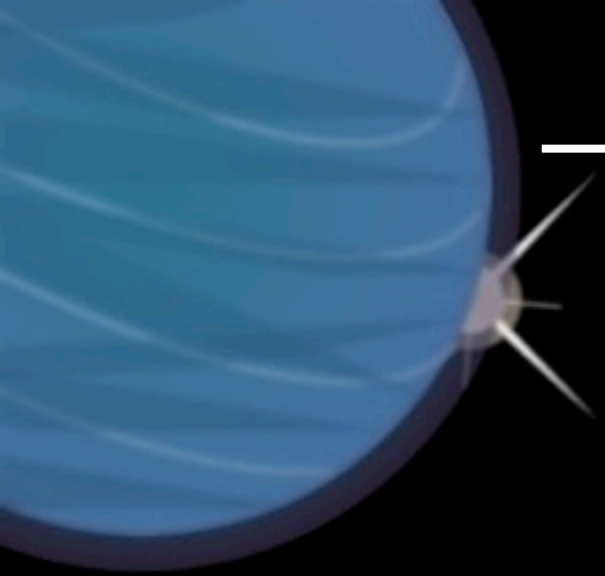
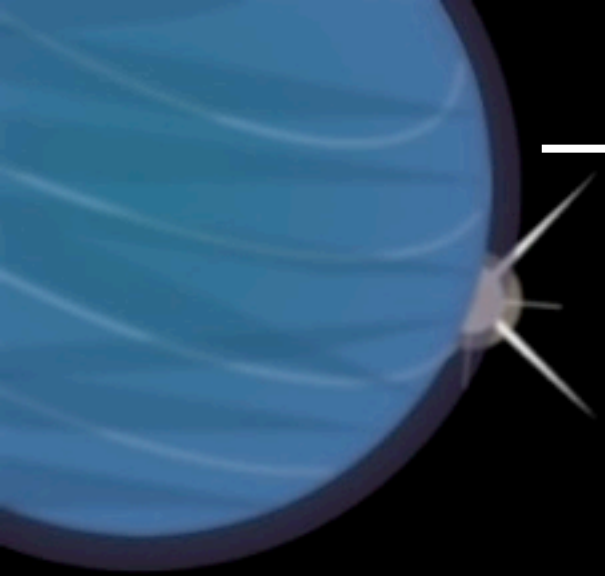


# Outline

- Introduction to HD 189733b
- Evidence for clouds on HD 189733b
  - Transmission spectra
  - Recent albedo spectrum from Evans et al.
- Cloud models and dayside retrievals
  - Constraints from albedo
  - Effect on emission spectra
  - Impact of multiple scattering v. single scattering in model calculation
- Conclusions



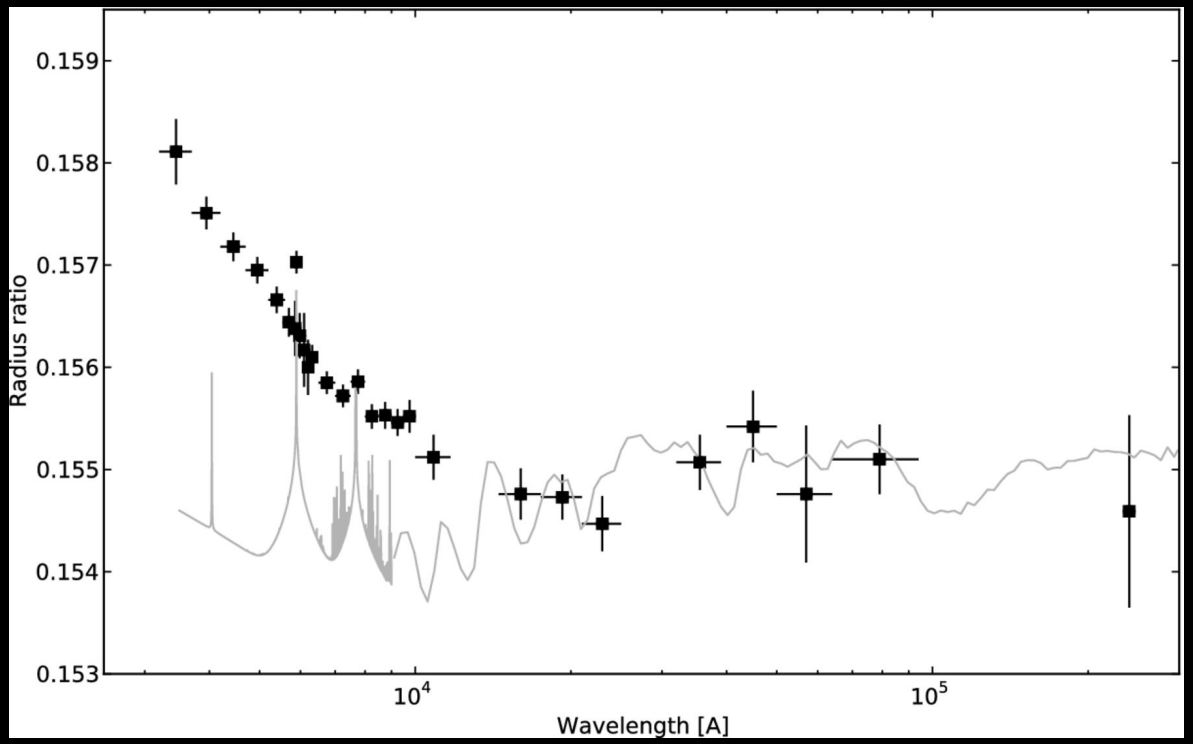
# HD 189733b

- One of the best-studied ‘hot Jupiters’ – good spectral coverage in both transmission and emission from the visible to mid-infrared
- Orbiting a K1.5V star ~60 ly away
- ~1.14 RJ, ~1.16 MJ, dayside equilibrium temperature estimated to be ~1200 K
- Recent HST/STIS results show the planet is blue

# Evidence for clouds

## Transmission

- Transit lightcurves from 290 nm – 28.5 μm re-analysed by Pont et al. 2013
- Planet radius is bigger at shorter wavelengths than expected from $H_2$-He Rayleigh scattering



