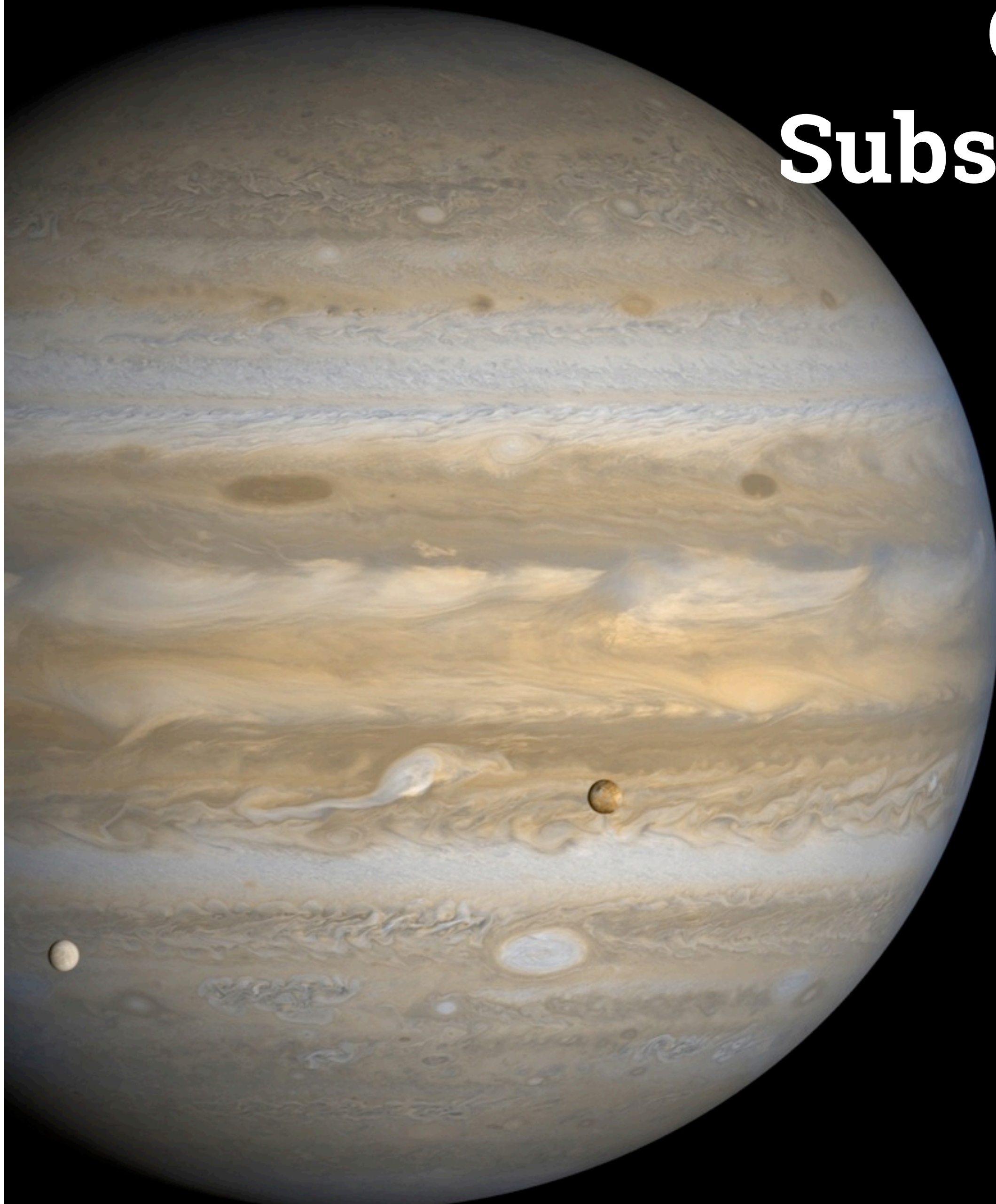
Cloud Chemistry in Substellar Atmospheres



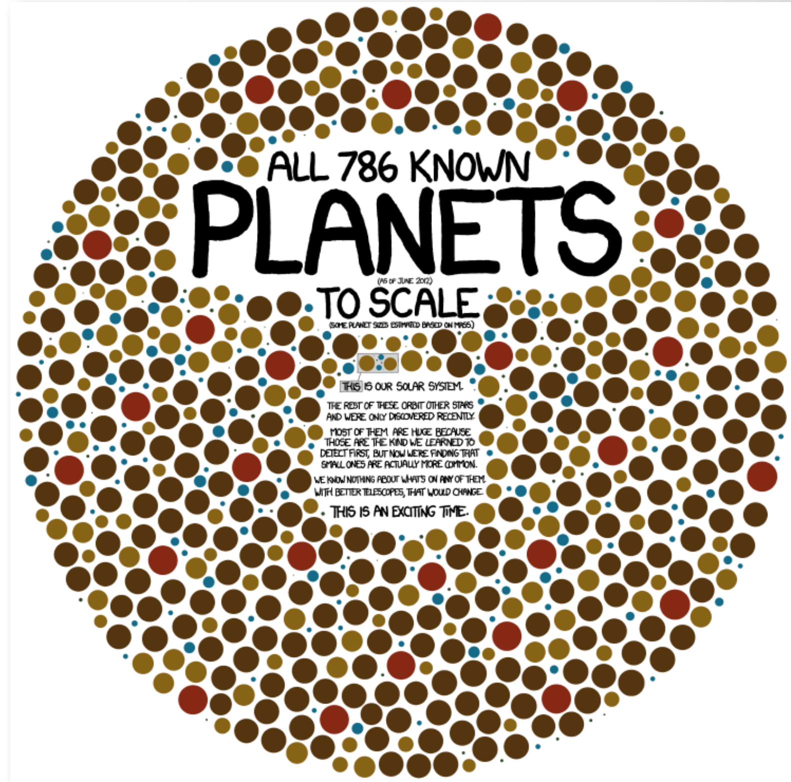
Channon Visscher

SSI CEPS Tele-Talk

17 June 2016

Outline

- overview of substellar objects
- major chemical processes
  - equilibrium processes
  - disequilibrium processes
  - role of cloud formation



“one gets such wholesale returns of conjecture out of such a trifling investment of fact”

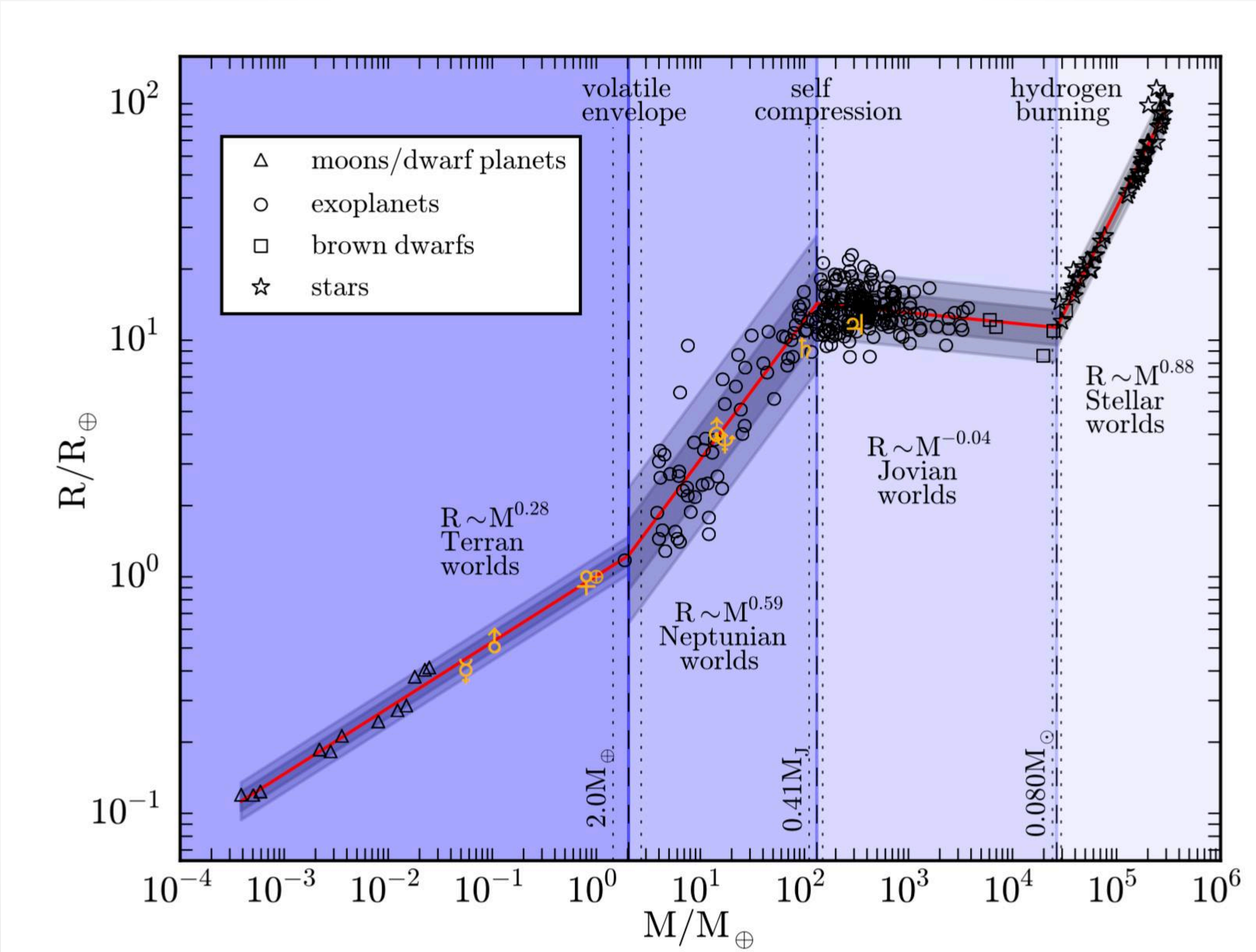
xkcd

Substellar objects

object (class)	mass	properties
stars	> 75 M_J	fusion in interior
brown dwarfs	13 to 75M_J	temporary D fusion
L dwarfs		warmest BDs, C as CO
T dwarfs		CH_4 in spectra
Y dwarfs		lower T_{eff} (300-600 K)
planets	< 13 M_J	no fusion

