PEPS

Turbulent mixing, chemical disequilibrium and cloud formation in substellar atmospheres

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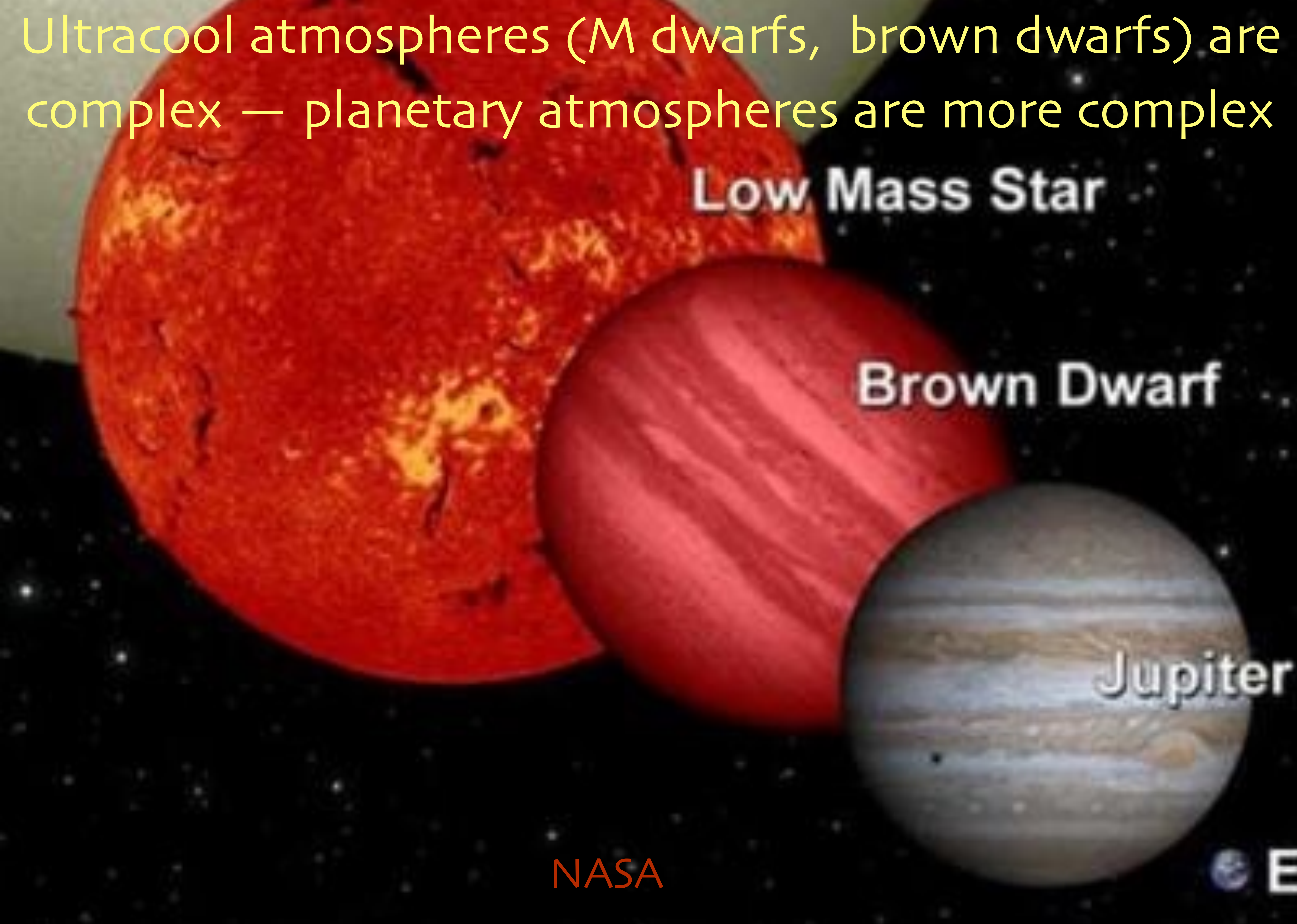
Ultracool atmospheres (M dwarfs, brown dwarfs) are complex — planetary atmospheres are more complex



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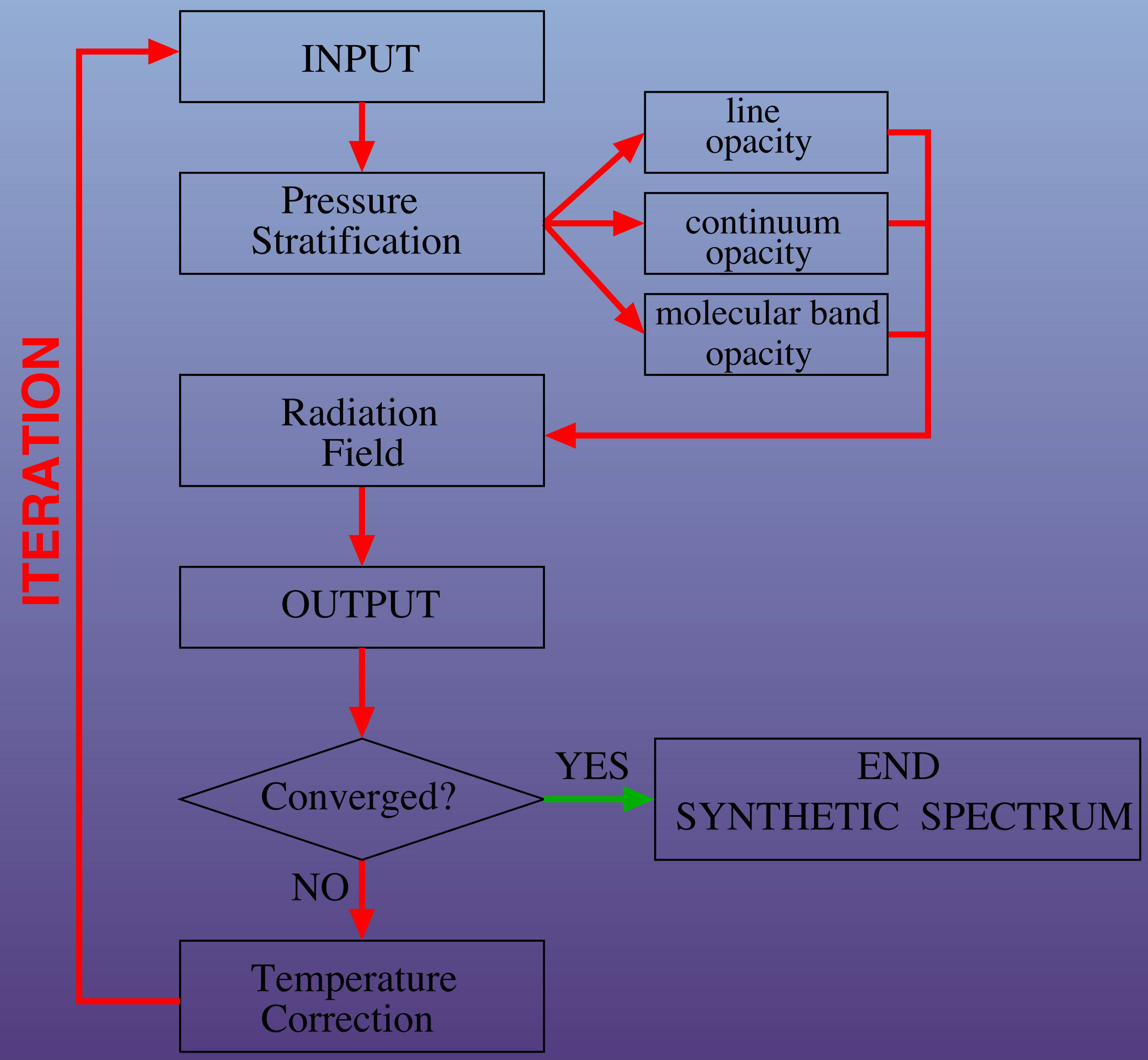
(Sub-) stellar atmosphere modelling

- independent Variables (minimal):
  - effective temperature T_{eff}
  - surface gravity $g(r) = GM/r^2$
  - mass M or radius R or luminosity $L = 4\pi R^2 \sigma T_{eff}^4$
  - composition ("metallicity")