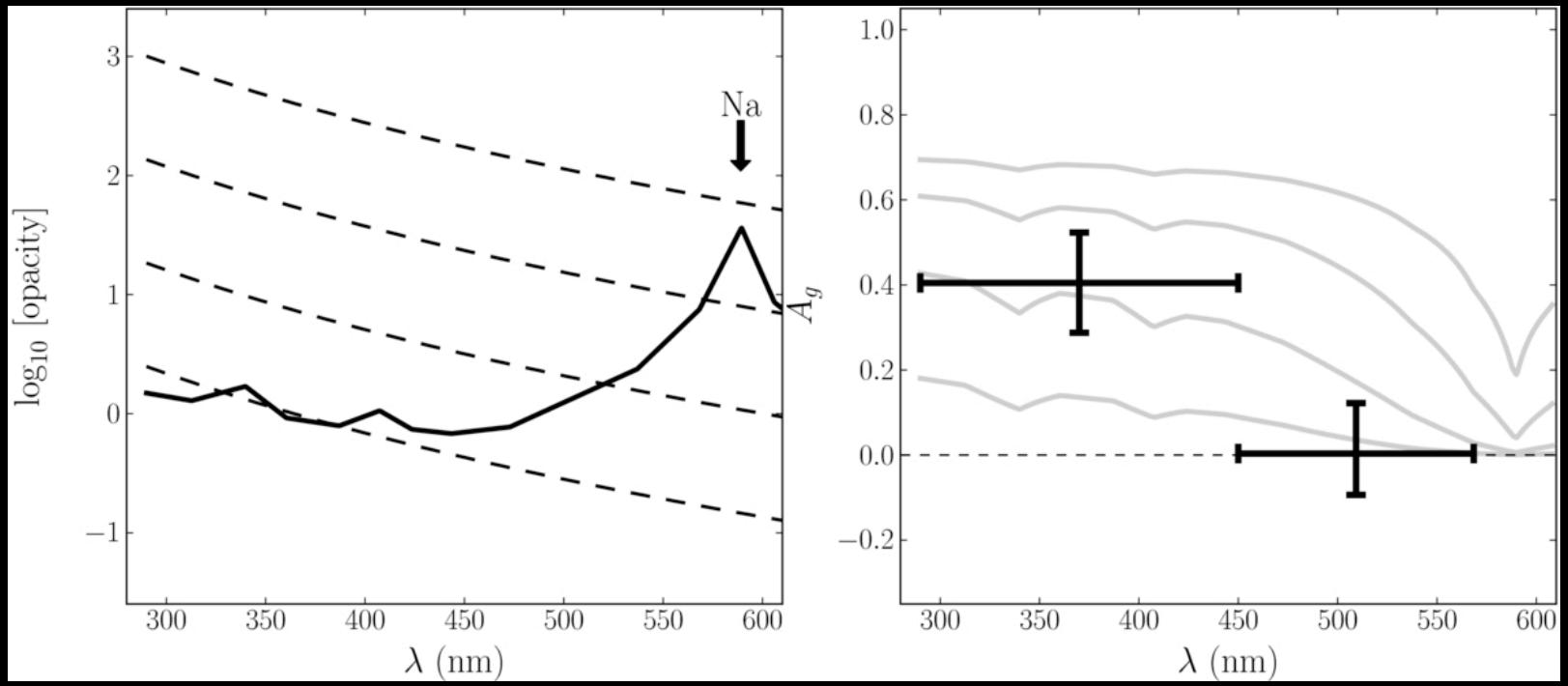

- Transmission spectrum is relatively flat elsewhere
- Evidence for haze at high altitudes, possibly cloud lower down

**Pont F et al. MNRAS 2013;432:2917-2944**

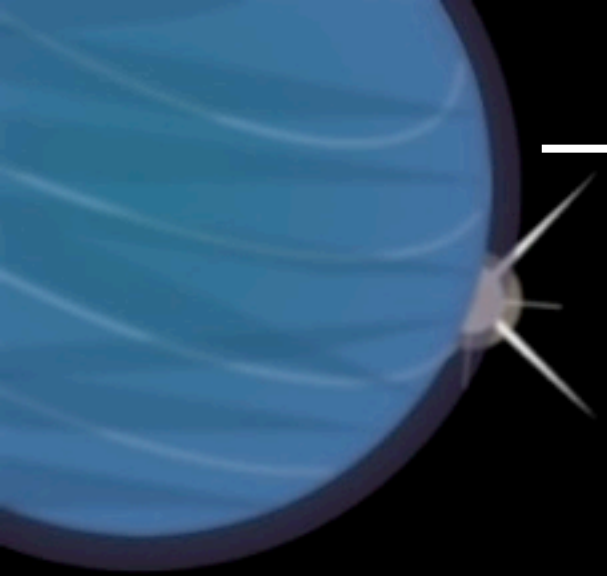
# Evidence for clouds

## Reflection

- Recent Hubble/STIS reflection spectrum shows a decrease in albedo from blue to red
- Sodium absorption likely cause of downward albedo slope, but may also be influenced by scattering particles




Evans T et al. ApJ 2013;772:L16



# Cloud-free models

## Reflection

- Need at least 1.5 ppmv Na
- 5 ppmv Na (~solar) up to 50 ppmv Na all produce reasonable slope without cloud
- Constraints from spectrum insufficient to determine Na abundance – for now, use solar
- K has little effect. TiO/VO not yet considered, HD 189733b probably too cold but can't rule it out entirely

# Cloudy atmosphere models

## Reflection

- We calculate synthetic disc-averaged STIS reflection spectra (NEMESIS – Irwin et al. 2008)
- Range of sizes/optical depths/altitudes of enstatite cloud particles
- Reject models for which $\chi^2 > 10$.

| O.D\Size (μm) | 10 | 3 | 1 | 0.3 | 0.1 | 0.03 | 0.01 |
|---|---|---|---|---|---|---|---|
| 10.0 | | | | | | | |
| 1.0 | | | | | | | |
| 0.8 | | | | | | | |
| 0.6 | | | | | | | |
| 0.4 | | | | | | | |
| 0.2 | | | | | | | |
| 0.1 | | | | | | | |

# Cloudy atmosphere models

## Reflection

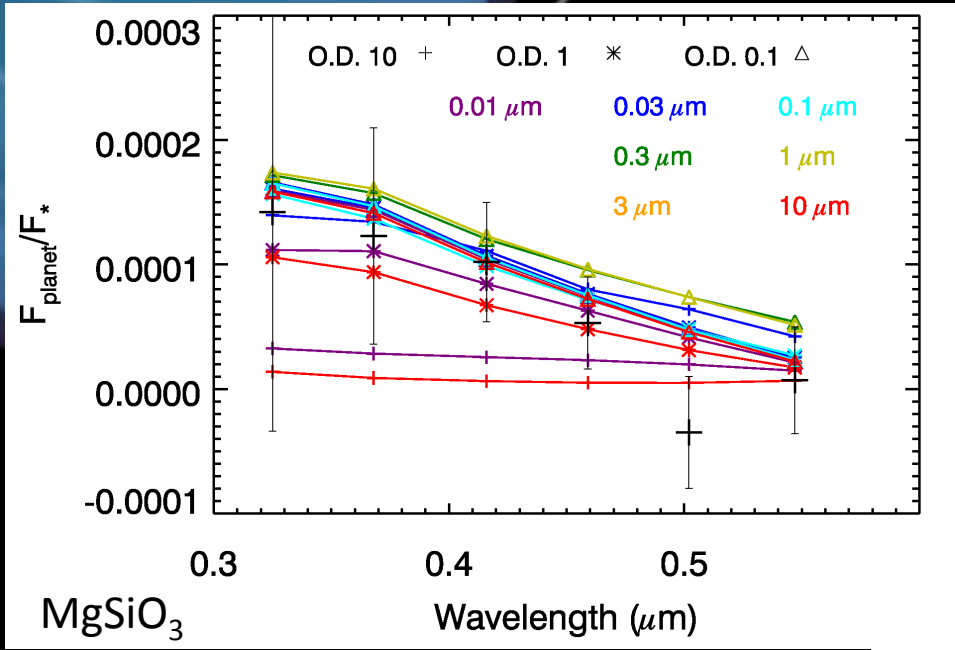
- Of course, particles not necessarily enstatite – for multiple scattering, composition can affect spectra