- first approximation: solar abundances of heavy elements (> He)
- expect similar chemical behavior for similar *P* - *T* conditions

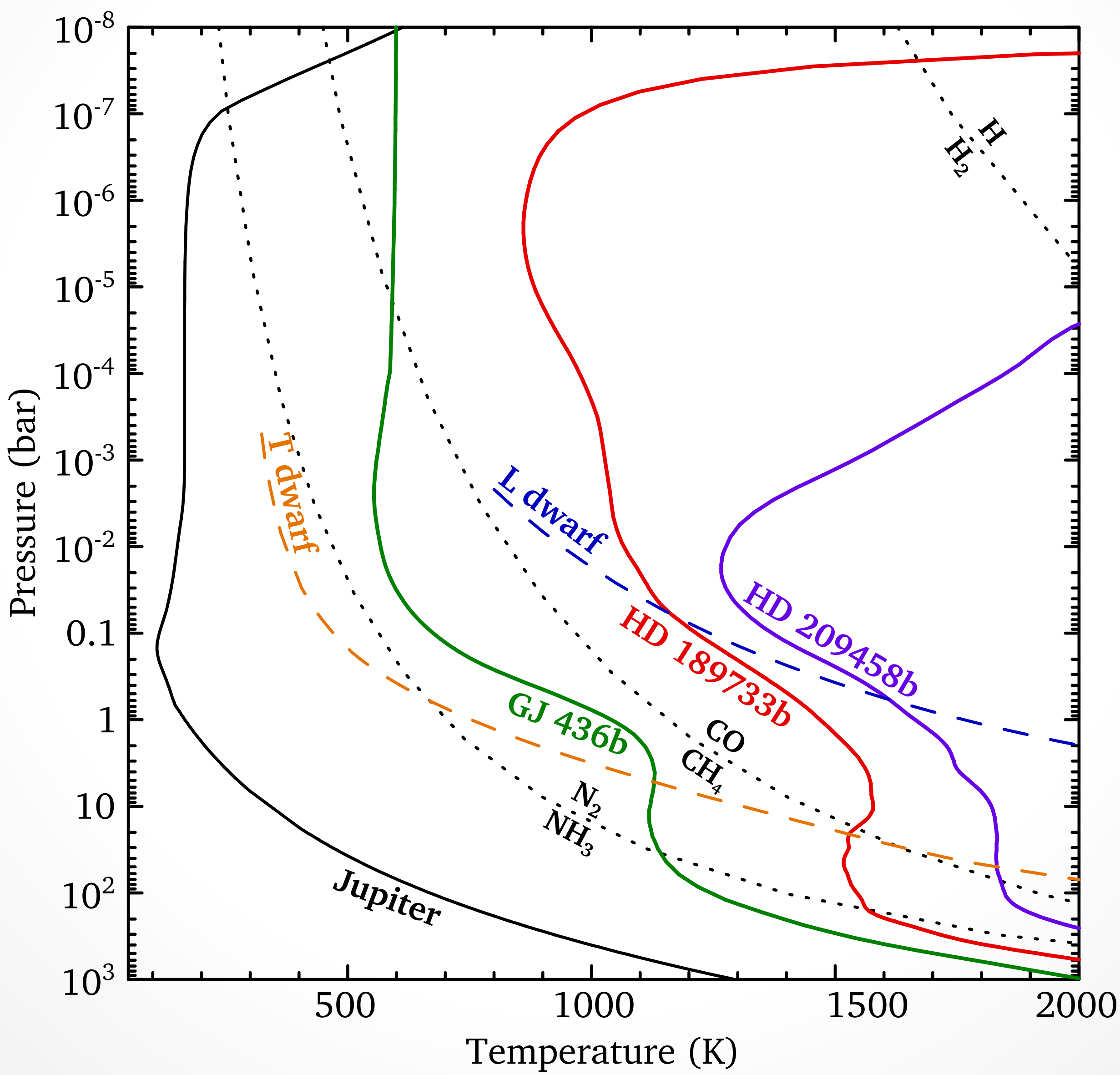
Substellar objects



Chen & Kipping 2016

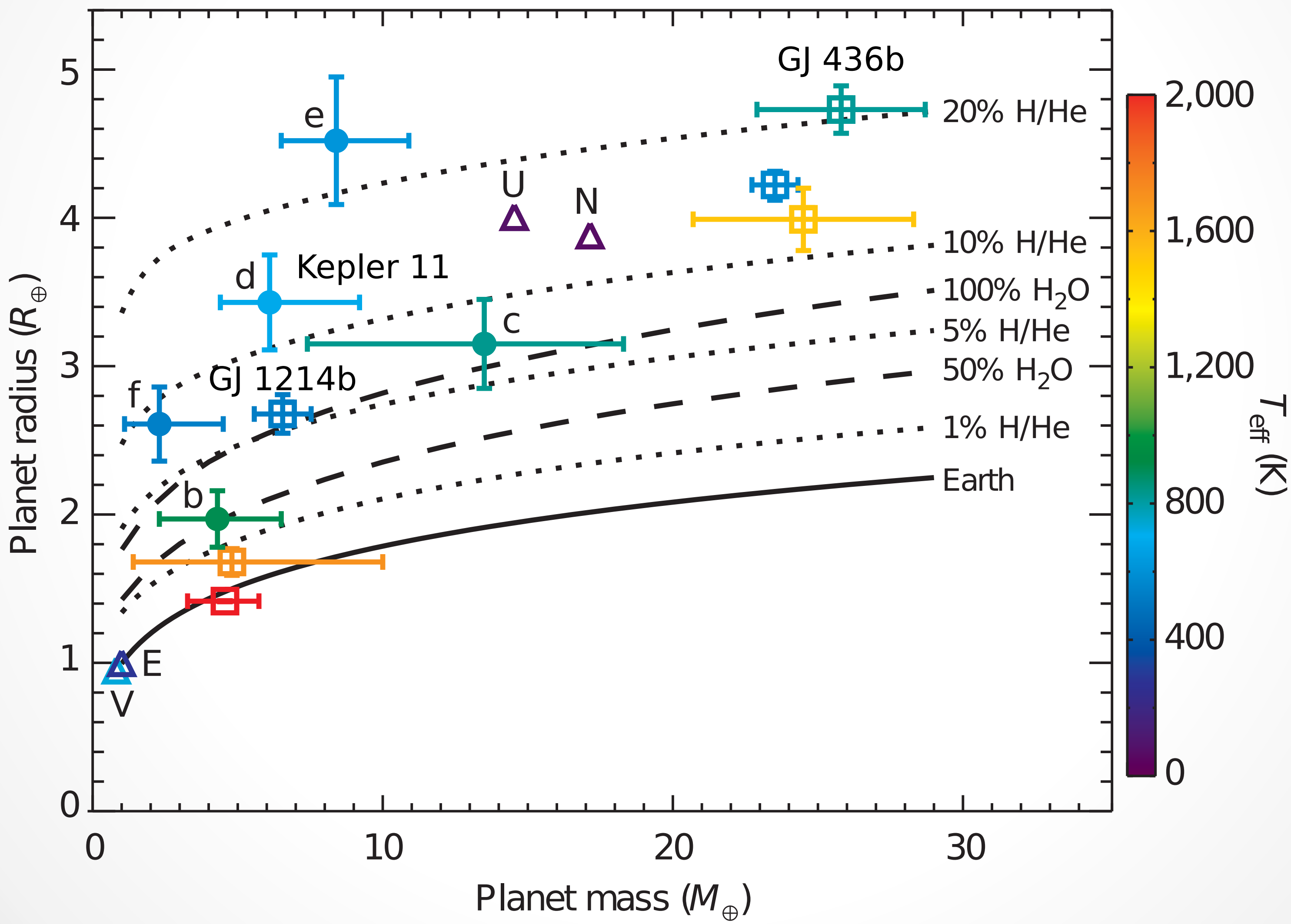
Substellar objects

- expect similar chemical behavior for similar *P* - *T* conditions



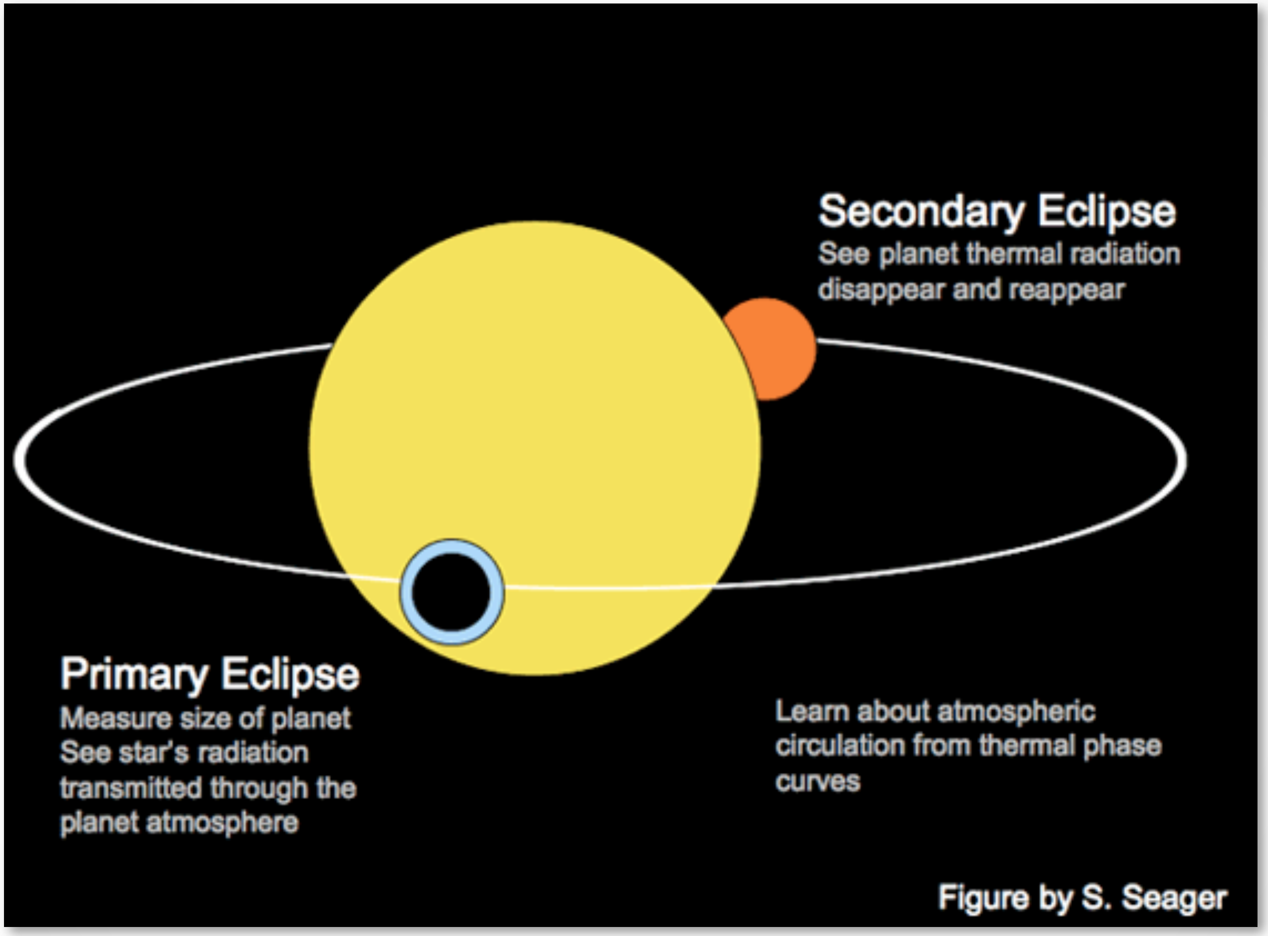
Low-mass exoplanets

- may also possess H/He envelope



Lissauer et al 2011

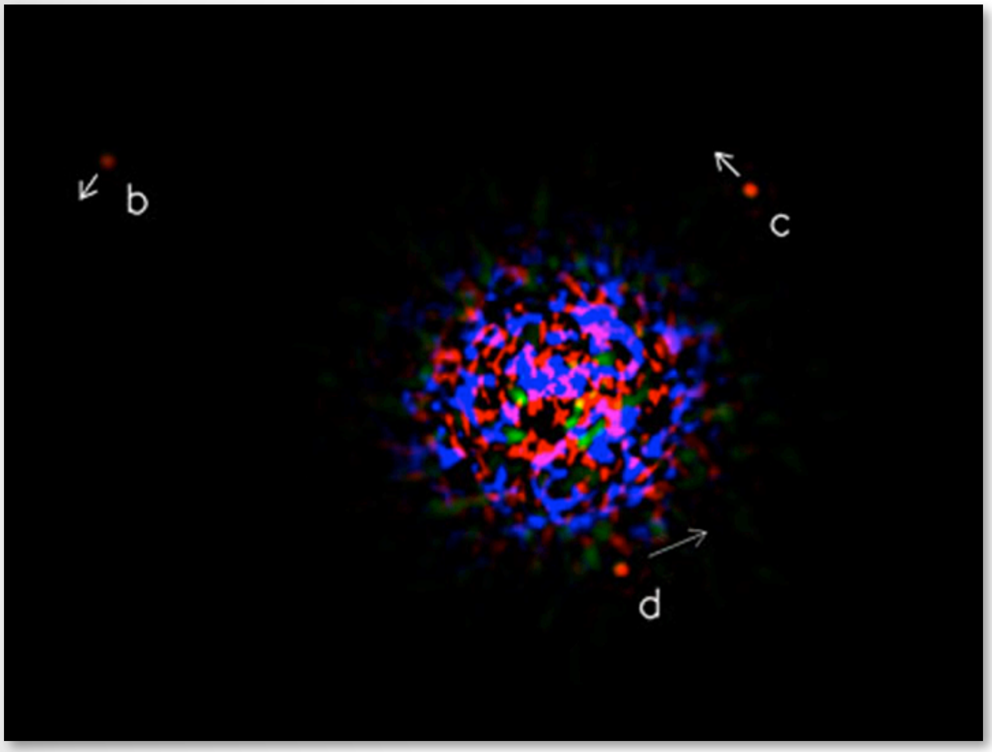