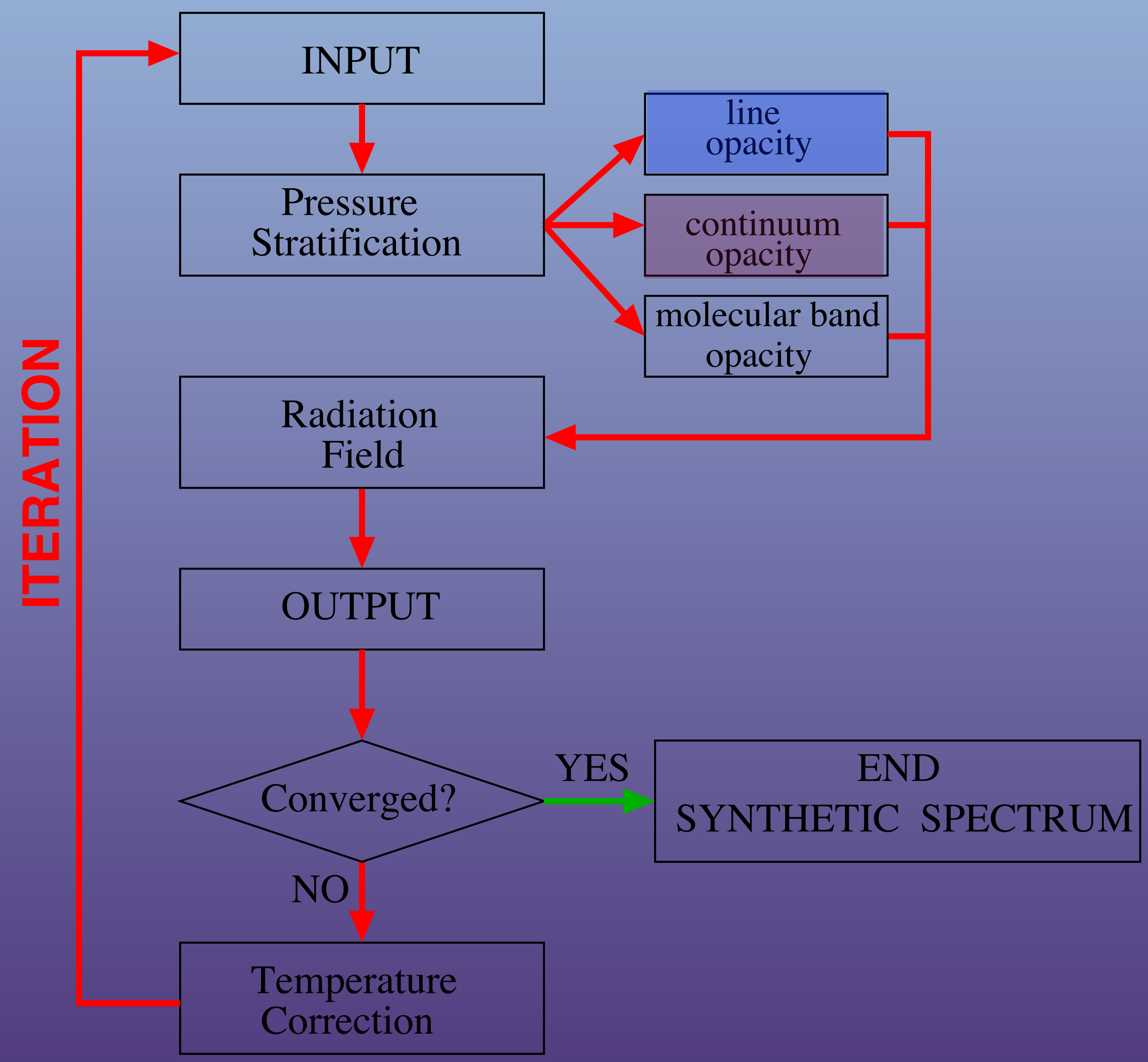


PHOENIX workflow (P. Hauschildt)

(Sub-) stellar atmosphere modelling

★ independent Variables (minimal):

- effective temperature T_{eff}
- surface gravity $g(r) = GM/r^2$
- mass M or radius R or luminosity $L = 4\,\pi\,R^2\,\sigma\,T_{eff}^{\;4}$
- composition ("metallicity")
- convection ➙ (micro-) turbulence & mixing
- rotation
- chemical peculiarities



PHOENIX workflow (P. Hauschildt)

➙ self-contained and internally consistent structure in 1D

(Ultra)cool Atmospheres — Molecular Bands

Importance of molecular bands dependent on

- Line strengths → *gf*, Abundances
- Line shapes
- Line numbers
- Line distribution

Bands with complex spectra
(polyatomic molecules)
produce strongest blanketing effects.

Molecular Bands — Methane

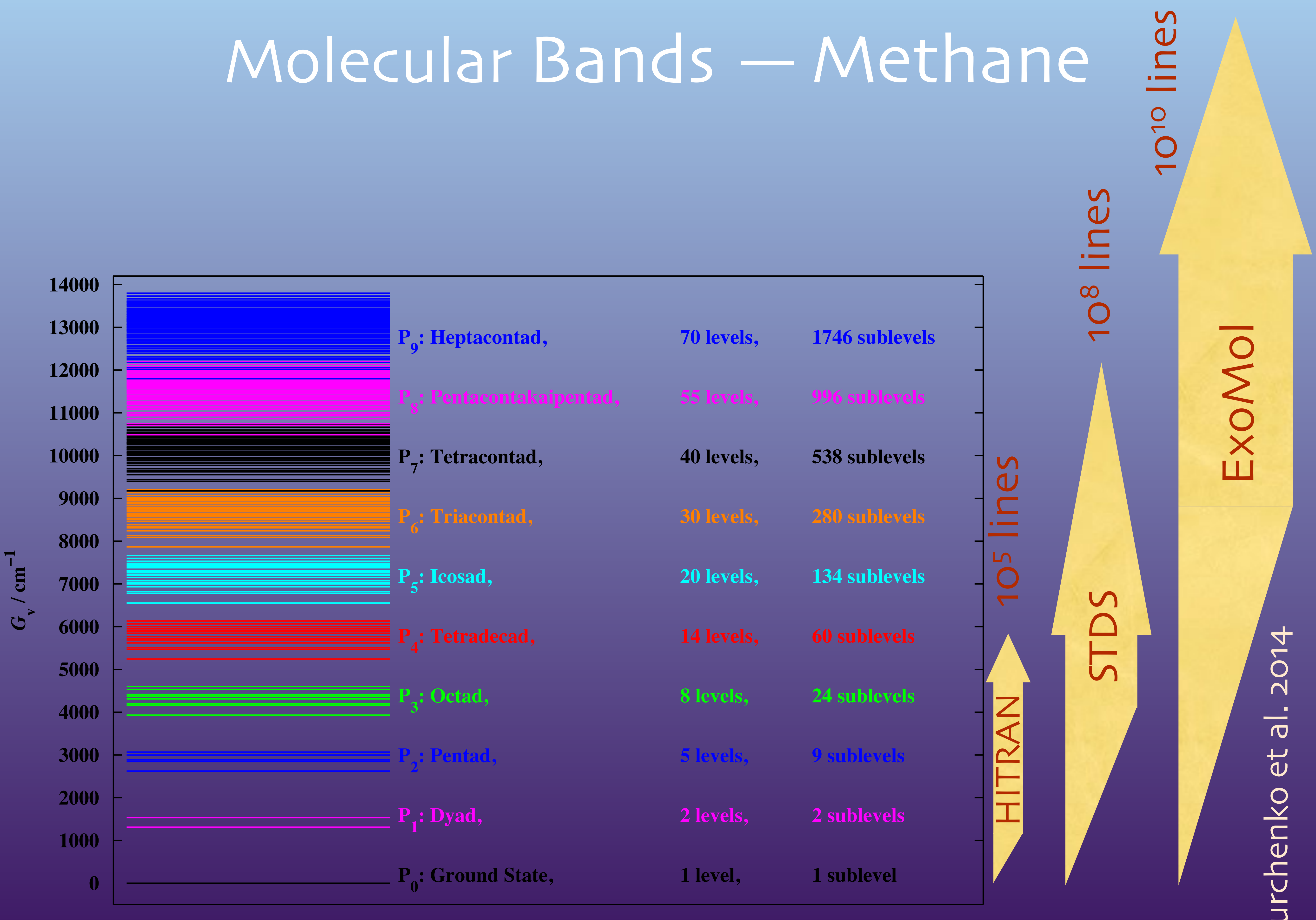
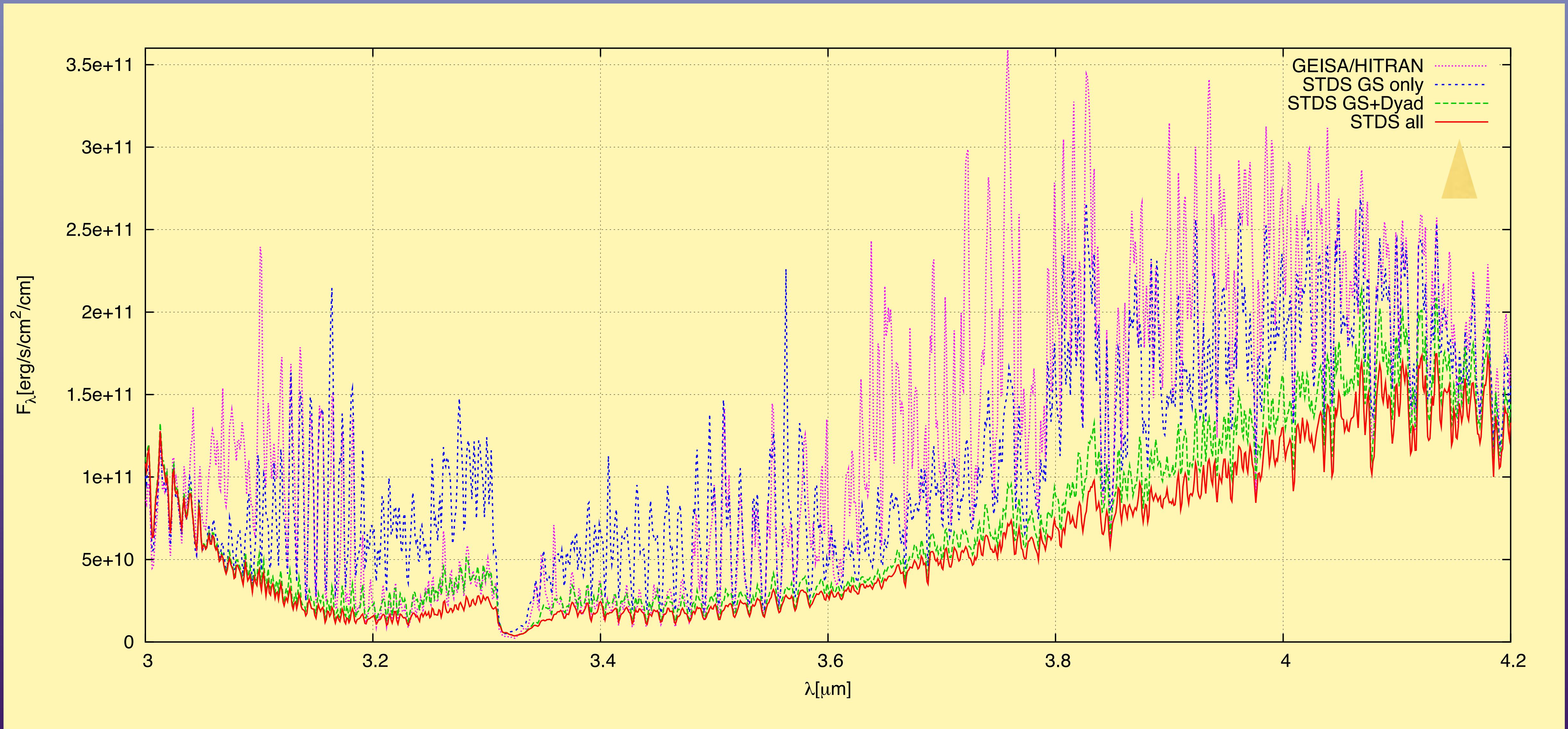