- Also test MnS (possible condensate at HD 189 temperature – Morley et al. 2012)

| O.D\Size (μm) | 10 | 3 | 1 | 0.3 | 0.1 | 0.03 | 0.01 |
|---|---|---|---|---|---|---|---|
| 10.0 | | | | | | | |
| 1.0 | | | | | | | |
| 0.8 | | | | | | | |
| 0.6 | | | | | | | |
| 0.4 | | | | | | | |
| 0.2 | | | | | | | |
| 0.1 | | | | | | | |

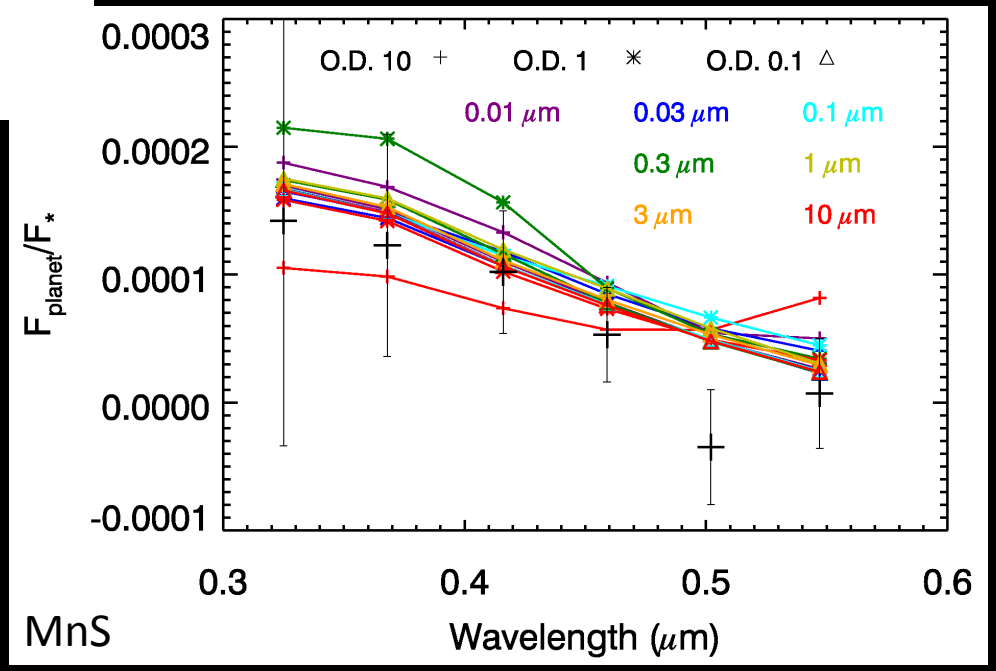
# Cloudy atmosphere models

## Reflection




- Clear that errors on reflection spectrum are large enough to permit many cloud models
- 5 ppm Na (solar) – 10 ppm Na allows 0.2 1 μm and 0.1 3 μm

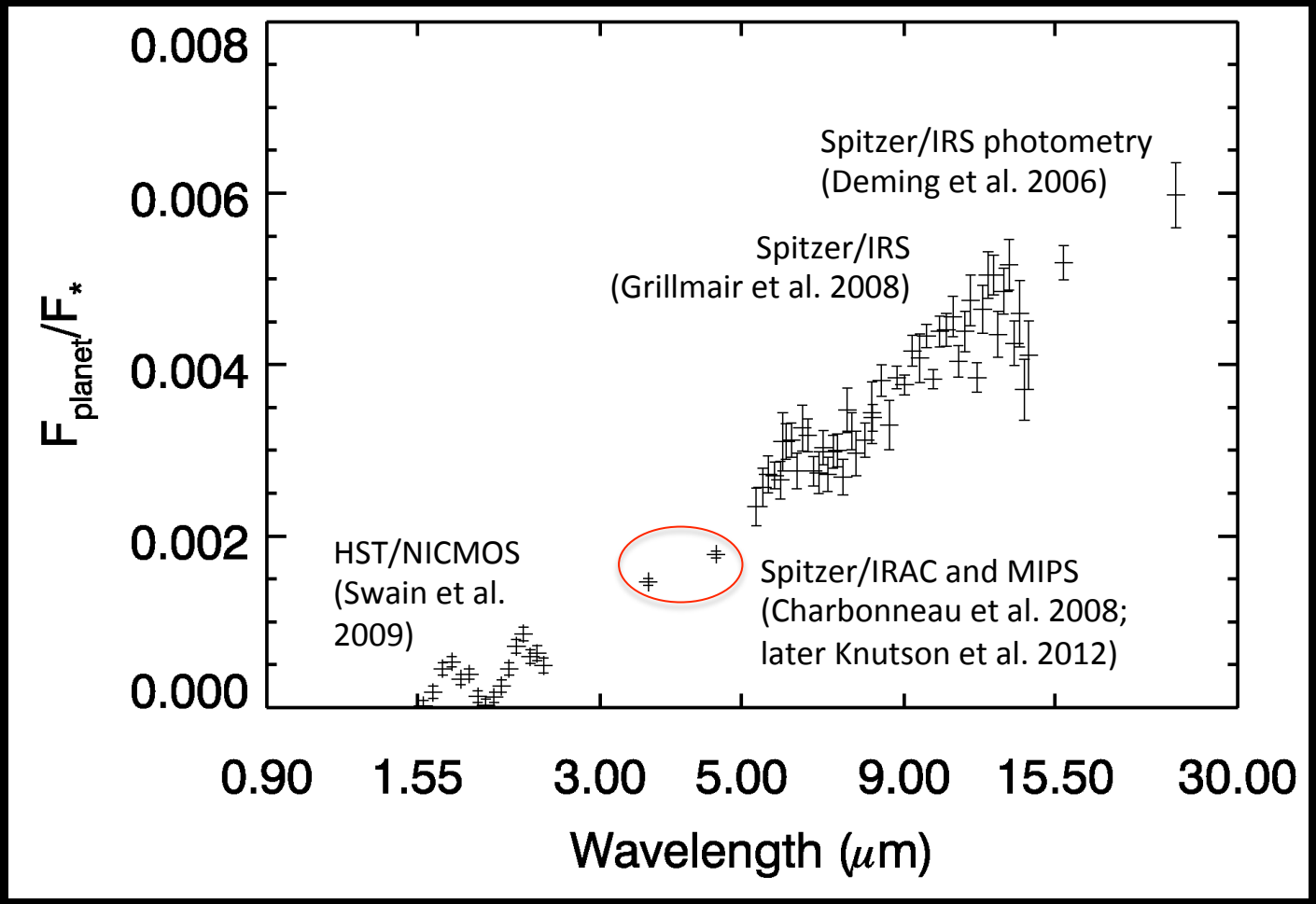
- More permitted cloud models for MnS – more reflective, less absorbing in visible