Transit observations

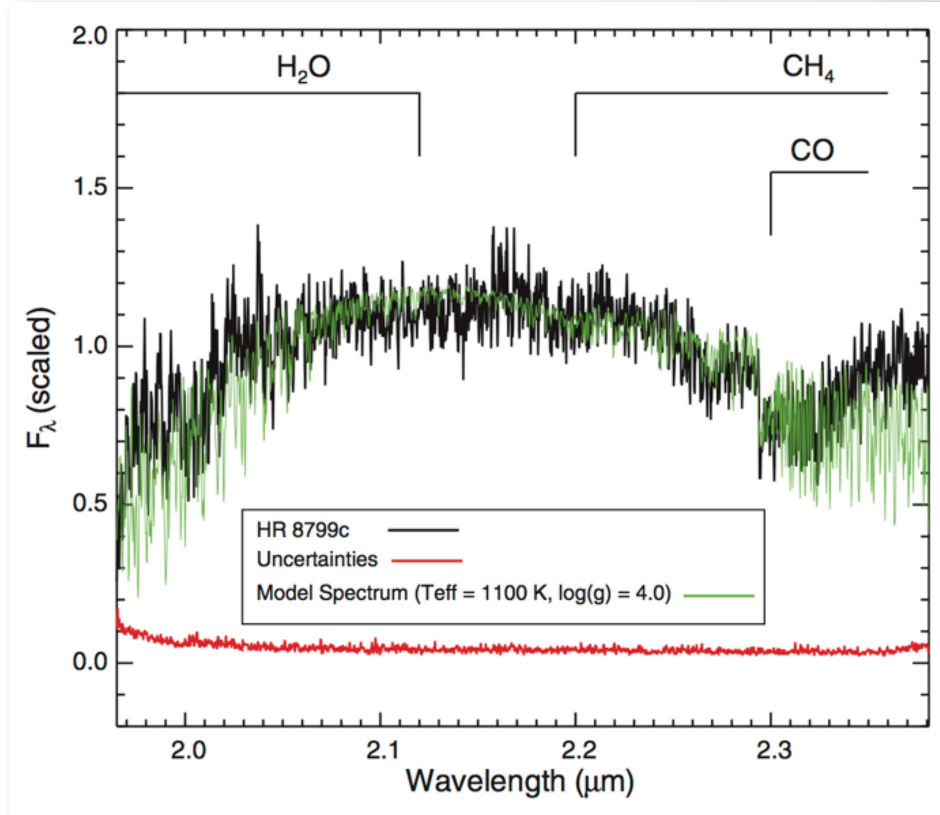


- provide constraints for theoretical models:
  - **bulk density,** atmospheric composition & structure
  - H, Na, $\mathbf{H_2O}$**, CO**, CO_2, $\mathbf{CH_4}$ have all been detected

transit geometry

Directly-imaged planets





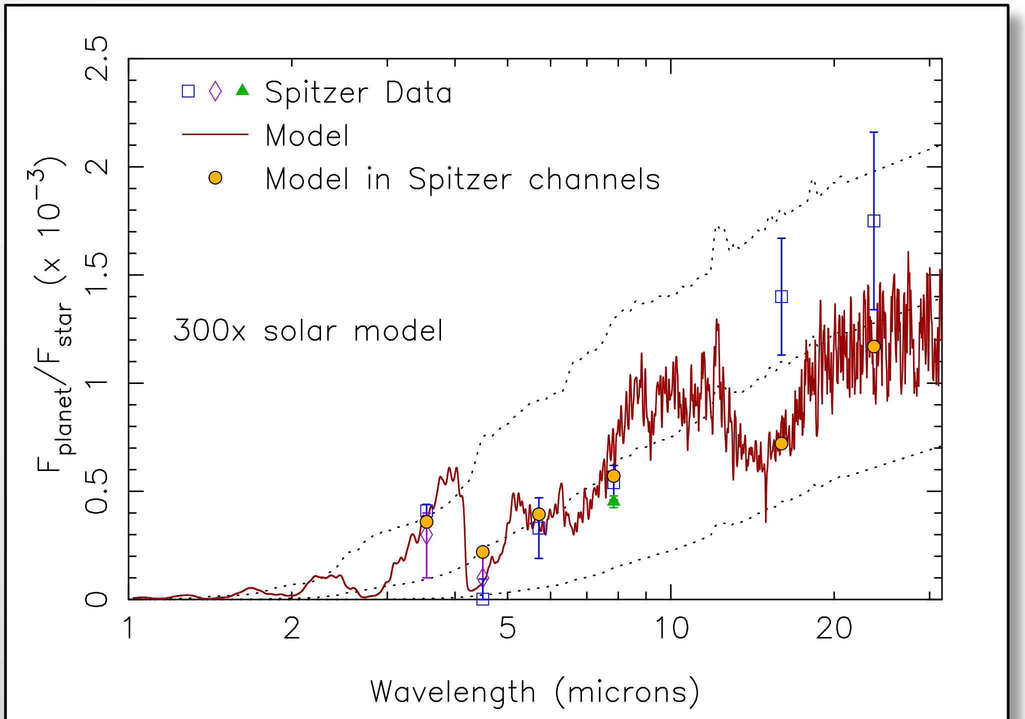
HR 8799 system; spectra of HR 8799c, Konopacky et al 2013

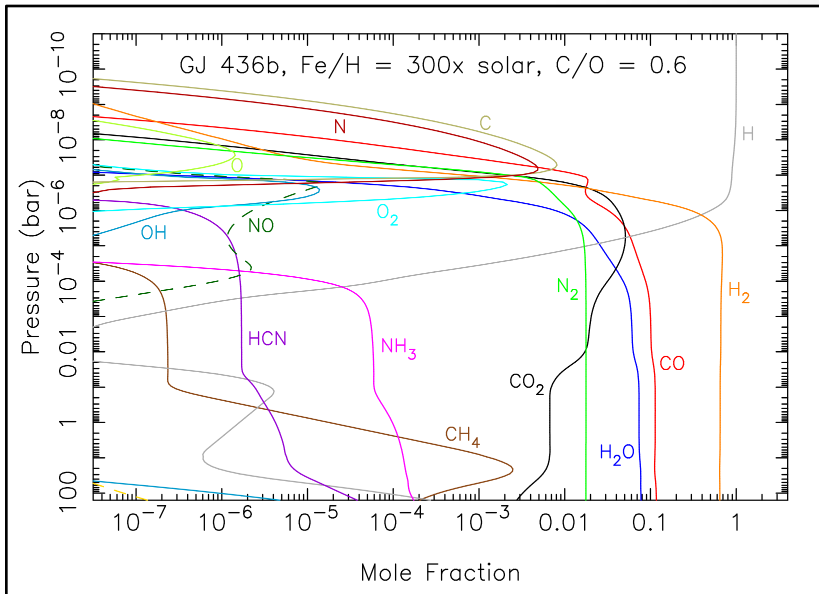
Model approach: what influences properties?