Fig. 2. Polyad energy-level structure for $^{12}CH_4$. Boudon et al. 2006

Molecular line blanketing: Methane

- 30 Mio. lines computed with the STDS program (Université de Bourgogne) — 2013 update: 80 Mio.
- Vibrational and rotational states up to ~ 8000 cm^{-1}
- Completeness: ~50% (mid-IR) - 10% (H-band) - 0% (Y/J)



Non-equilibrium Chemistry

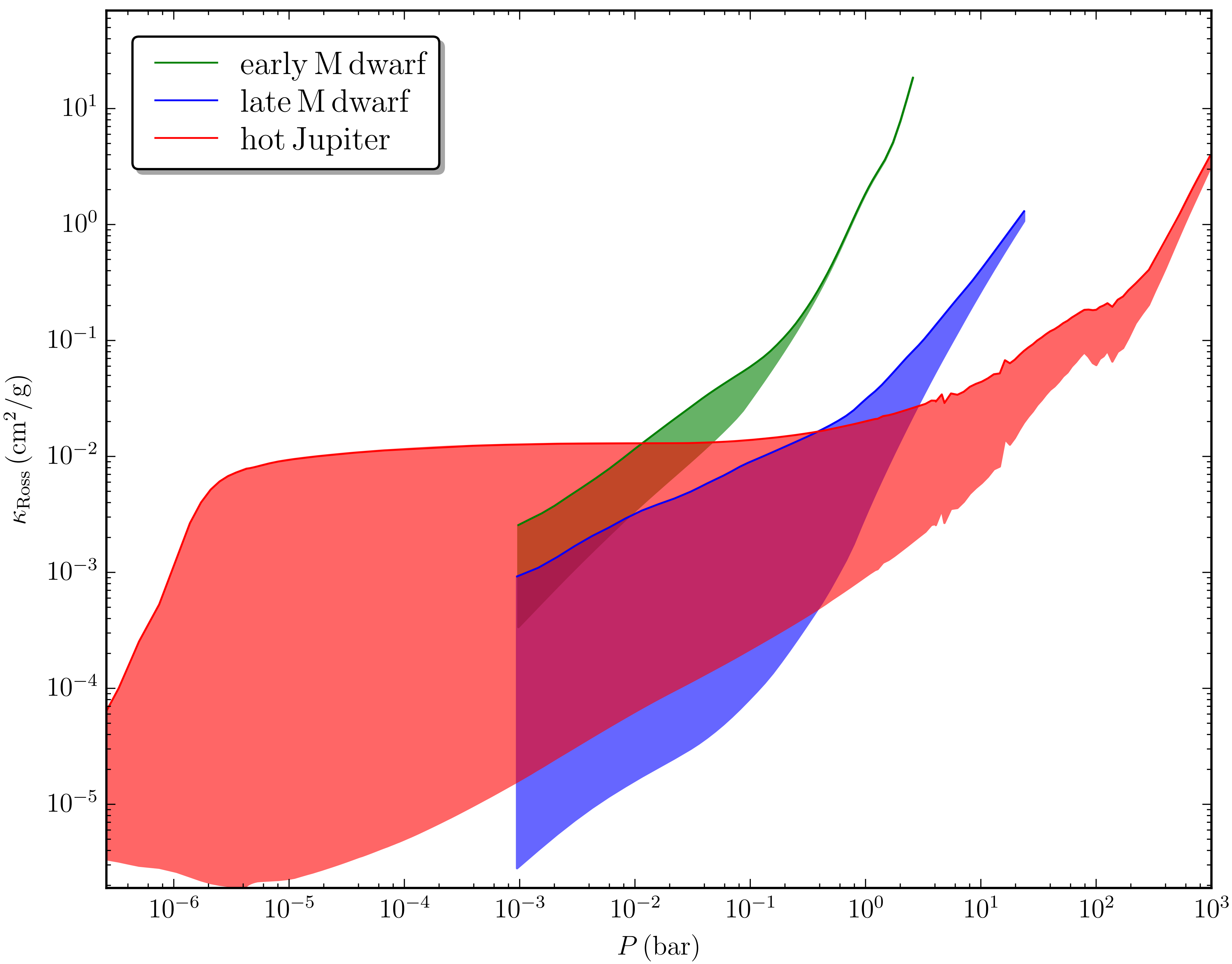
- Nitrogen- and Carbon chemistry is inhibited by slow reaction steps breaking up the C=O and N≡N bonds:
- $N_2 \longleftrightarrow NH_3$: limited by $N_2 + H_2 \rightleftharpoons 2\ NH$

  $K = 8.45 \times 10^{-8} \times e^{(-8151/T)}$ (Lewis & Prinn 1980)
- $CO \longleftrightarrow CH_4$: limited by $H_2 + CH_3O \rightleftharpoons CH_3OH + H$

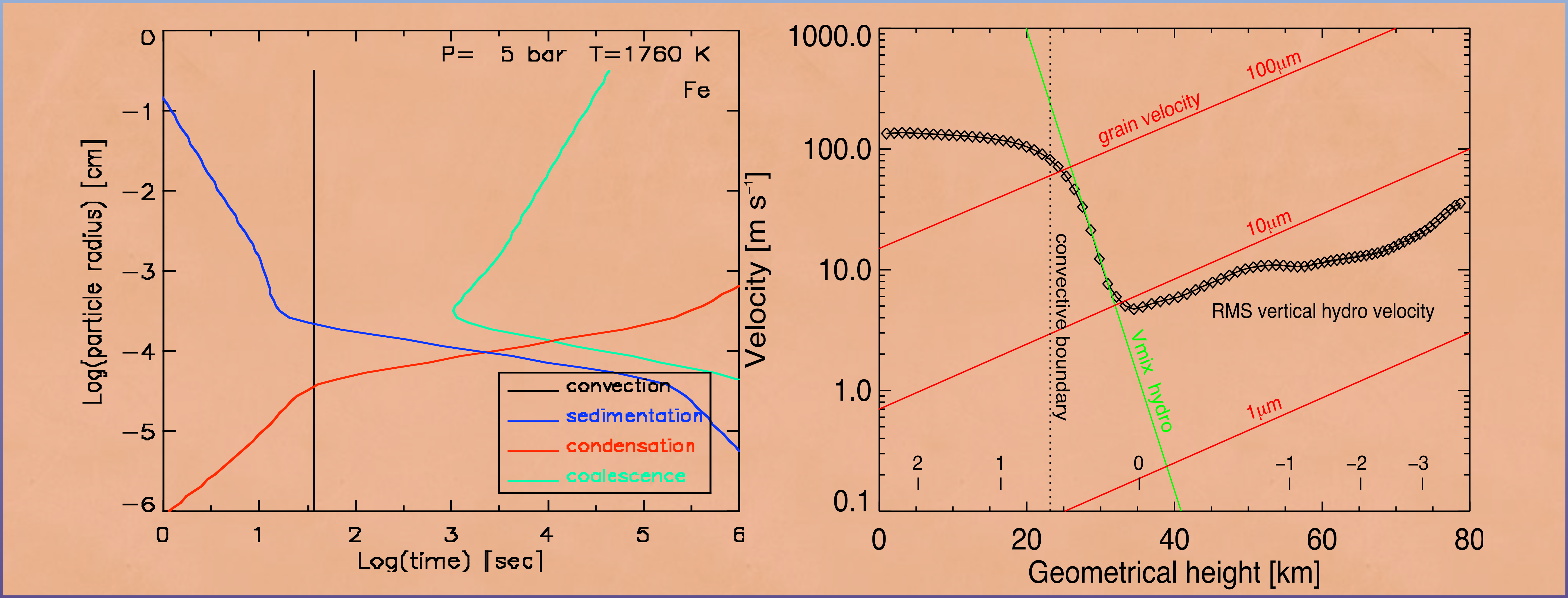
  $K = 1.77 \times 10^{-22} \times T^{-3.09}\ e^{(-3055/T)}$ (Visscher, Moses & Saslow 2010)
- $CO \longleftrightarrow CO_2$: limited by $CO + H_2O \rightleftharpoons CO_2 + H_2$