# Cloudy atmosphere models

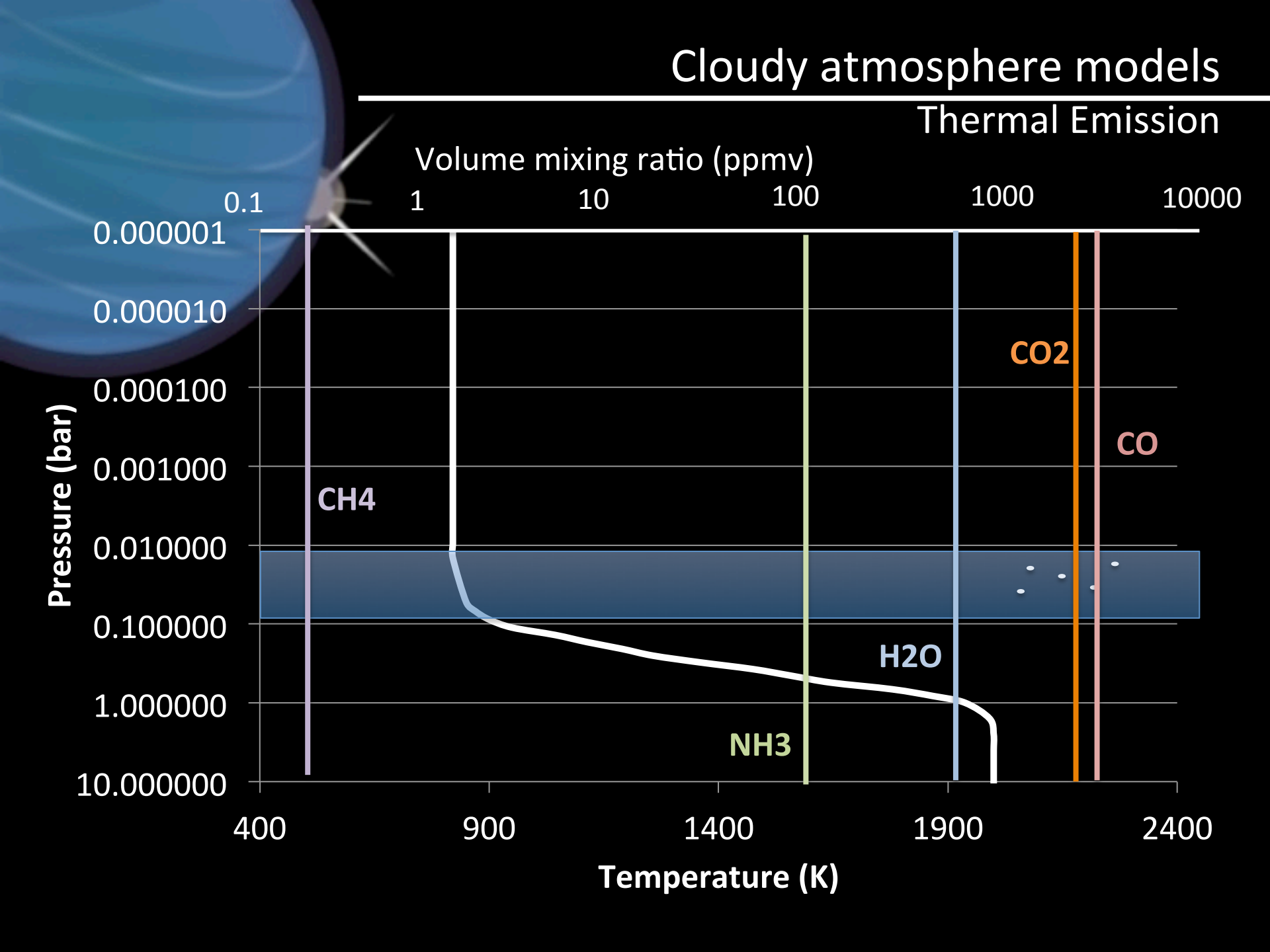
## Thermal Emission

- Analysed as in Lee et al. 2012 – some updates



# Cloudy atmosphere models

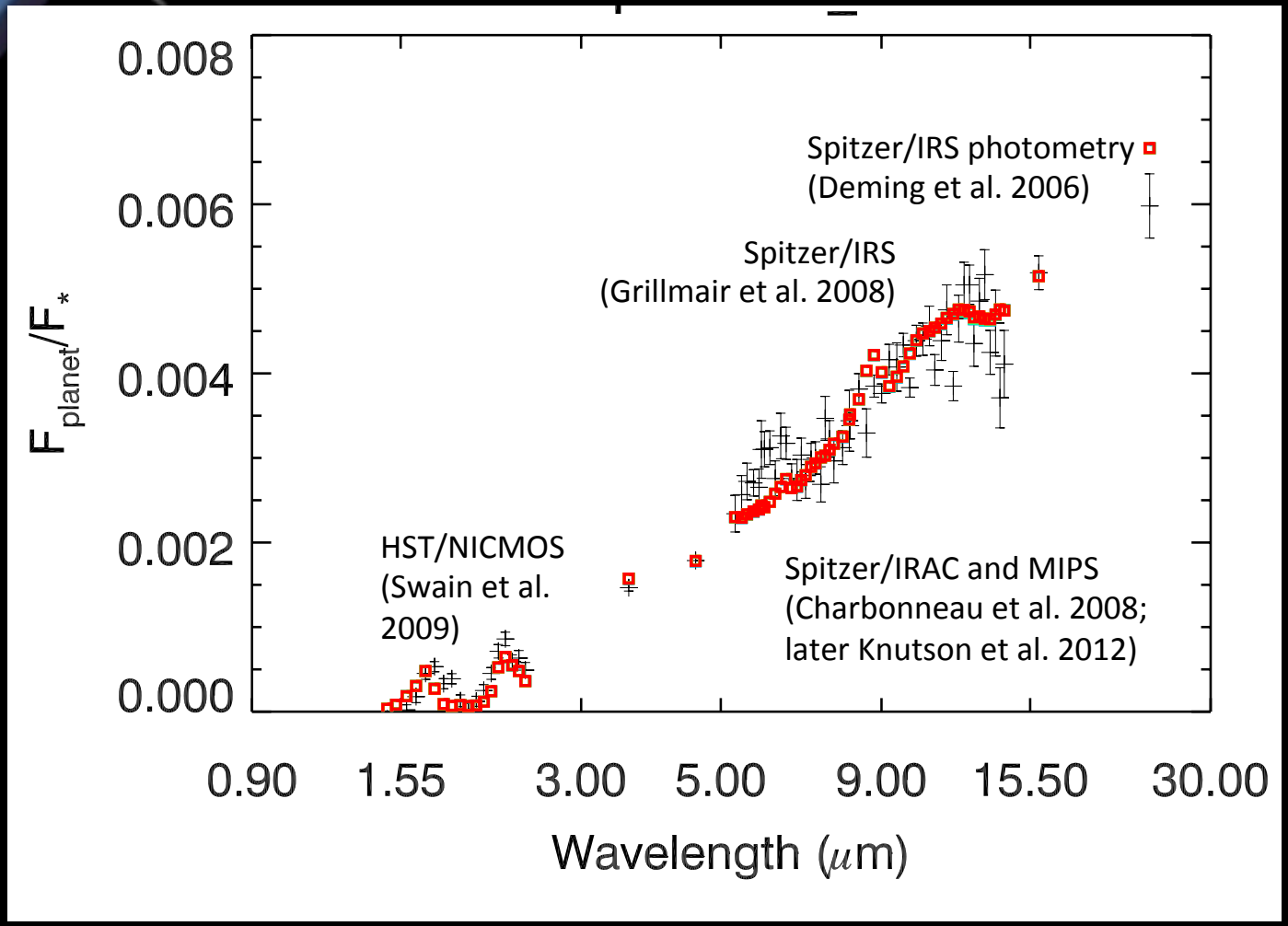
## Thermal Emission



# Cloudy atmosphere models

## Thermal