observations
retrievals, constraints

spectral models
synthetic spectra

chemical models
bulk composition
gas chemistry
cloud formation

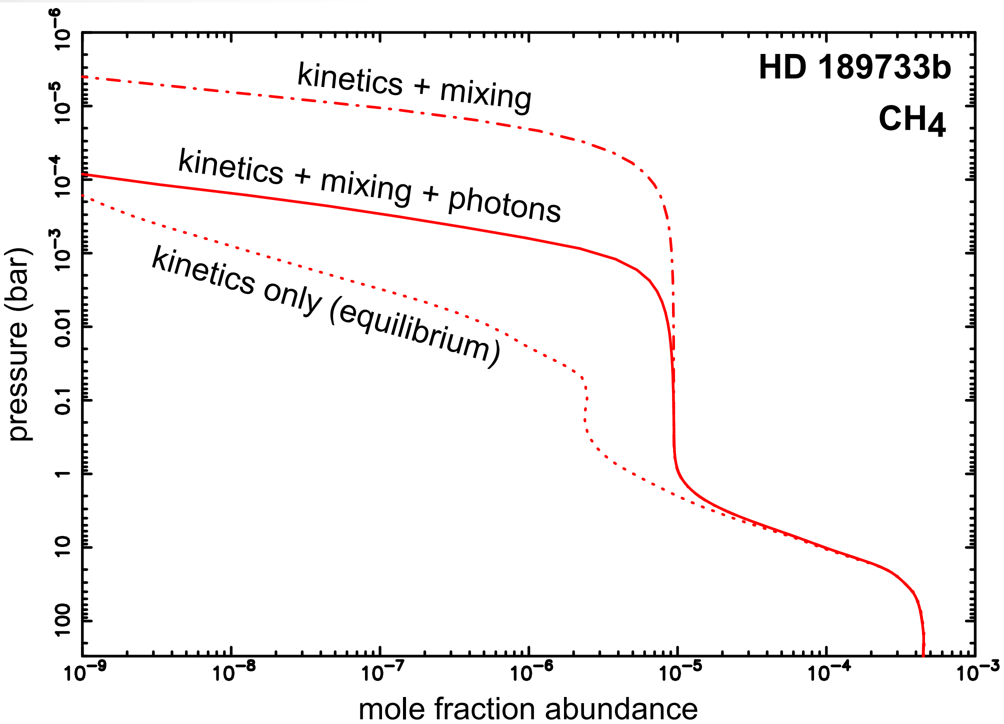


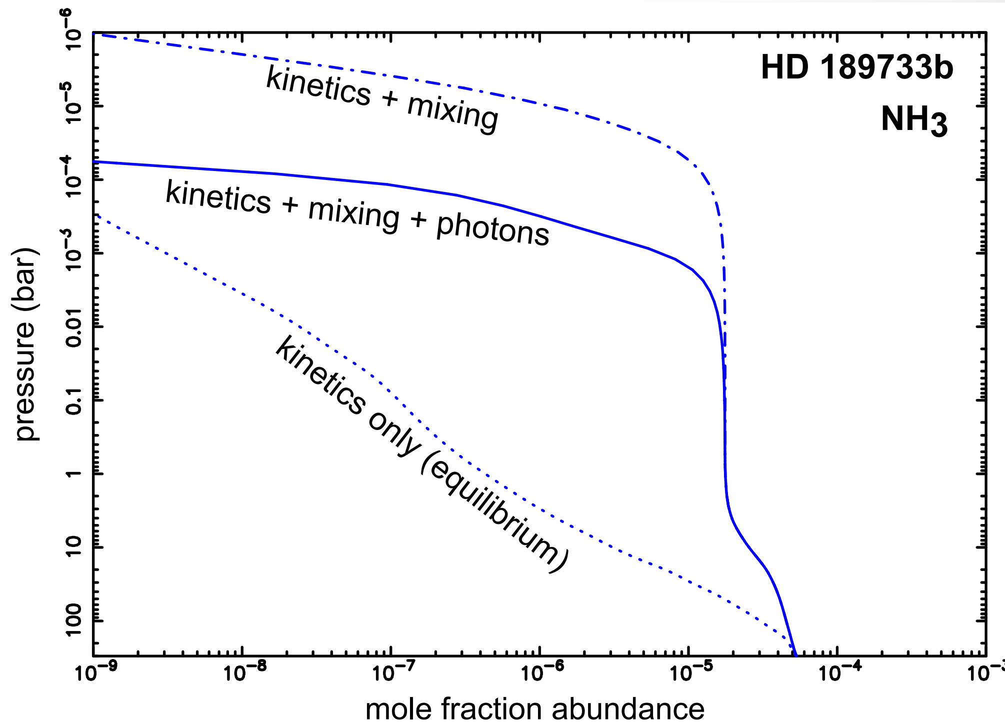


model-data comparison (left); atmospheric chemistry (right) for GJ 436b; Moses, Line, Visscher et al 2013

Chemical regimes in exoplanet atmospheres

- chemical equilibrium is a useful first approximation, **but substellar atmospheres are not in complete equilibrium**
- may see three **chemical regimes:**
  - equilibrium, quench, photochemical

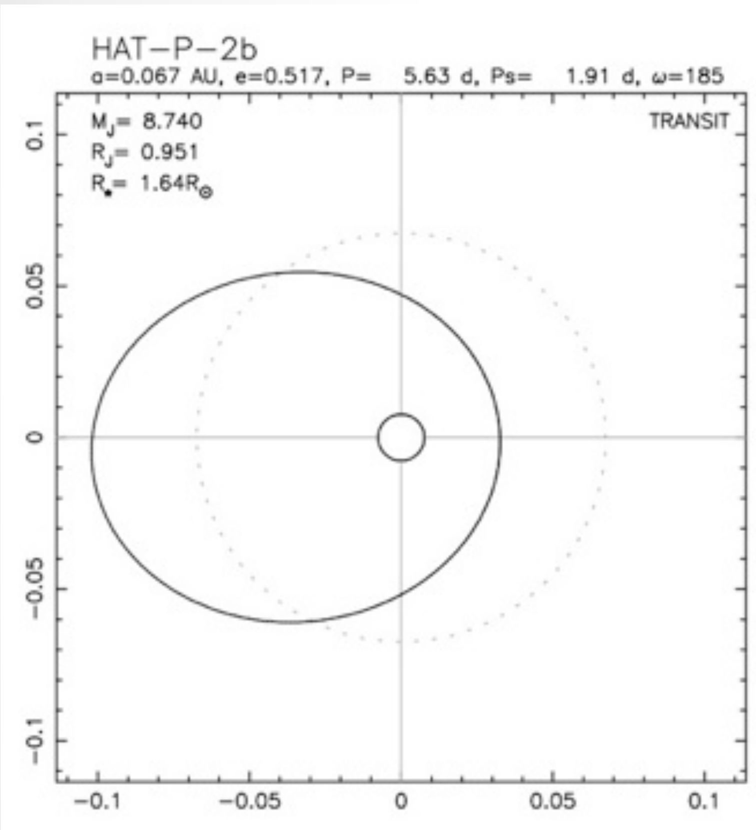


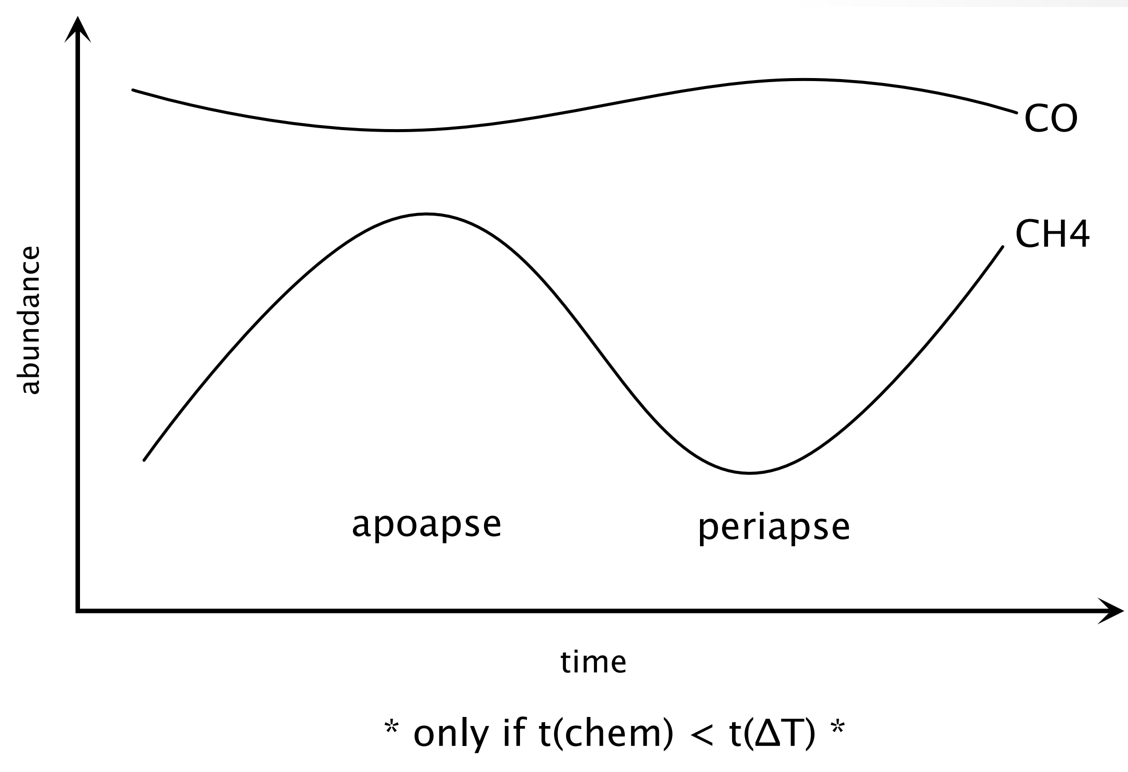


chemistry on HD 189733b; Moses, Visscher et al 2010; Visscher and Moses 2011

Orbit-induced variations in chemistry

- for close-in, eccentric orbits
  - can chemistry keep up with changes in temperature?
  - *not at high altitudes (P < 4 bar for HAT-P-2b)*





orbit of HAT-P-2b (left); Visscher 2012; see also Iro & Deming 2012, Lewis et al 2013