  $K = 6.44 \times 10^{3} \times T^{-3.09}\ e^{(33889/T)}$ (Graven & Long 1954)

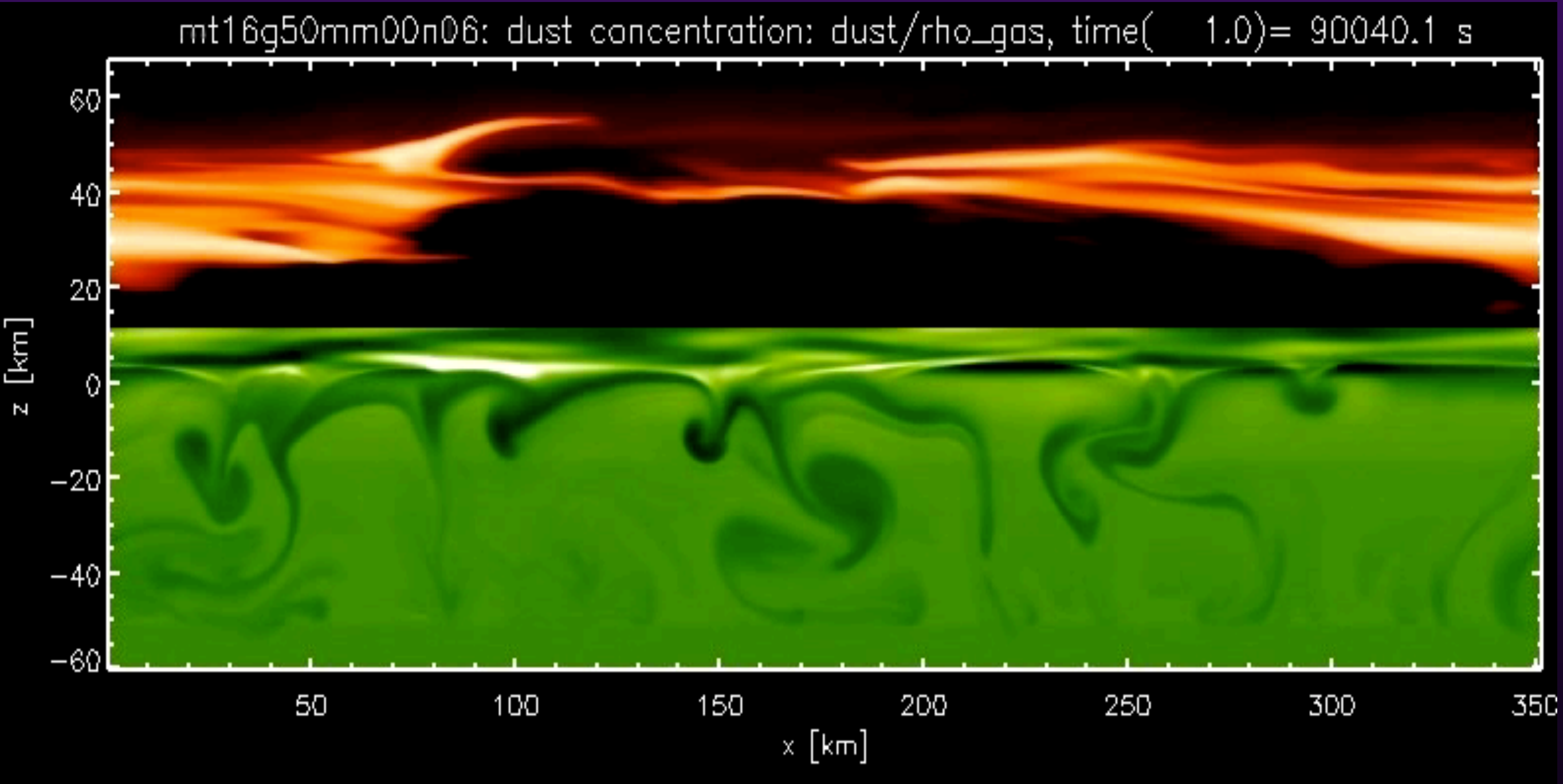
Model atmospheres — molecular opacity



Turbulence & Mixing in Cool



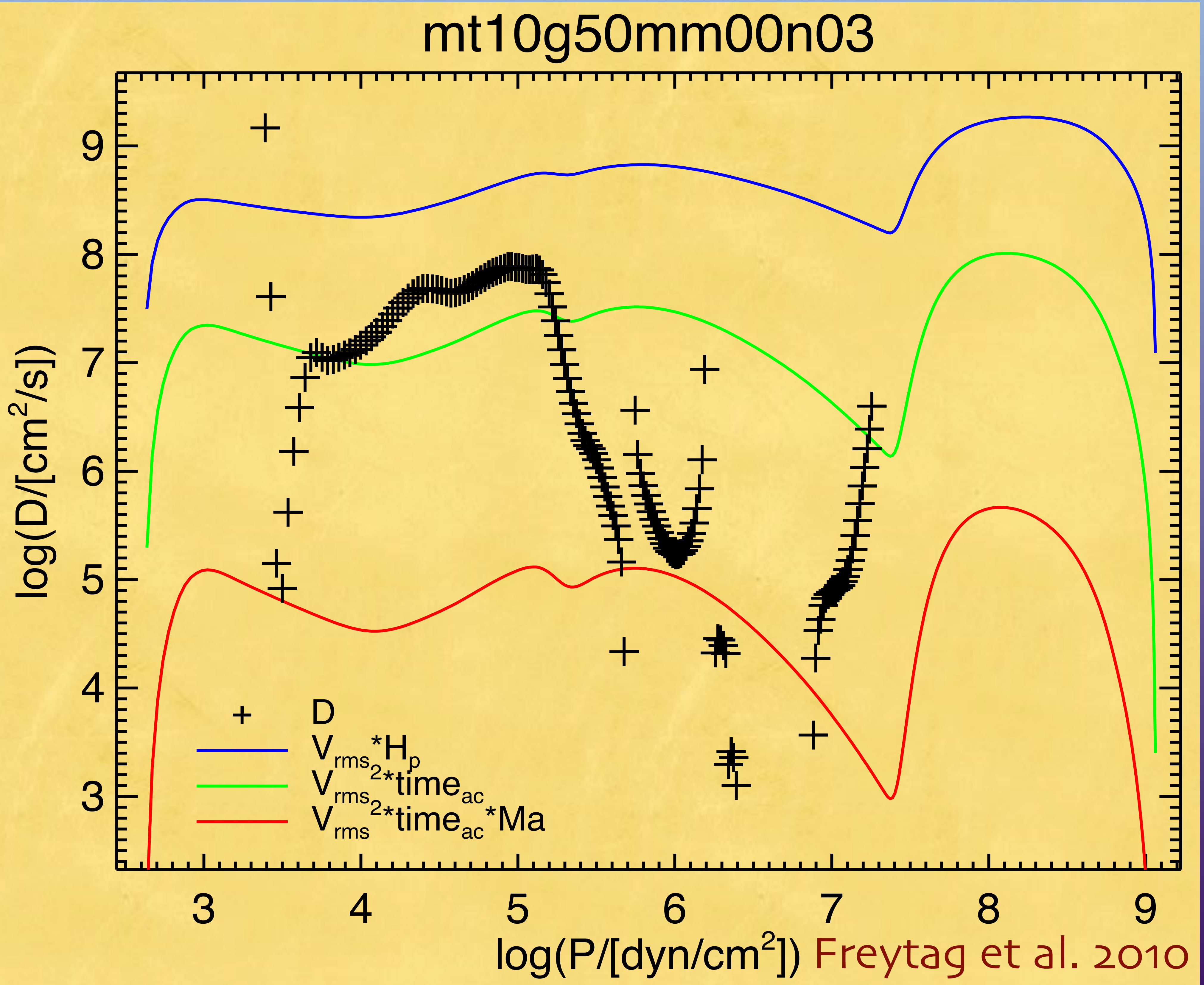
- $\tau_{mix} = H_P/v$ or $D = v \cdot H_P$ to be compared to
  - dust formation and sedimentation timescales



CO5BOLD 2D-Hydrodynamic Simulation of 1600 K L dwarf atmosphere
with Forsterite (Mg_2SiO_4) cloud model