Emission

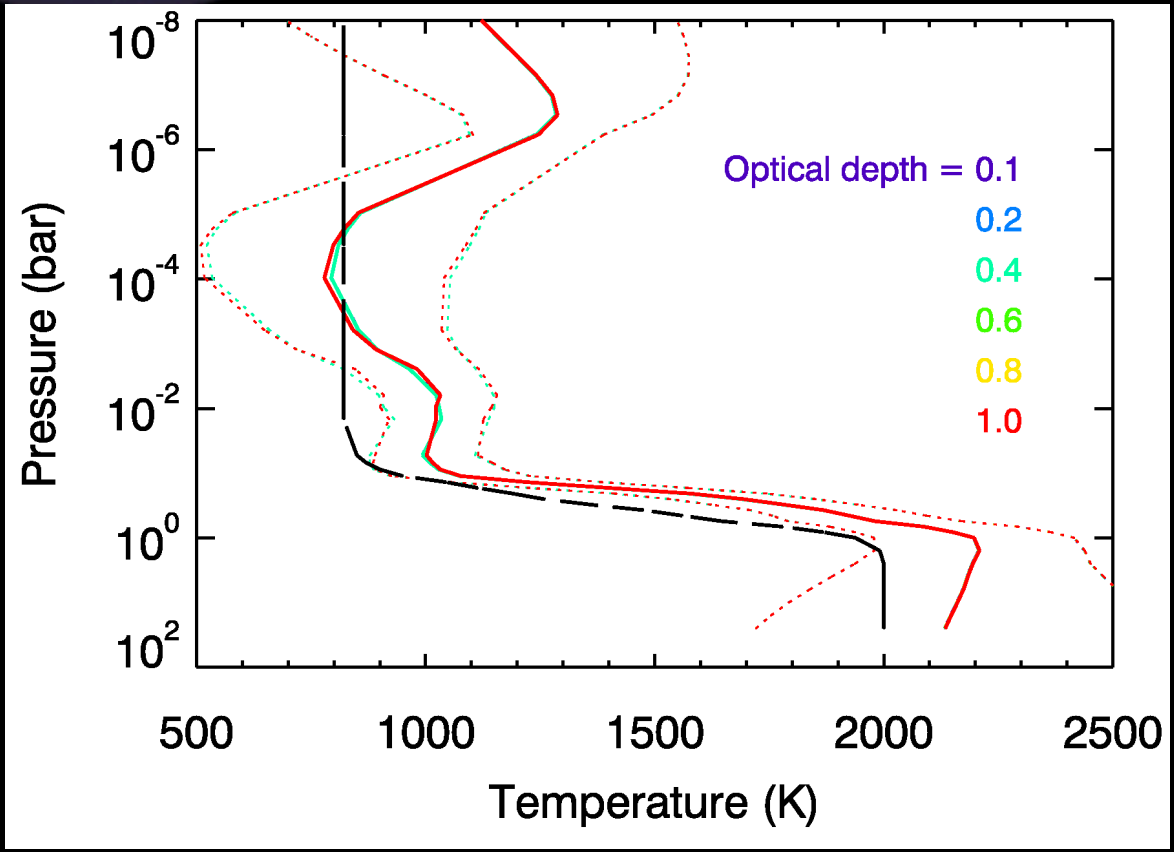
- Quality of spectral fit reasonably good



# Cloudy atmosphere models

## Thermal Emission

- Perform retrieval of temperature profile, $H_2O$, $CO_2$, CO, $CH_4$, $NH_3$ for each of the permitted cloud models