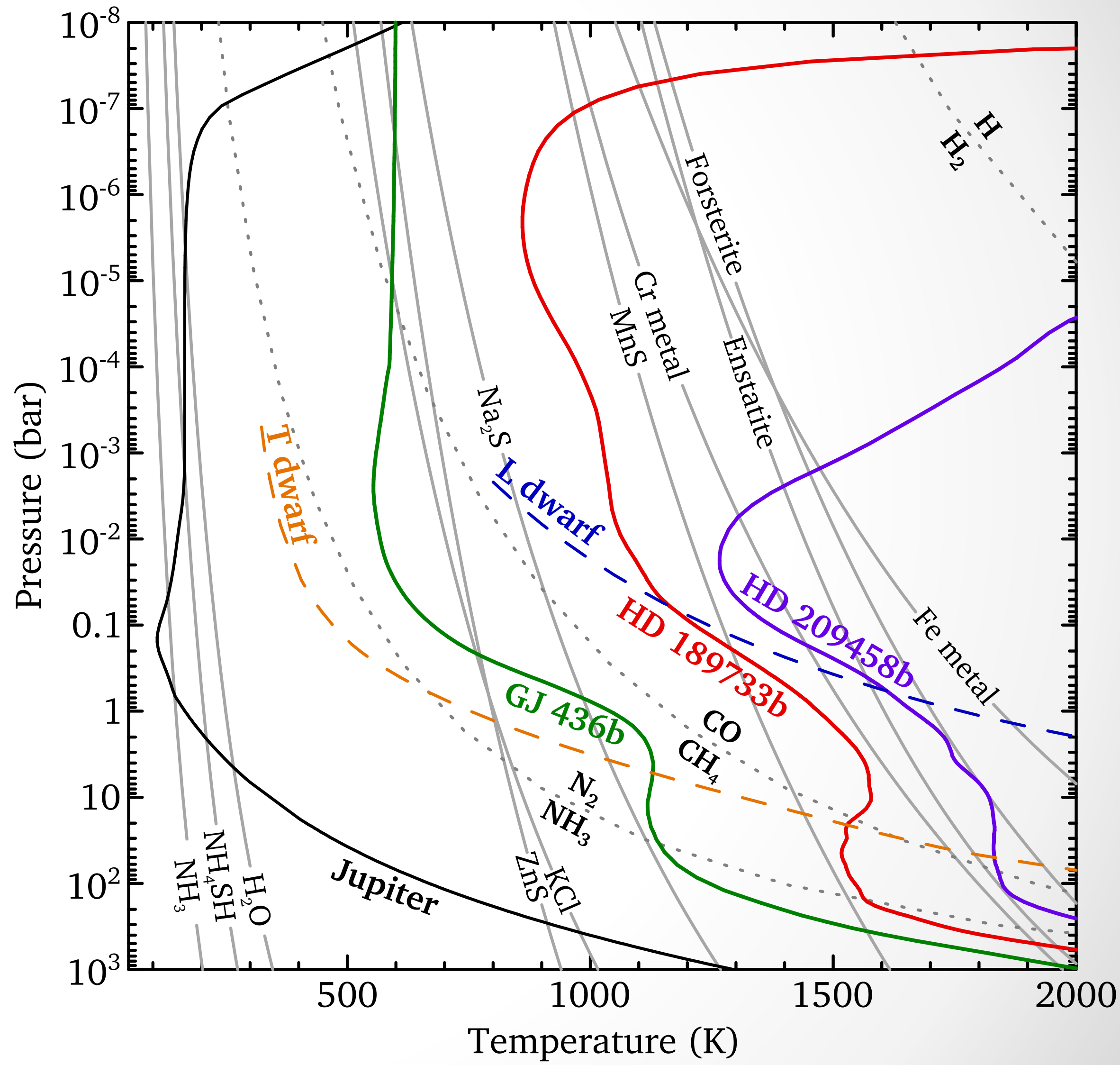
Equilibrium condensation chemistry

- condensation curves defined by stability

$$\mathrm{Fe(gas)} = \mathrm{Fe(met)}$$
$$a_{\mathrm{Fe(met)}} = K P_{\mathrm{Fe}}$$

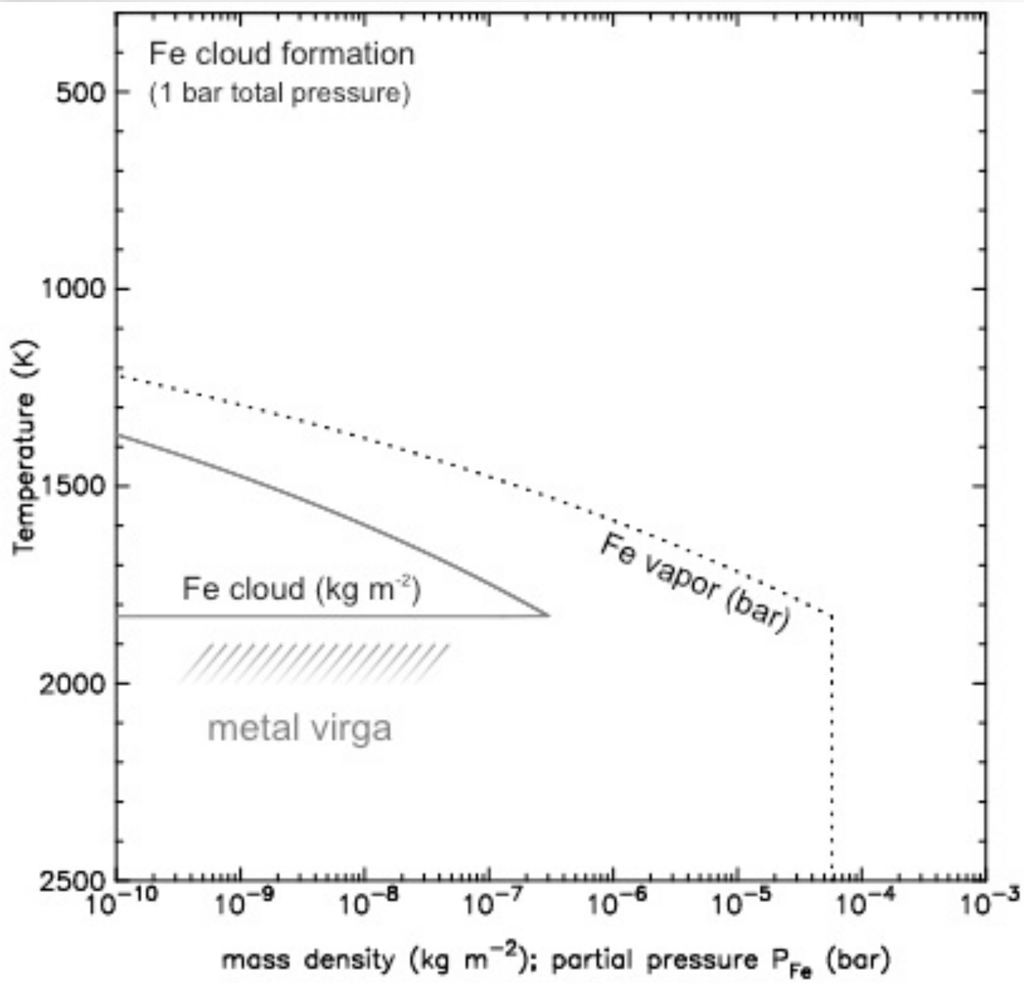
- intersection between *P-T* profile and condensation curve defines cloud base

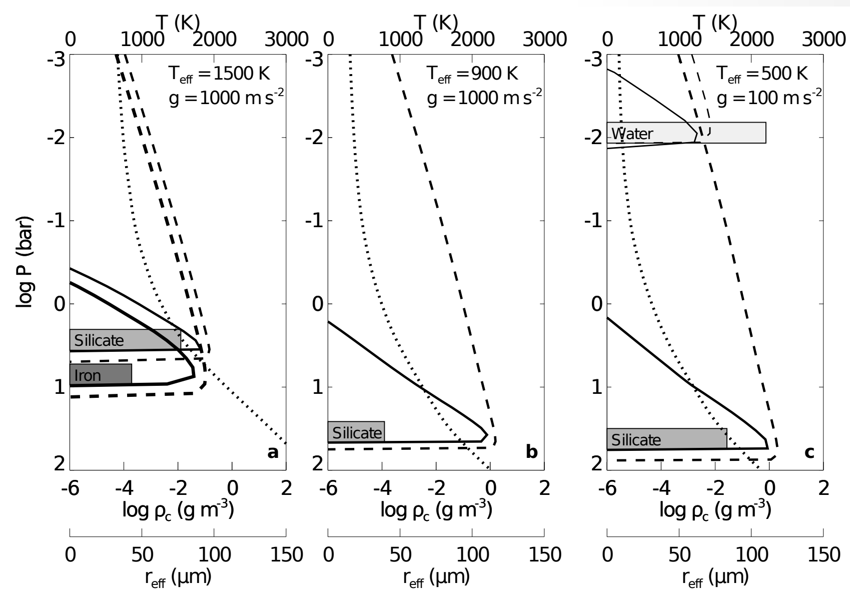
- *Fe metal & silicate clouds are consistent with Jupiter and brown dwarf observations*



After Visscher et al 2006, 2010 and Morley et al 2012

Metal ~~rain~~ virga?