Freytag et al. 2010

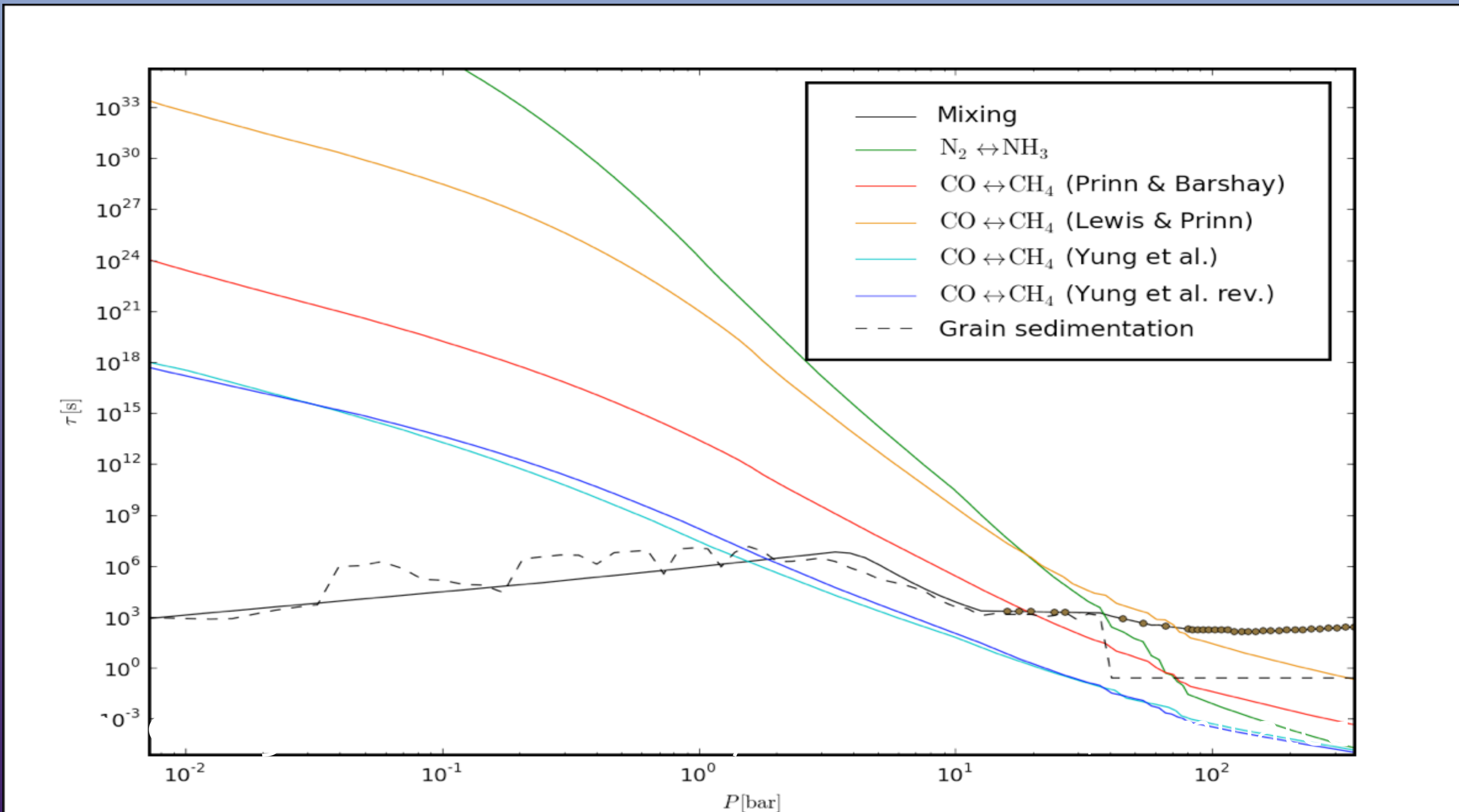
Mixing and Diffusion - a closer Look



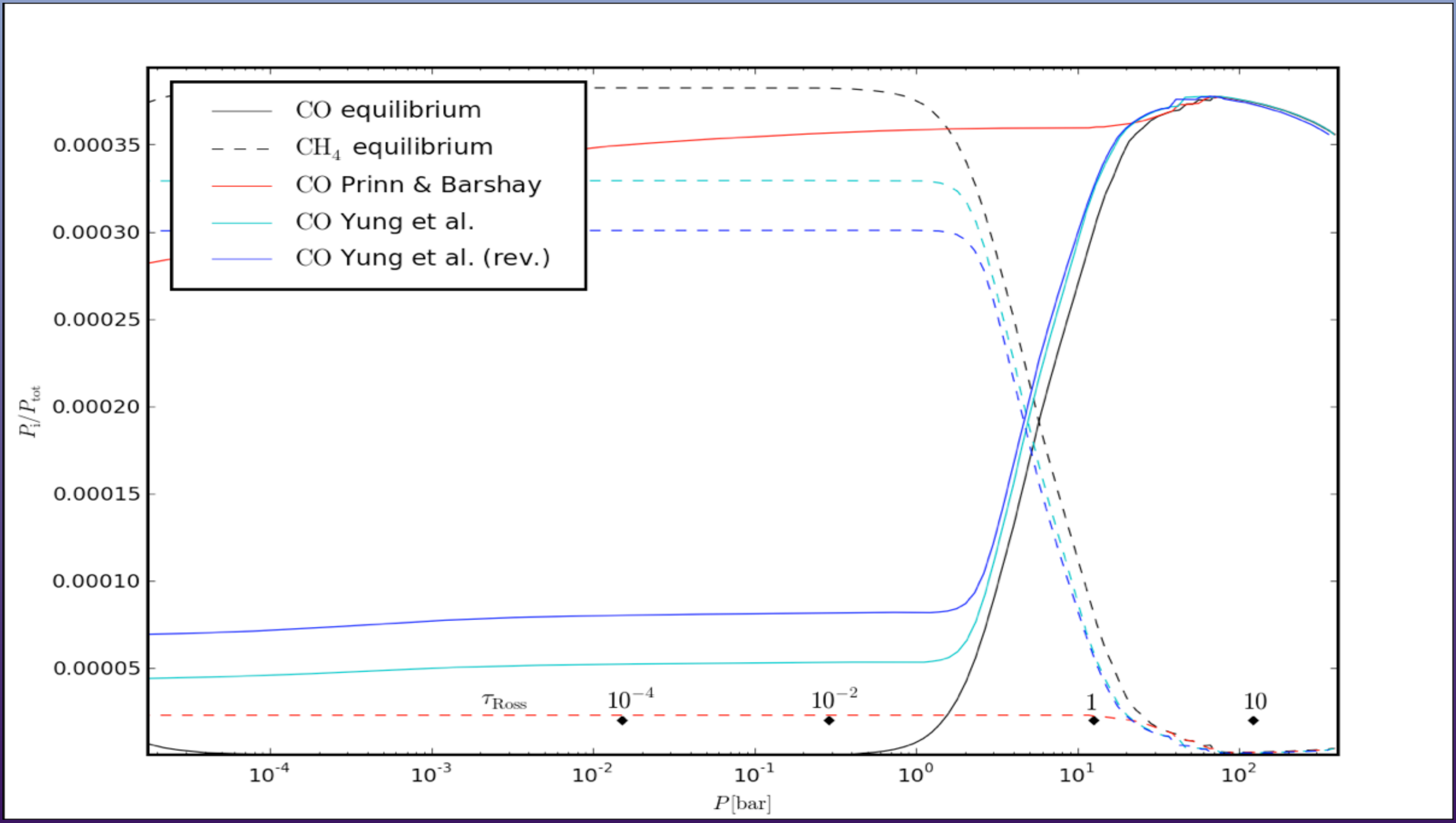
Freytag et al. 2010

convective overshoot and gravity wave excitation dominant in brown dwarfs

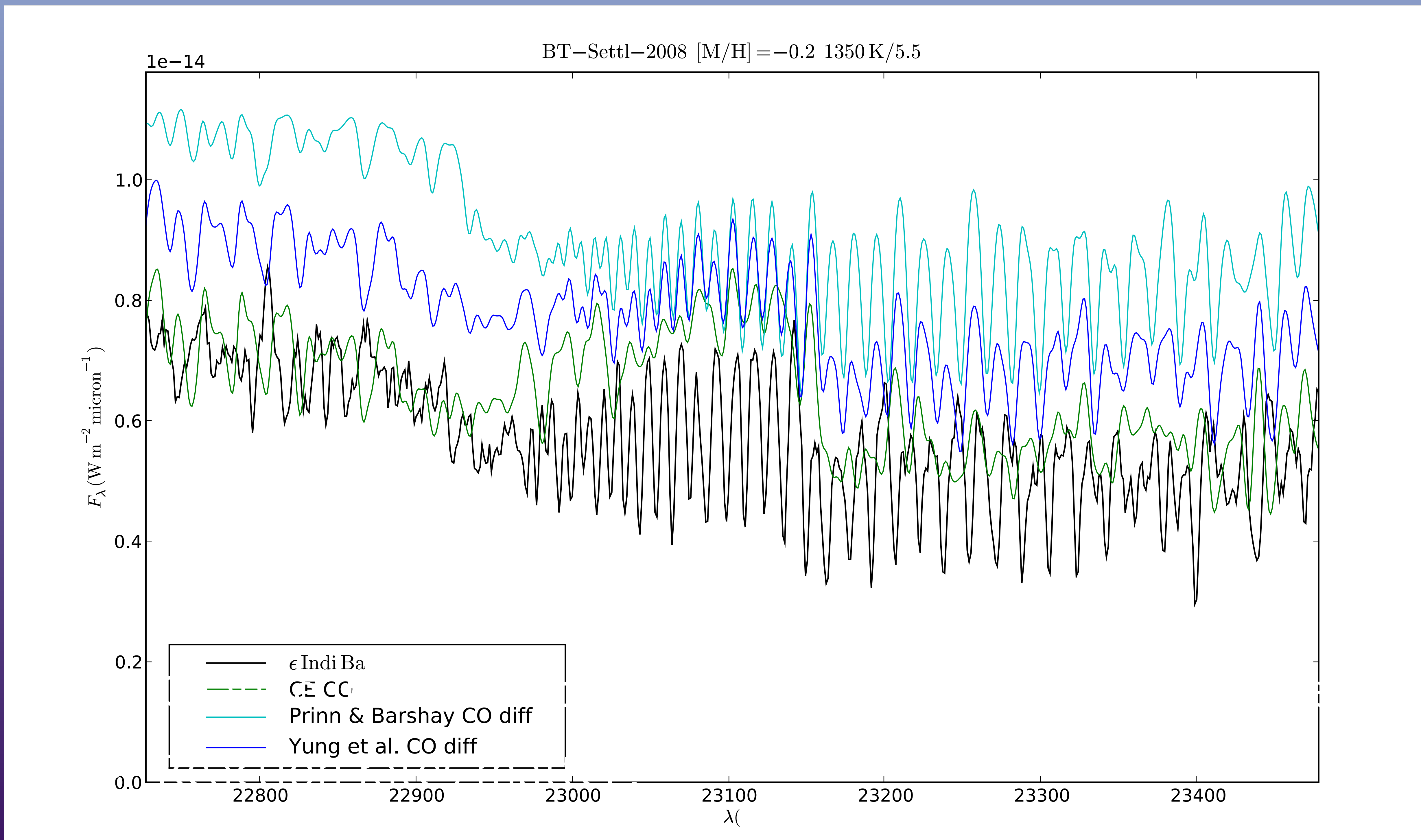
Chemistry across the L-T transition



Chemistry across the L-T transition



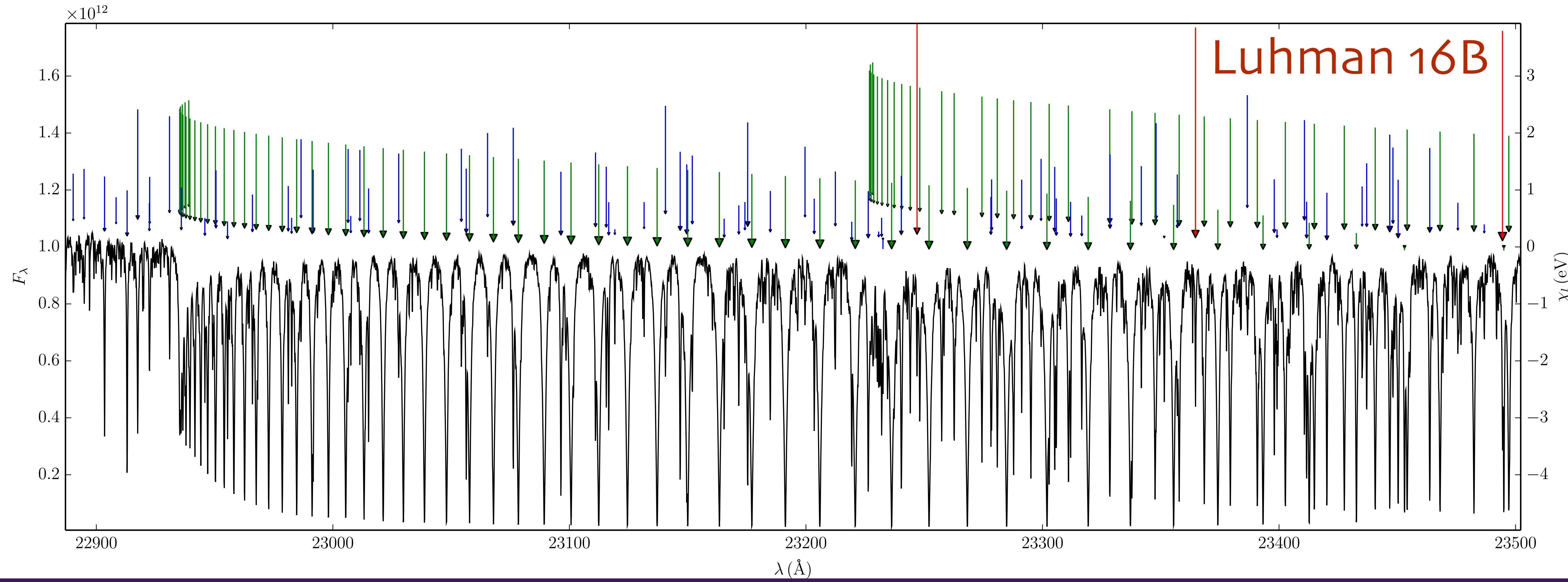