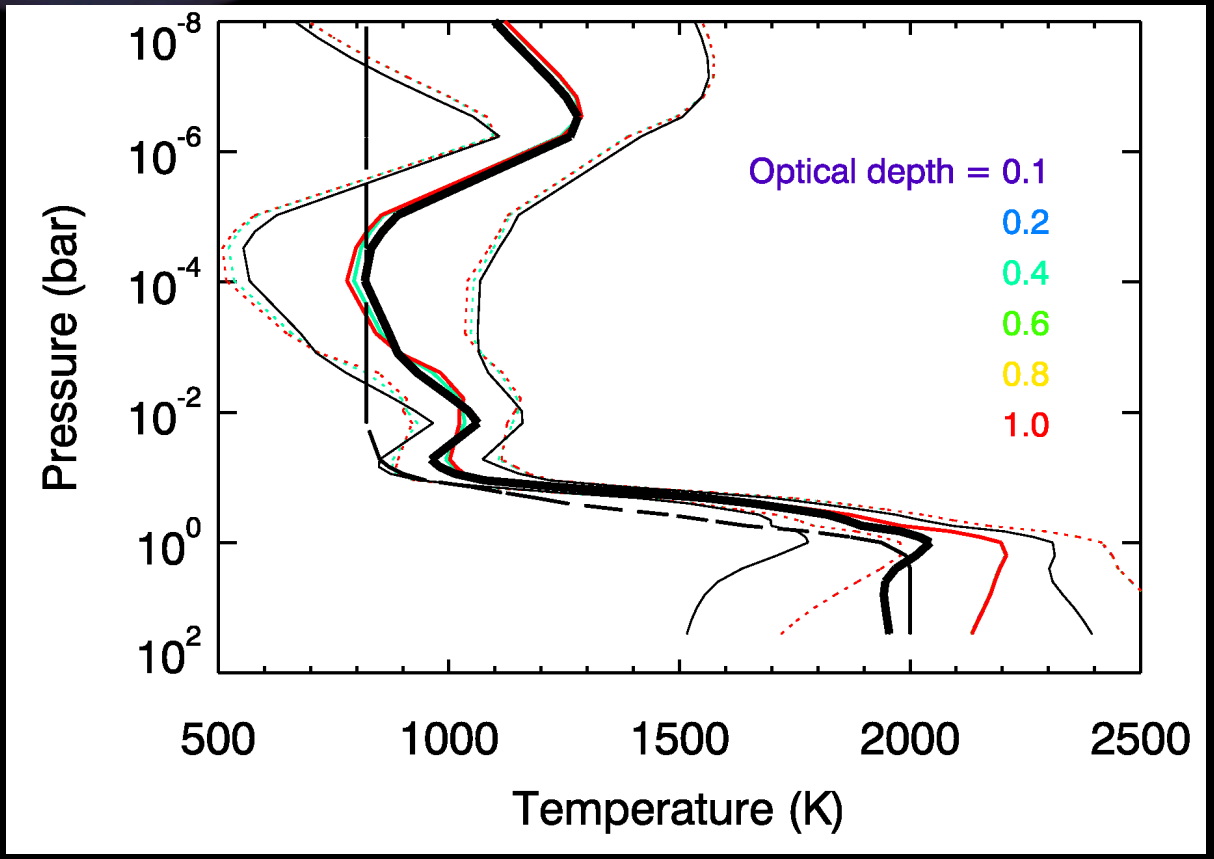



Particle size is 0.1 µm. Optical depths go from 0.1 to 10 at 0.25 µm. Retrieved temperature is given by thick lines, the error envelope is shown by dotted lines. *A priori* temperature is shown by dashed line.

# Cloudy atmosphere models

## Thermal Emission

- Effect of single-scattering v. multiple scattering

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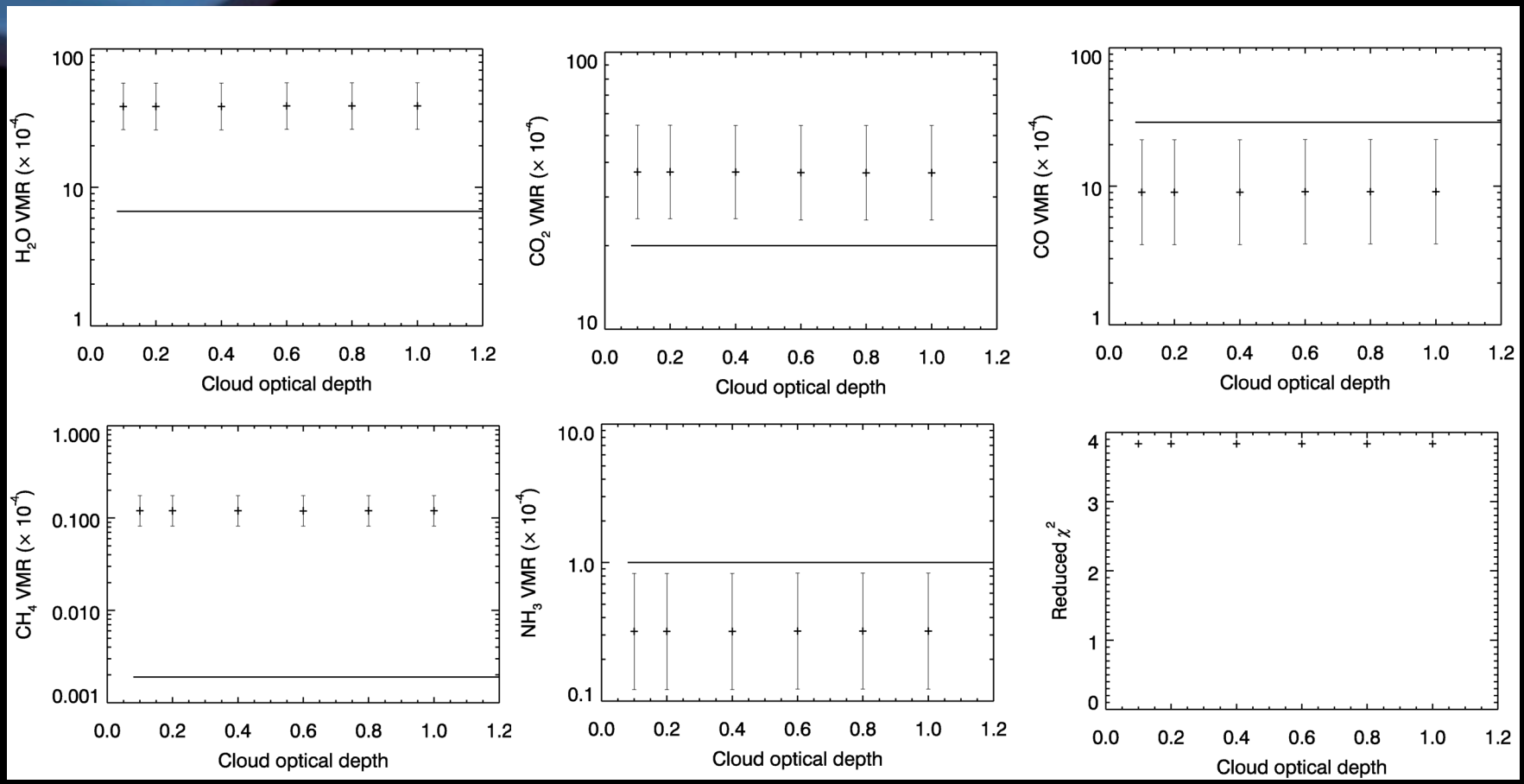
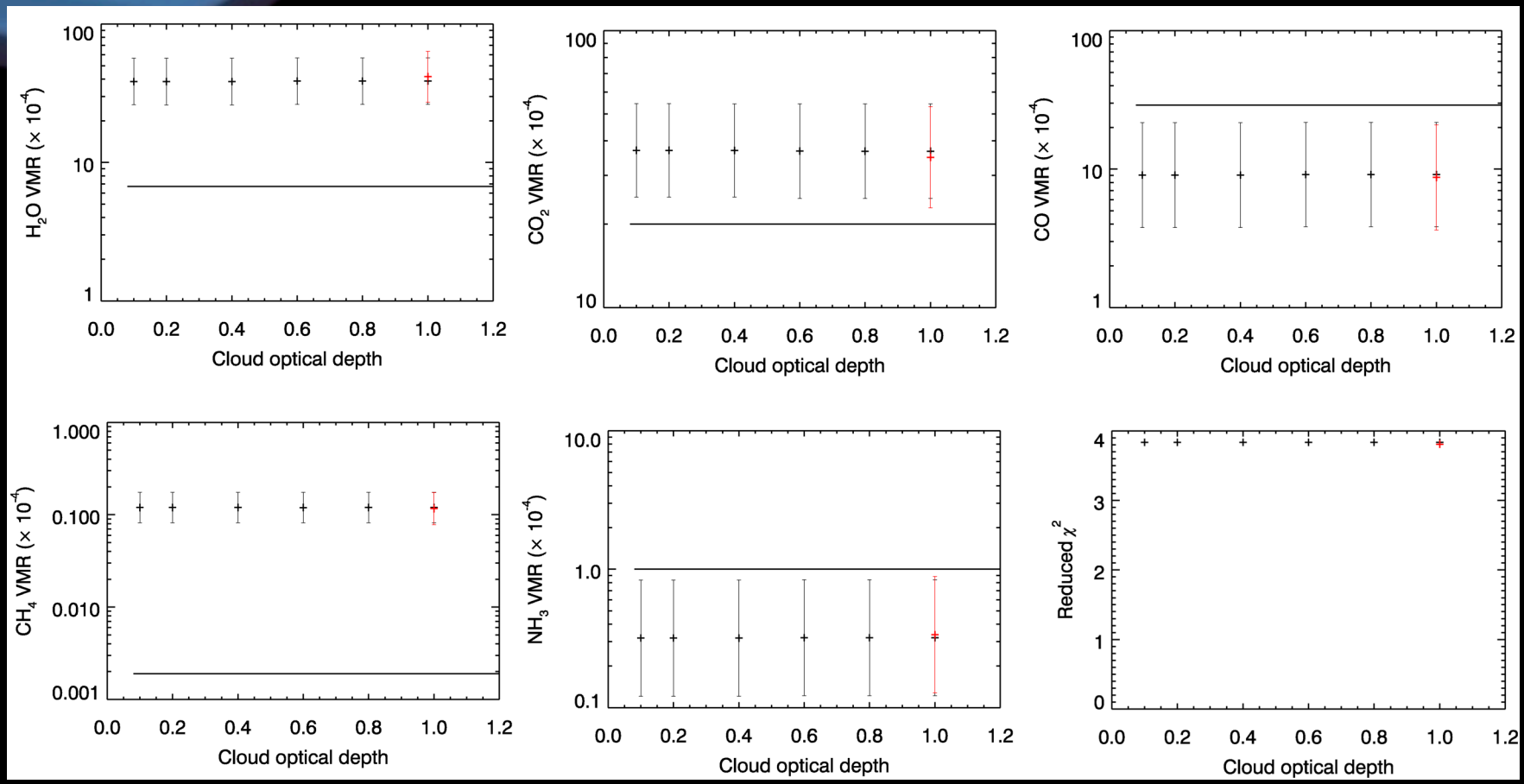