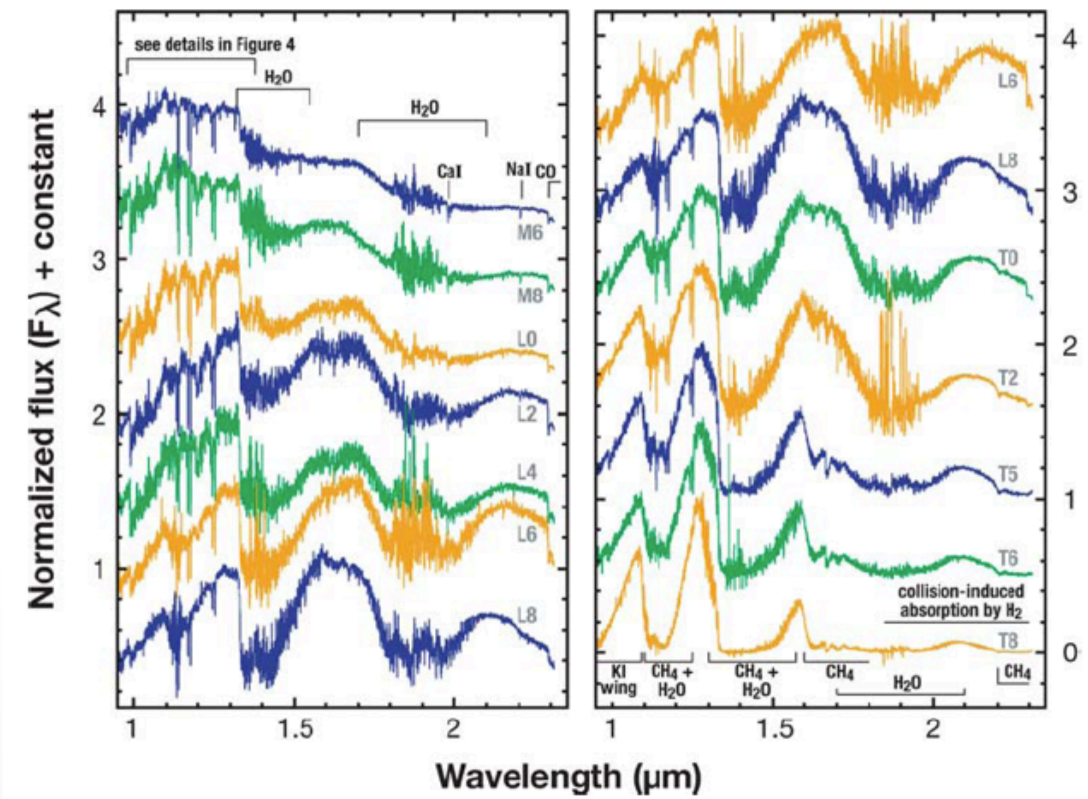




based upon Visscher et al 2010 results; Ackerman & Marley 2001 clouds with "sedimentation factor"

Equilibrium condensation chemistry

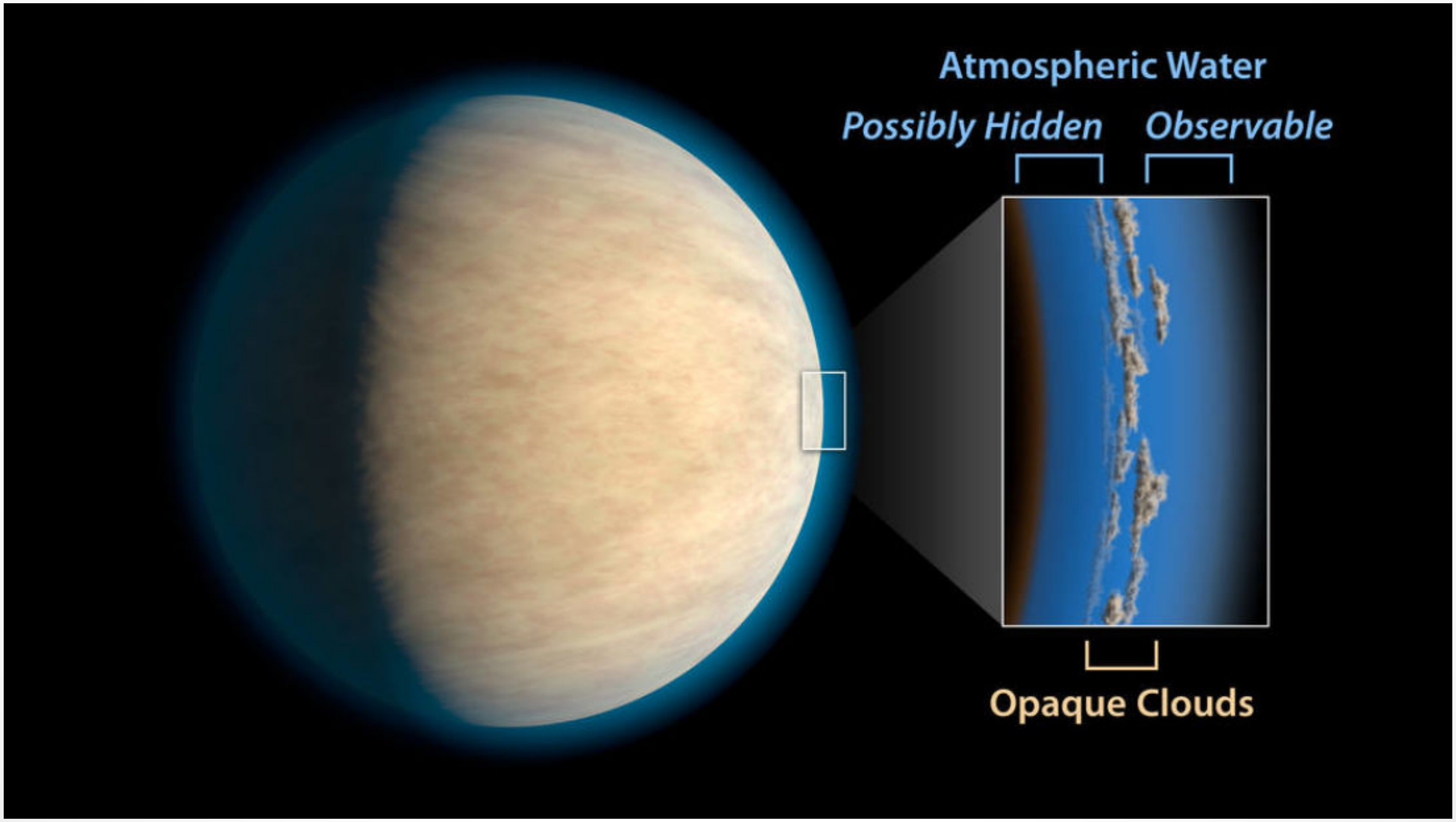
- Jupiter: observed H_2S requires deep Fe removal
- presence of GeH_4, absence of SiH, even though A_{Si}>>A_{Ge}
- detection of Na, K, in brown dwarfs implies Al, Si removal
- disappearance of Na, Fe, Mg, Si, Ca features in later BD spectral types
- silicate spectral features in brown dwarfs and hot exoplanets



Kirkpatrick (2005) spectral classification of L and T brown dwarfs; cf. Visscher et al 2010

Clouds on planets and brown dwarfs

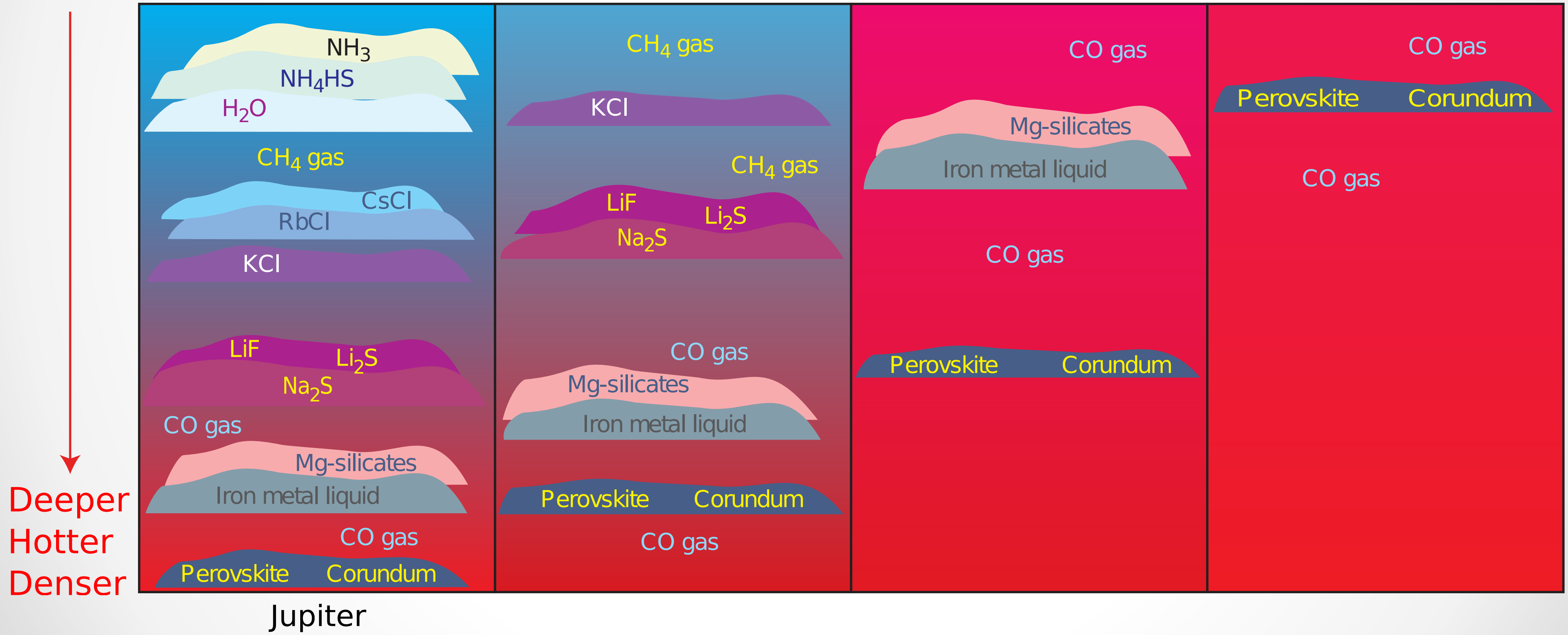
- strongly affect observational properties:
  - introduce condensed particles (reflection, absorption, scattering)
  - remove atoms and molecules from the gas phase