Chemistry across the L-T transition

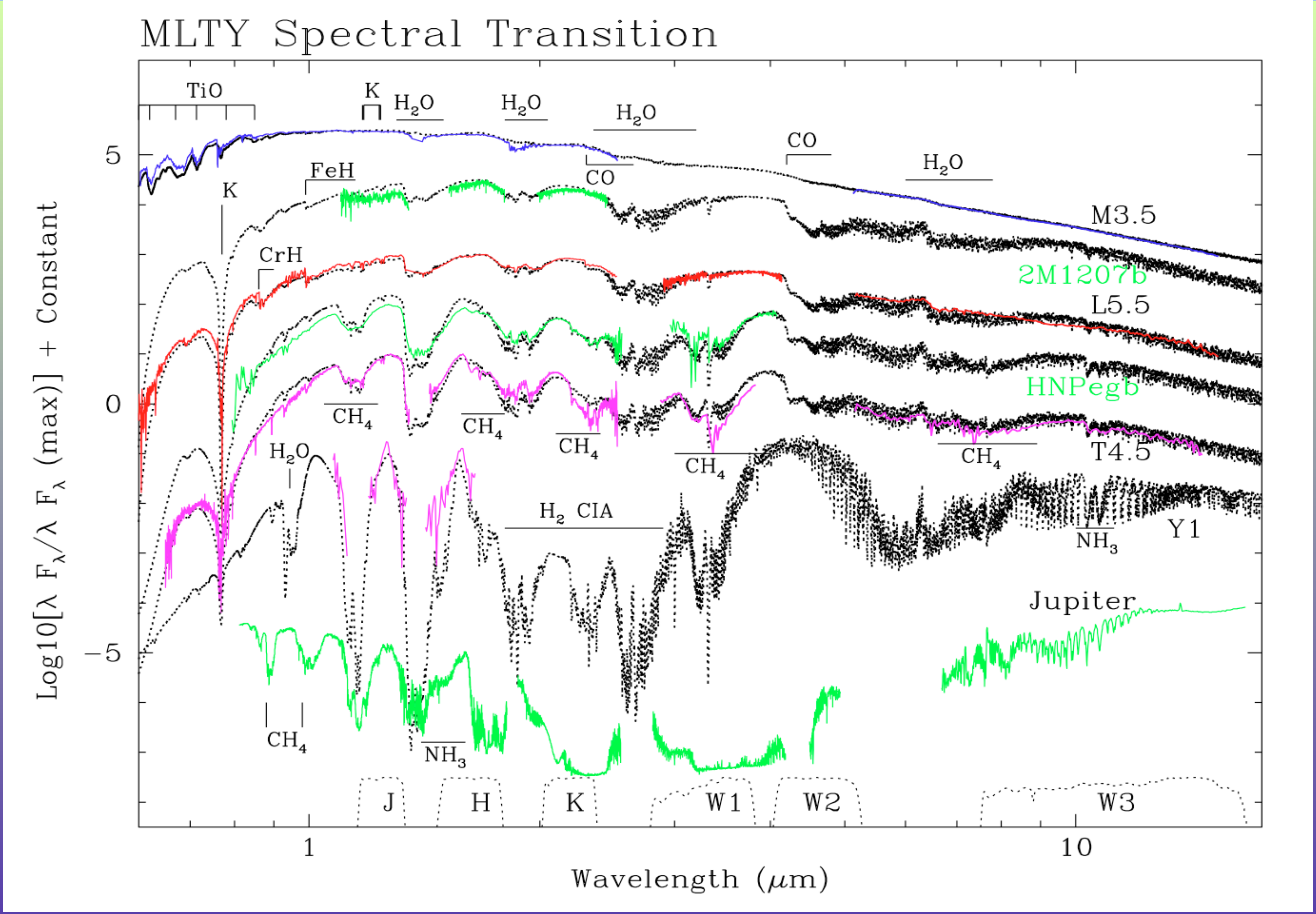


King et al. 2010

Molecular Line Profiles

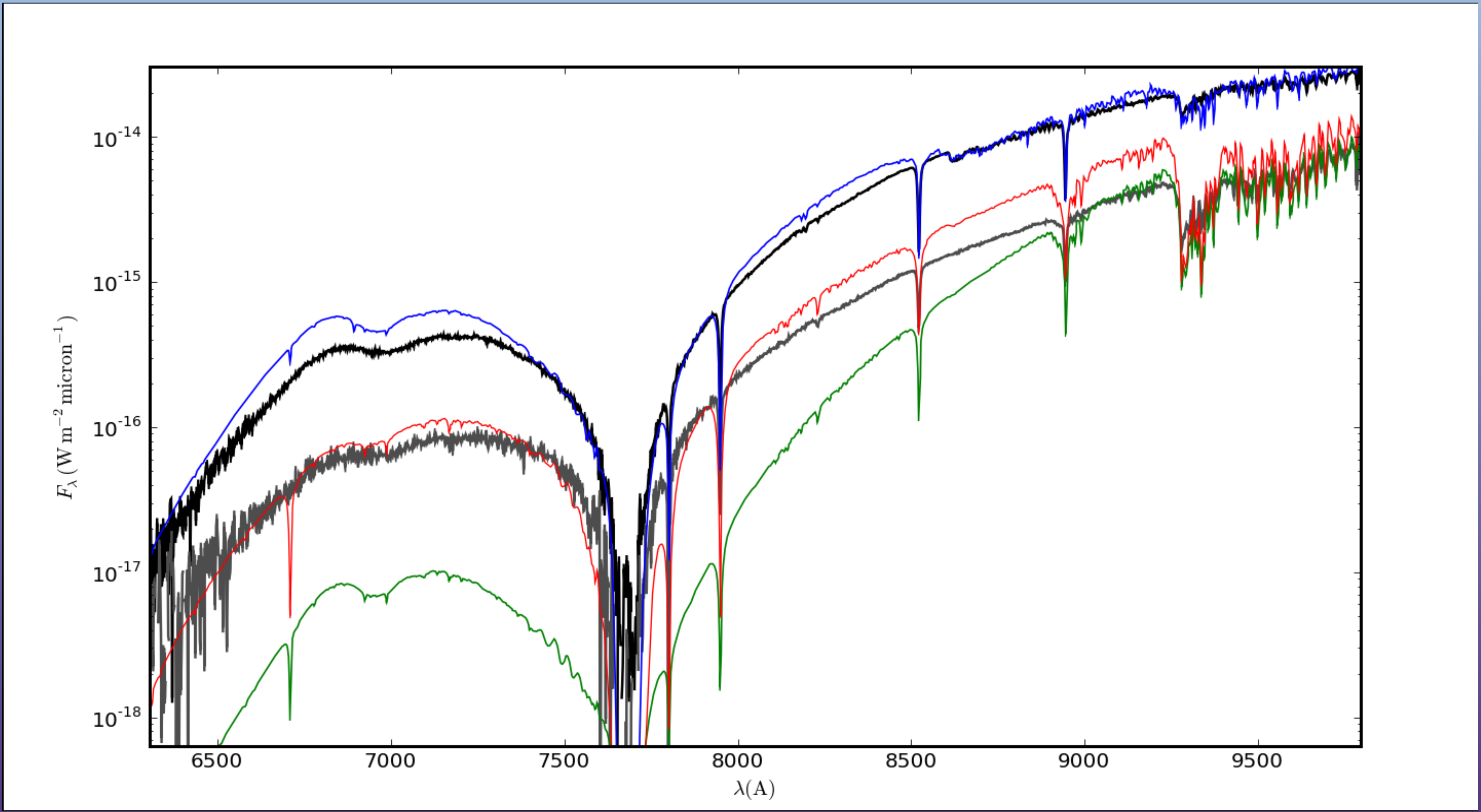
- Molecular line data for stellar atmosphere calculations:
  - Extensive data available from spectroscopy line lists (HITRAN and others)
  - Often damping widths and shifts included, sometimes temperature dependence