# Cloudy atmosphere models

## Thermal Emission

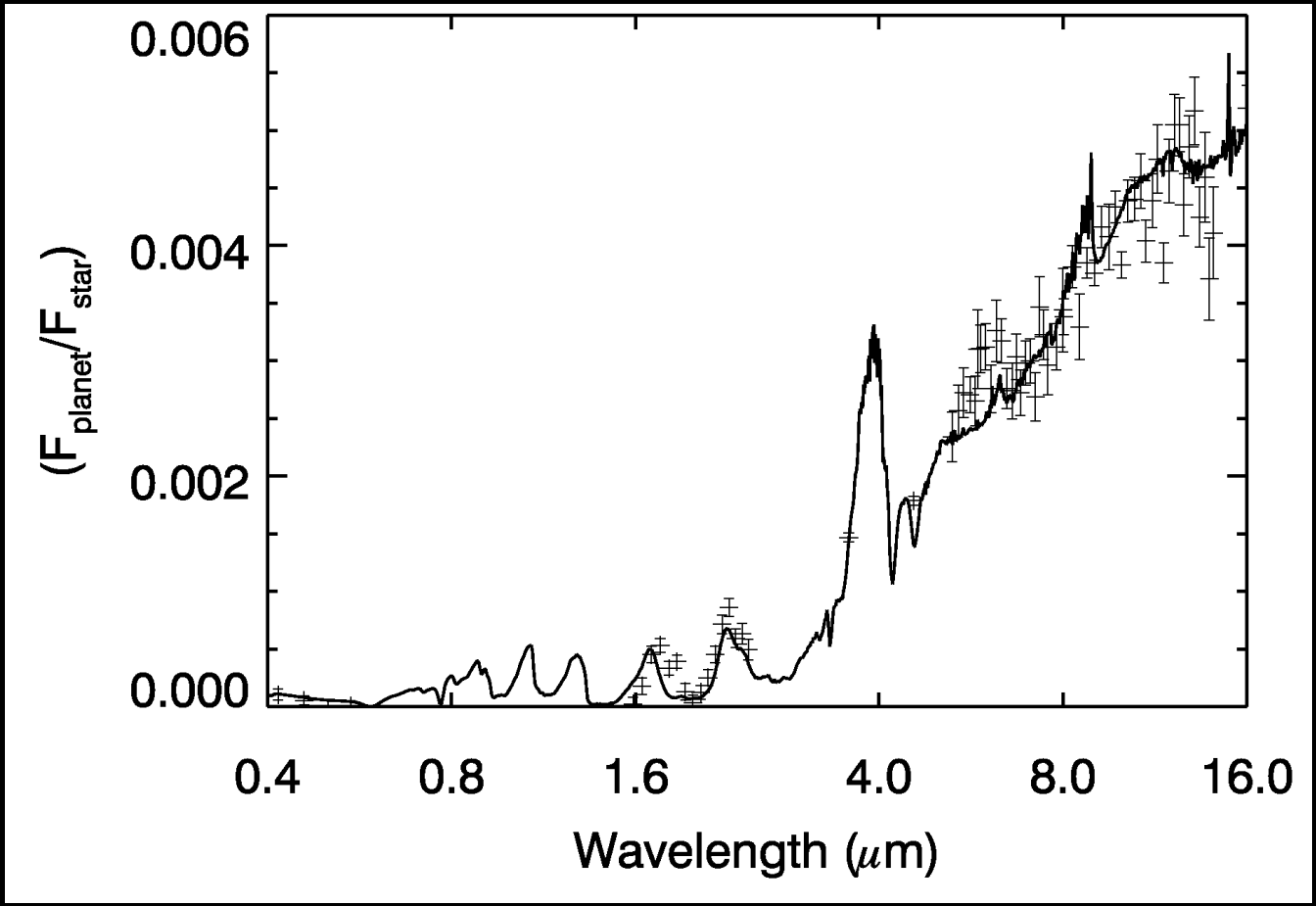
- Effect of single-scattering v. multiple scattering