Iyer et al (2016): clouds on exoplanets obscure H_2O features in transmission spectra

Clouds on planets and brown dwarfs

- strongly affect observational properties:
  - introduce condensed particles (reflection, absorption, scattering)
  - remove atoms and molecules from the gas phase



Lodders 2004

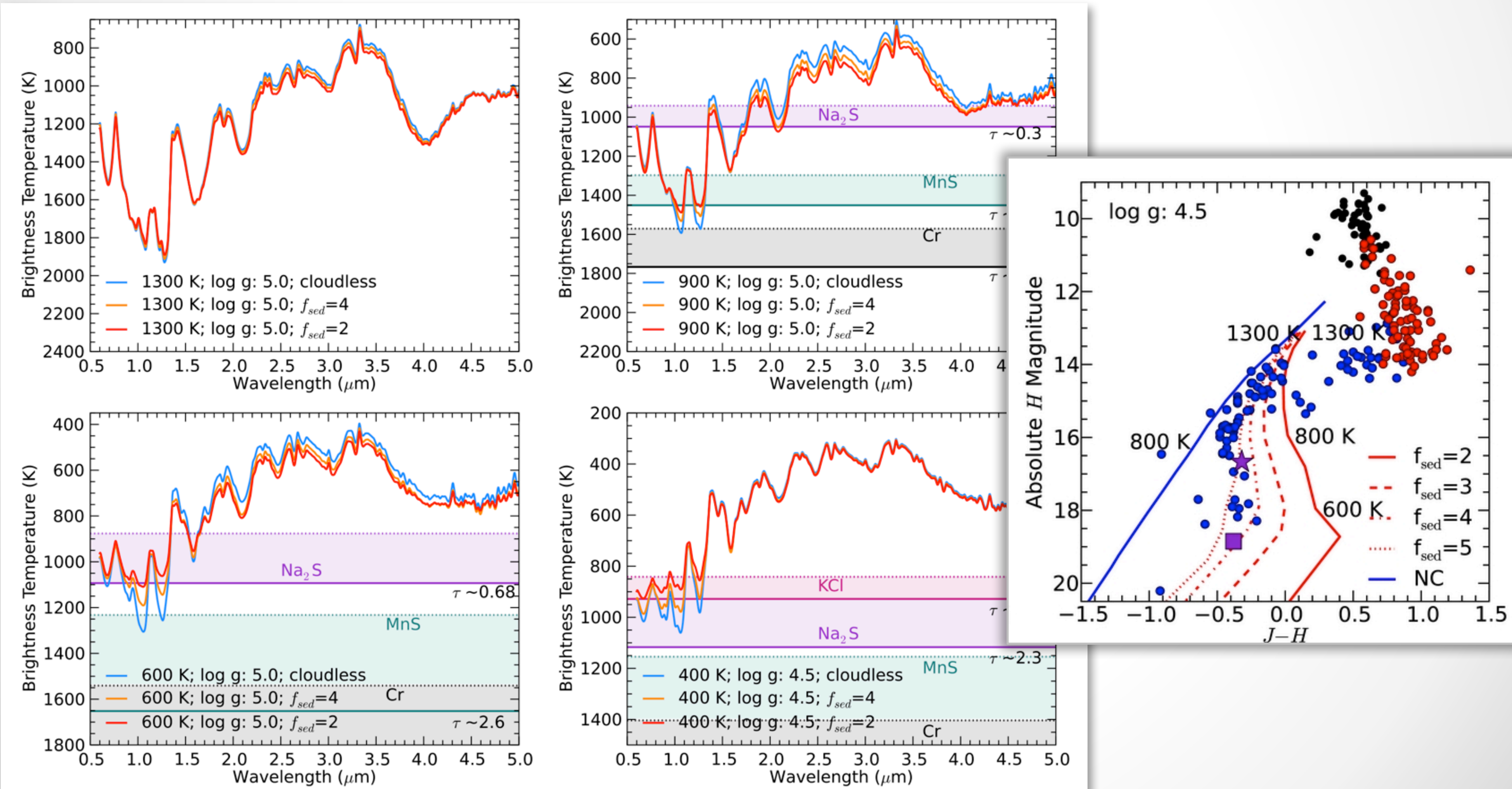
Relative cloud masses

condensate	relative cloud mass
H_2O	87386
CH_4	50627
$MgSiO_3$ (enstatite)	43838
Fe metal	20853
NH_3	11644
NH_4SH	9241
Mg_2SiO_4 (forsterite)	1254
Na_2S	1000
Ca, Al, Ti silicates and oxides (total)	360
MnS	355
Cr metal	298
KCl	123
ZnS	53
NH_4Cl	37
other chlorides	1

Assuming element abundance ratios are solar (Lodders 2003) and complete condensation

Clouds on cool brown dwarfs

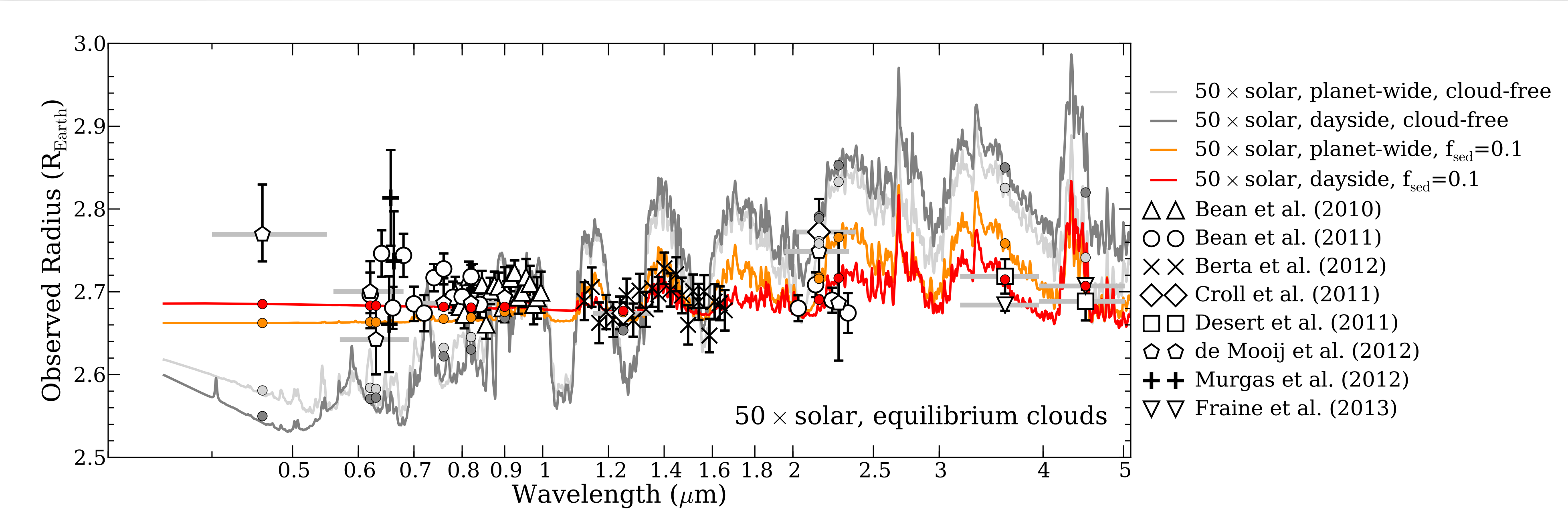
- exploring effects of “minor” cloud species on brown dwarfs
  - Morley et al (2012) after Ackerman & Marley 2001 cloud models
- effect consistent with color-magnitude trends for cool brown dwarfs



Morley, Fortney, Marley, Visscher, et al. (2012); brightness temperatures & color-color diagram

Hazes on the "Super Earth" GJ 1214b

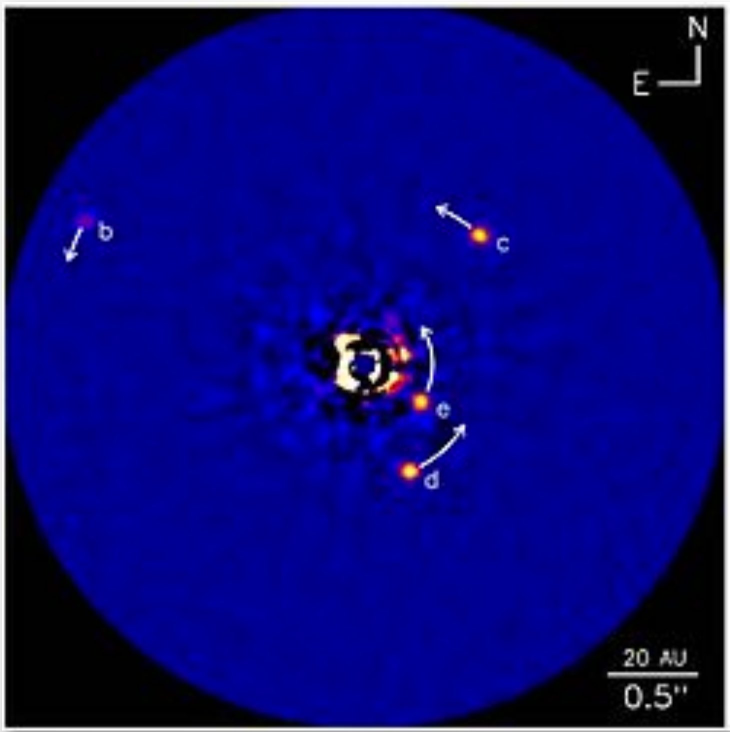
- "minor" clouds such as chlorides and sulfides
  - hazes may help explain "flat" spectra of GJ1214b
  - 6.5 Earth mass, 0.014 AU orbit (M type star)