- Effects of dust and transition from CO- to CH_4-chemistry

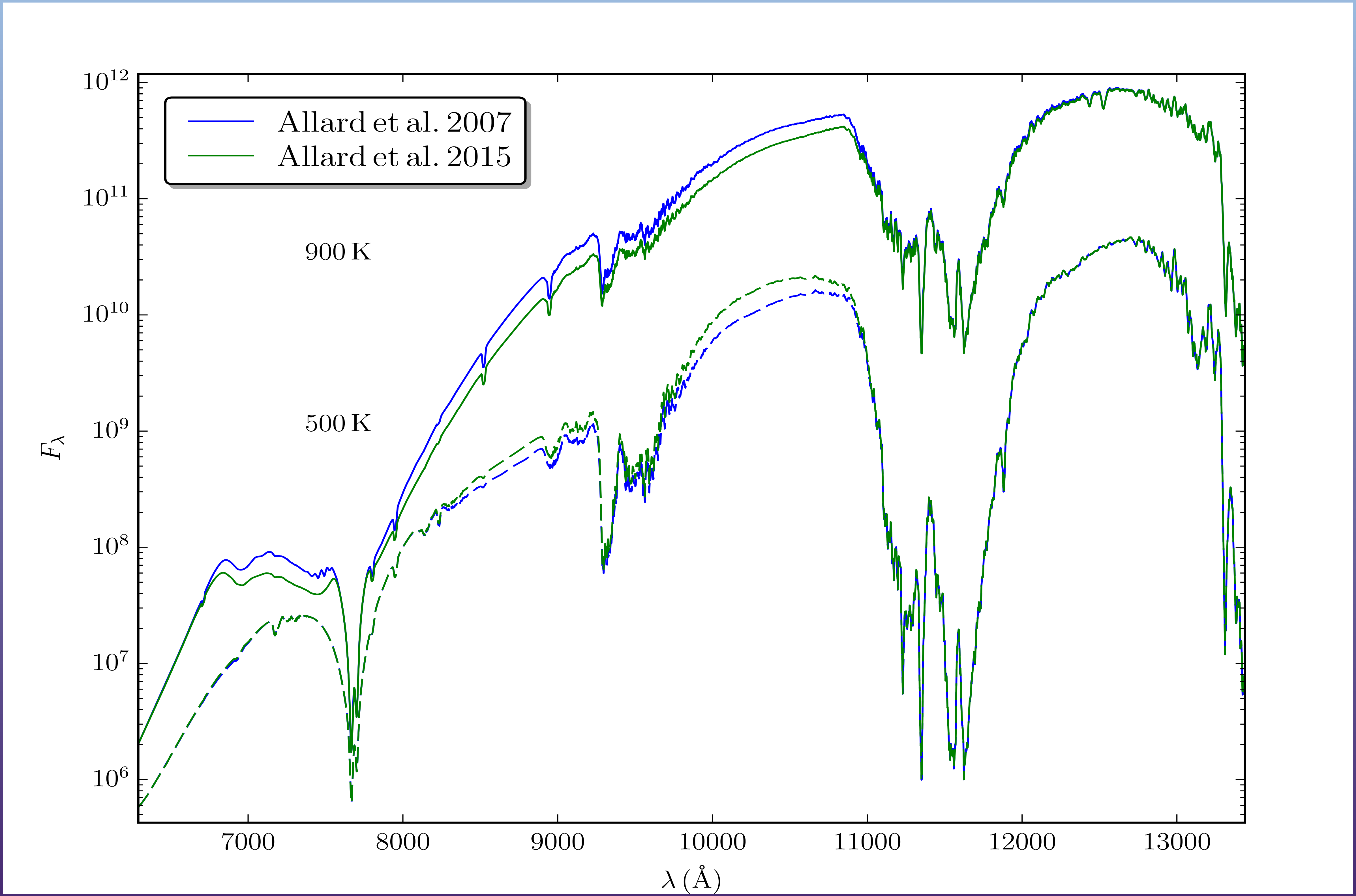
Condensation



King et al. 2010

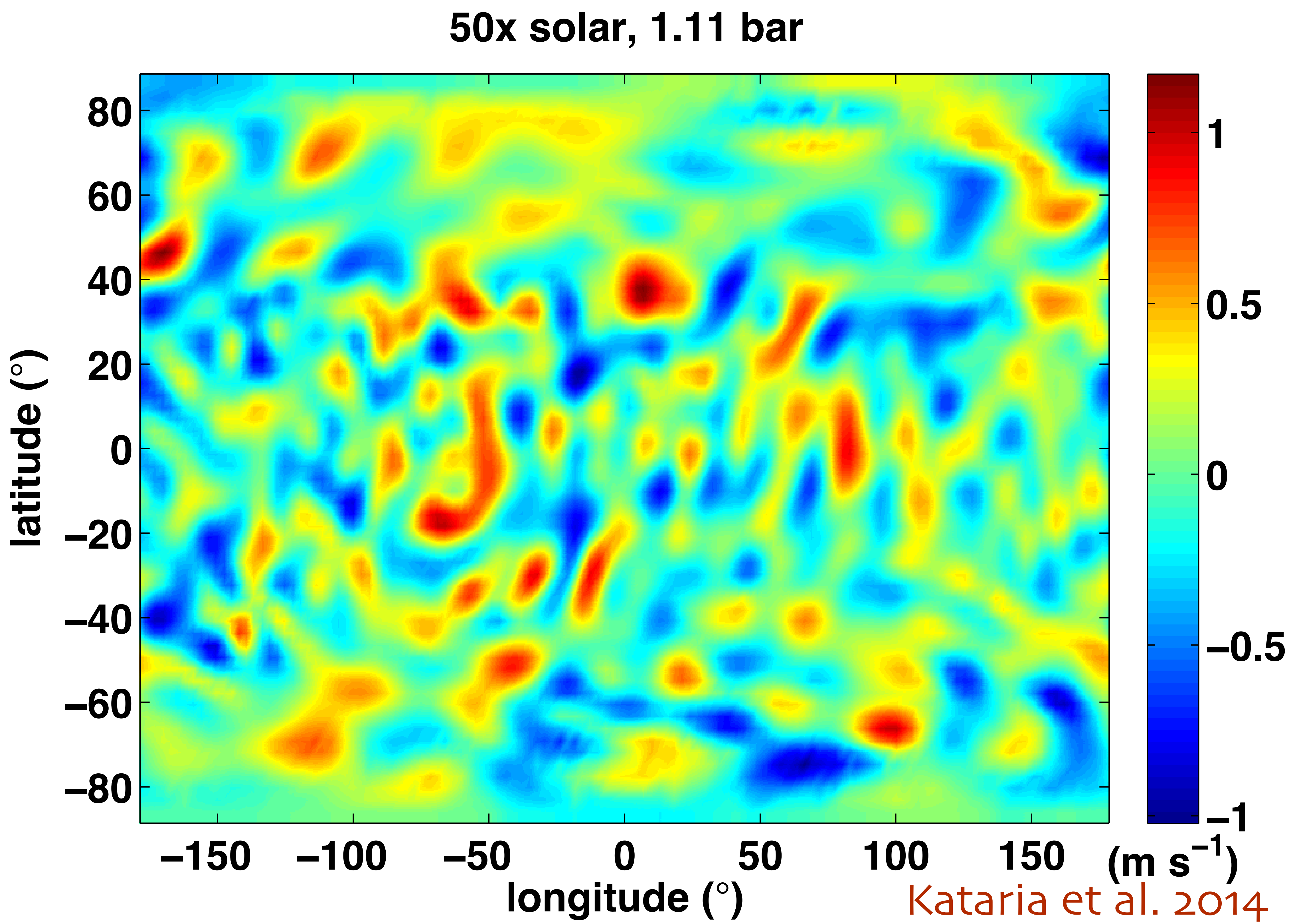
- cloud opacity changes spectral energy distribution
- depletion changes gas phase composition ➙ changes spectra as well

Condensation



- depletion and accurate broadening theory important
  — Allard et al. in prep.