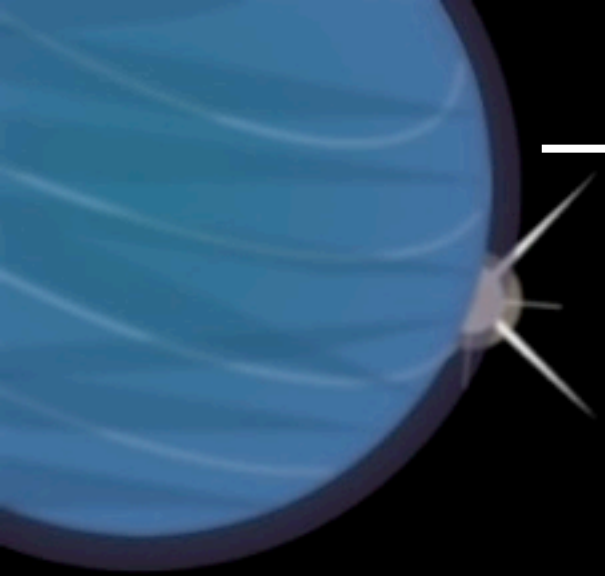


# Cloudy atmosphere models

## Future observations?

- In an ideal world…



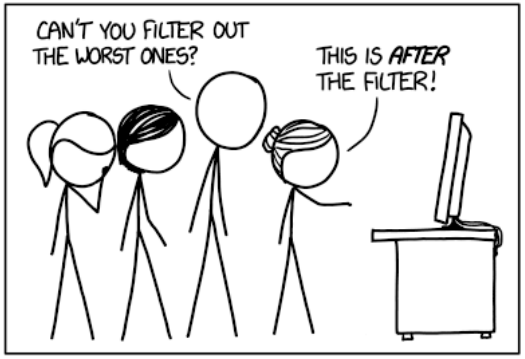


# Conclusions

- Cloudy atmosphere models + 5 ppmv Na can adequately reproduce STIS reflection spectra (as can cloud-free models with 5-10 ppmv Na)
- Presence of permitted clouds have some influence on retrieval but not significant
- Multiple scattering v. single scattering has some effect but not outside retrieval error
- Large range of cloud models possible, need further observations to provide stronger constraint
- Watch this space for: altitude dependence, Na, TiO/VO degeneracy

AUGUST 2013:
THE INTERNATIONAL ASTRONOMICAL UNION DECIDES TO START NAMING EXOPLANETS, AND — FOR THE FIRST TIME EVER — ASKS FOR SUGGESTIONS FROM THE GENERAL PUBLIC.

THEY IMMEDIATELY REGRET THIS DECISION.




| STAR | PLANET | SUGGESTED NAME |
|---|---|---|
| GLIESE 667C | b | SPACE PLANET |
| | c | PILF |
| | d | A STAR |
| | e | e'); DROP TABLE PLANETS;-- |
| | f | BLOGOSPHERE |
| | g | BLOGODROME |
| | h | EARTH |
| TAU CETI | b | SID MEIER'S TAU CETI B |
| | c | GIANT DOG PLANET |
| | d | TINY DOG PLANET |
| | e | PHIL PLAINET |
| | f | UNICODE SNOWMAN |
| GLIESE 832 | b | ASSHOLE JUPITER |
| GLIESE 581 | b | WAIST-DEEP CATS |
| | c | PLANET #14 |
| | d | BALLDERAAN |
| | e | ETERNIA PRIME |
| | f | TAUPE MARS |
| | g | JELLY-FILLED PLANET |
| EPSILON ERIDANI | b | SKYDOT |
| | c | LASER NOISES |
| GLIESE 176 | b | PANDORA |
| | c | PANTERA |
| KEPLER-61 | b | GOLDENPALACE.COM |
| UPSILON ANDROMIDAE | c | STAMPY |
| | d | MOONCHILD |
| | e | HAMLOSPHERE |
| HD 20794 | b | COSMIC SANDS |
| | c | LEGOLAND |
| | d | PLANET WITH ARMS |
| HD 85512 | b | LAX MORALITY |
| | b | GOOD PLANET |
| | c | PROBLEMLAND |
| HD 40307 | d | SLICKLE |
| | e | SPARE PARTS |
| | f | NEW JERSEY VI |
| | g | HOW DO I JOIN THE IAU |
| GLIESE 163 | b | NEIL TYSON'S MUSTACHE |
| | c | HELP@GMAIL.COM |
| | d | HAIR-COVERED PLANET |
| PI MENSAE | b | MOON HOLDER |
| HD 189733 | b | PERMADEATH |
| KEPLER-22 | b | BLUE IVY |
| KEPLER-3284 | b | BLAINSLEY |
| KEPLER-3255 | b | UNICORN THRESHER |
| KEPLER-2418 | b | SPHERICAL DISCWORLD |
| KEPLER-1686 | b | EMERGENCY BACKUP EARTH |
| KEPLER-3010 | b | FEEEOOOOOOOOP |
| KEPLER-4742 | b | LIZ |


| | | |
|---|---|---|
| HD 40307 | d | SLICKLE |
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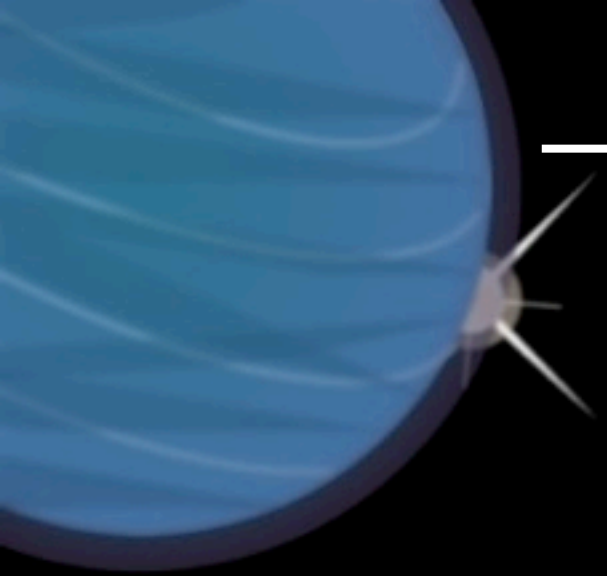
| PI MENSAE | b | MOON HOLDER |
| HD 189733 | b | PERMADEATH |
| KEPLER-22 | b | BLUE IVY |
| KEPLER-3284 | b | BLAINSLEY |


http://xkcd.com



# Cloudy atmosphere models

## Thermal Emission

- Perform retrieval of temperature profile, $H_2O$, $CO_2$, CO, $CH_4$, $NH_3$ for each of the permitted cloud models
- Use single-scattering assumption but test with full multiple-scattering retrieval for optical depth of 1 (or most optically thick case) for each size
- Not much dependence on altitude so use 100-10 mbar cloud
- Use NEMESIS radiative transfer + retrieval tool (Irwin et al. 2008)