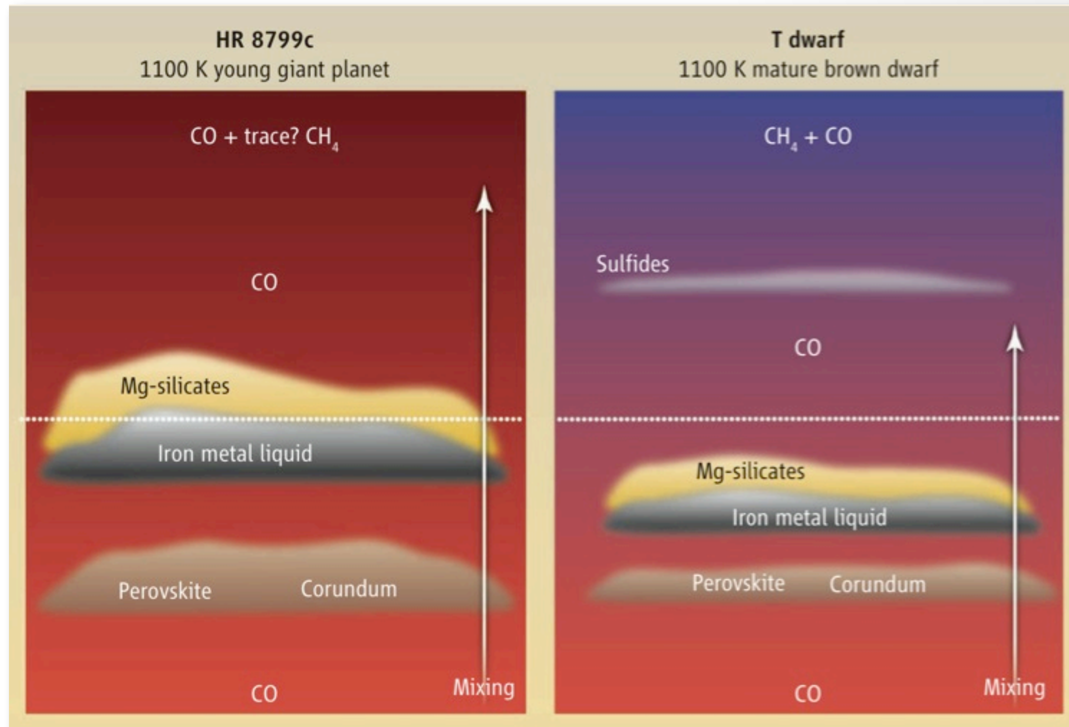


Visscher et al 2006; Morley, Visscher, et al 2012, 2013; see Kreidberg et al 2014

Clouds on hot exoplanets: HR 8799c

- young giant planets: similar atmospheric temperatures as brown dwarfs
  - Fe and Mg-silicate clouds may play a role on HR 8799-like planets
  - HR 8799c: 7.1 M_J, 1.3 R_J, 38 AU, orbiting young A/F star

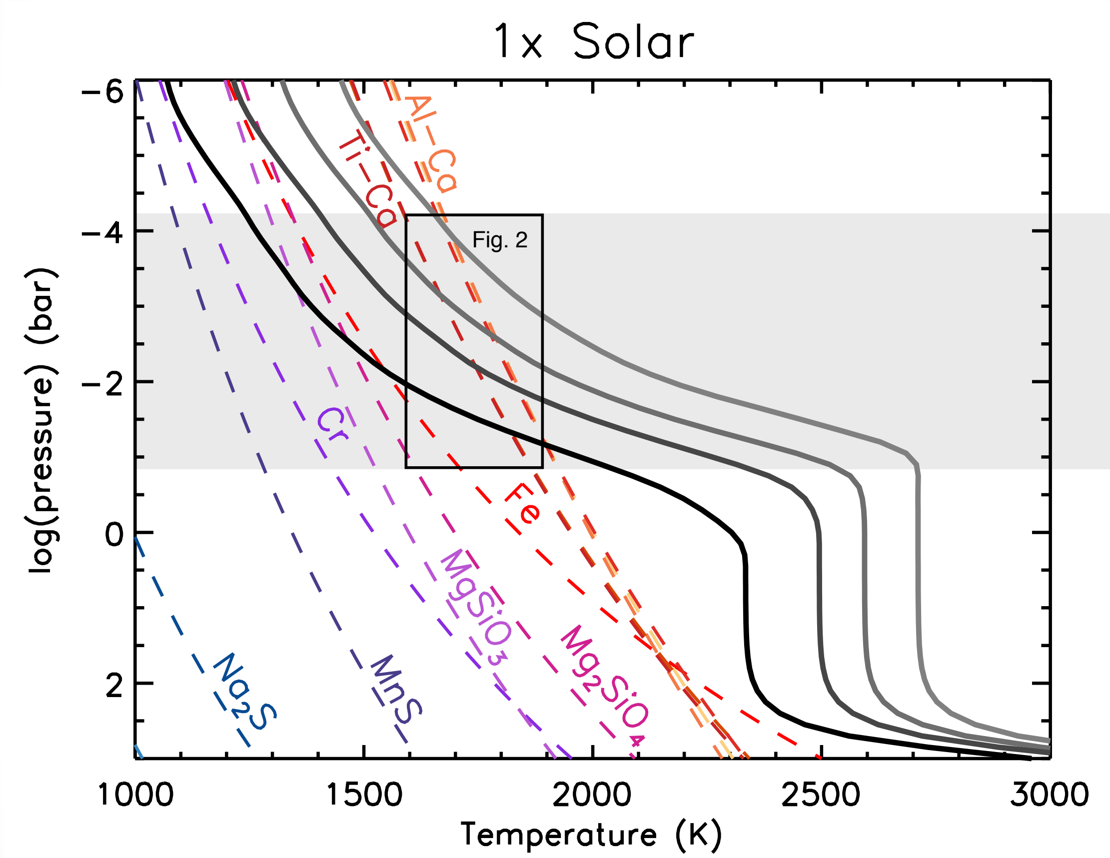




HR 8799 system; Marley 2013, after Lodders 2004

Clouds on hot exoplanets: high-T clouds

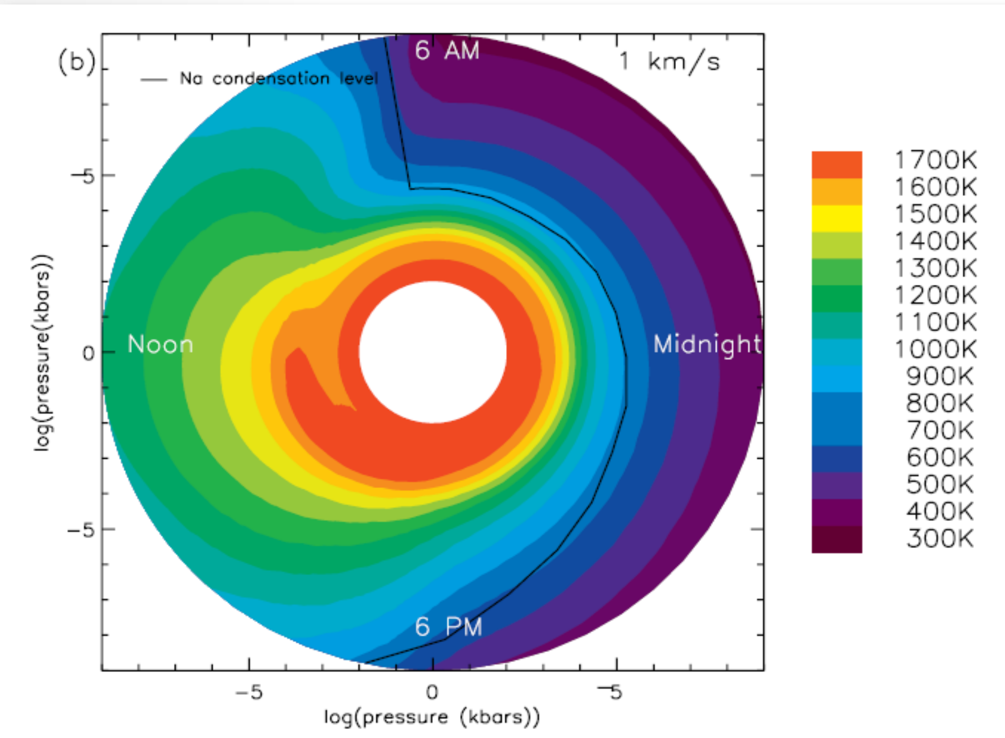
- hot exoplanet spectra may be influenced by Ca-Al-Ti clouds

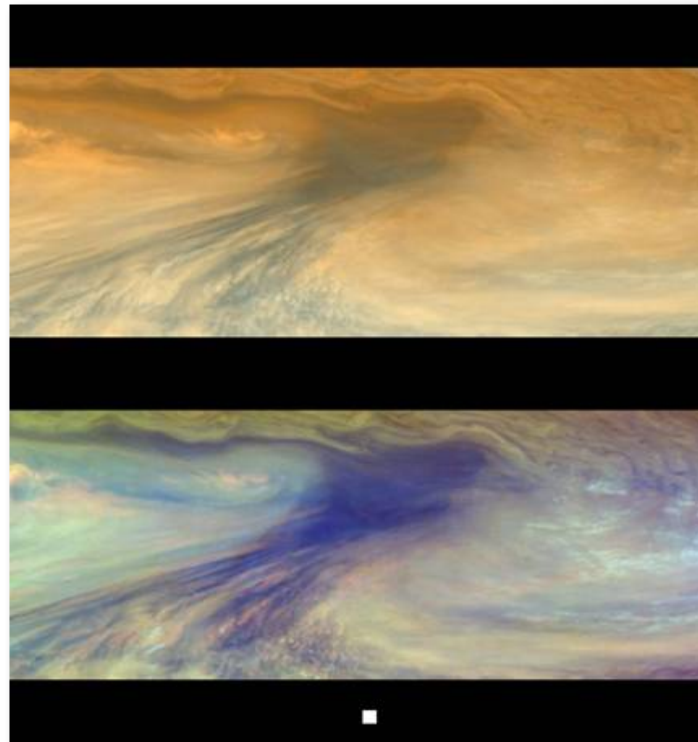


Wakeford, Visscher, et al submitted

Outstanding questions (ongoing & future work)

- what **chemical mechanisms** are involved in condensate formation?
- what are the **kinetics** of cloud formation?
- how might **mixing** & **orbital effects** influence cloud formation?
- how does variable **cloud coverage** influence spectra?





Iro et al 2005; dayside vs. nightside condensation of Na_2S; cloud gaps on Jupiter