Exoplanets — Irradiation and Circulation

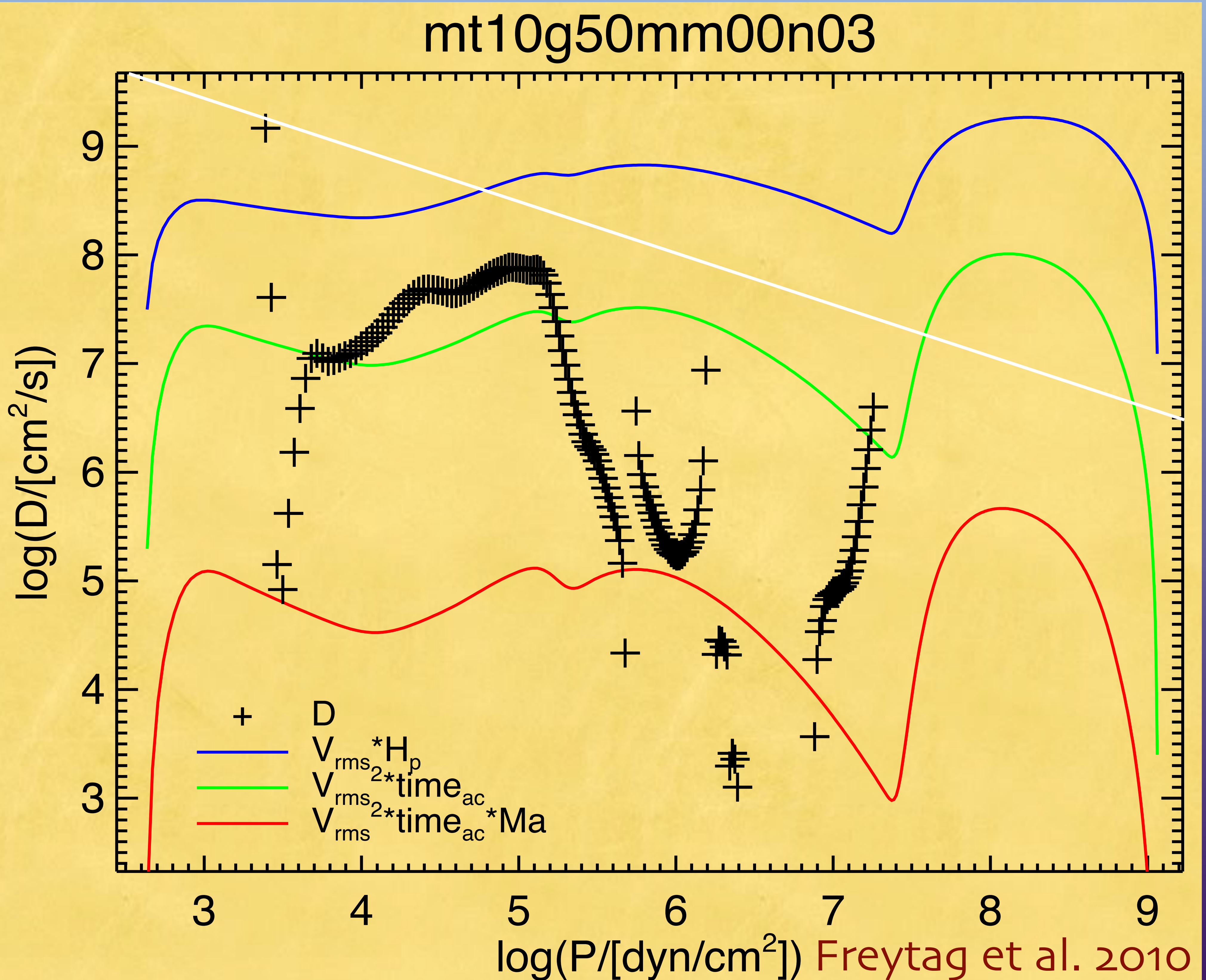


Kataria et al. 2014

GJ 1214b

- General Circulation models predict vertical wind components

Mixing and Diffusion - a closer Look



Freytag et al. 2010

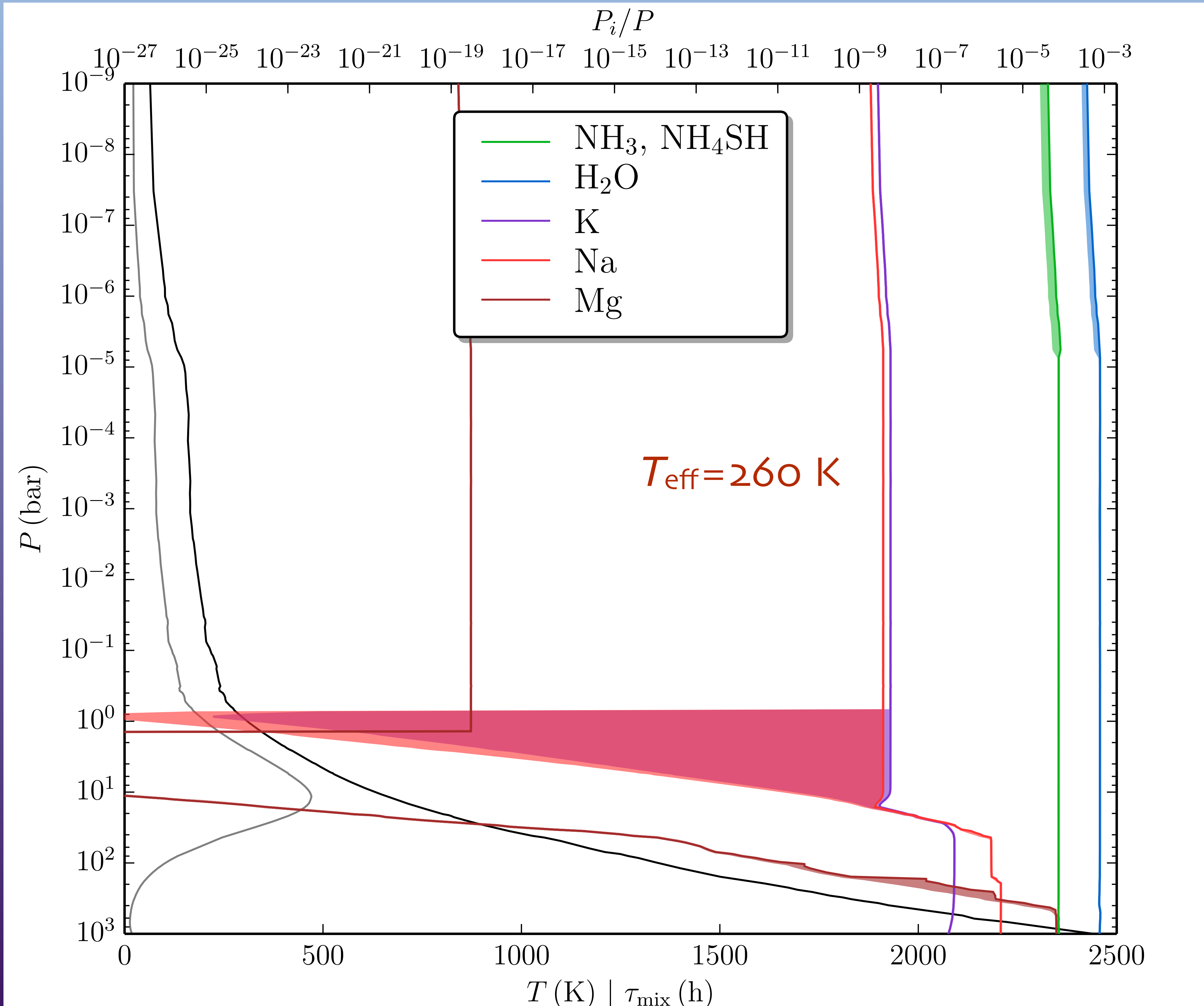
convective overshoot and gravity wave excitation dominant in brown dwarfs

— but in planets too inefficient (Schwarzschild boundary @ $\tau \gtrsim 100$

→

global circulation important!

Clouds in Brown Dwarfs and Planets



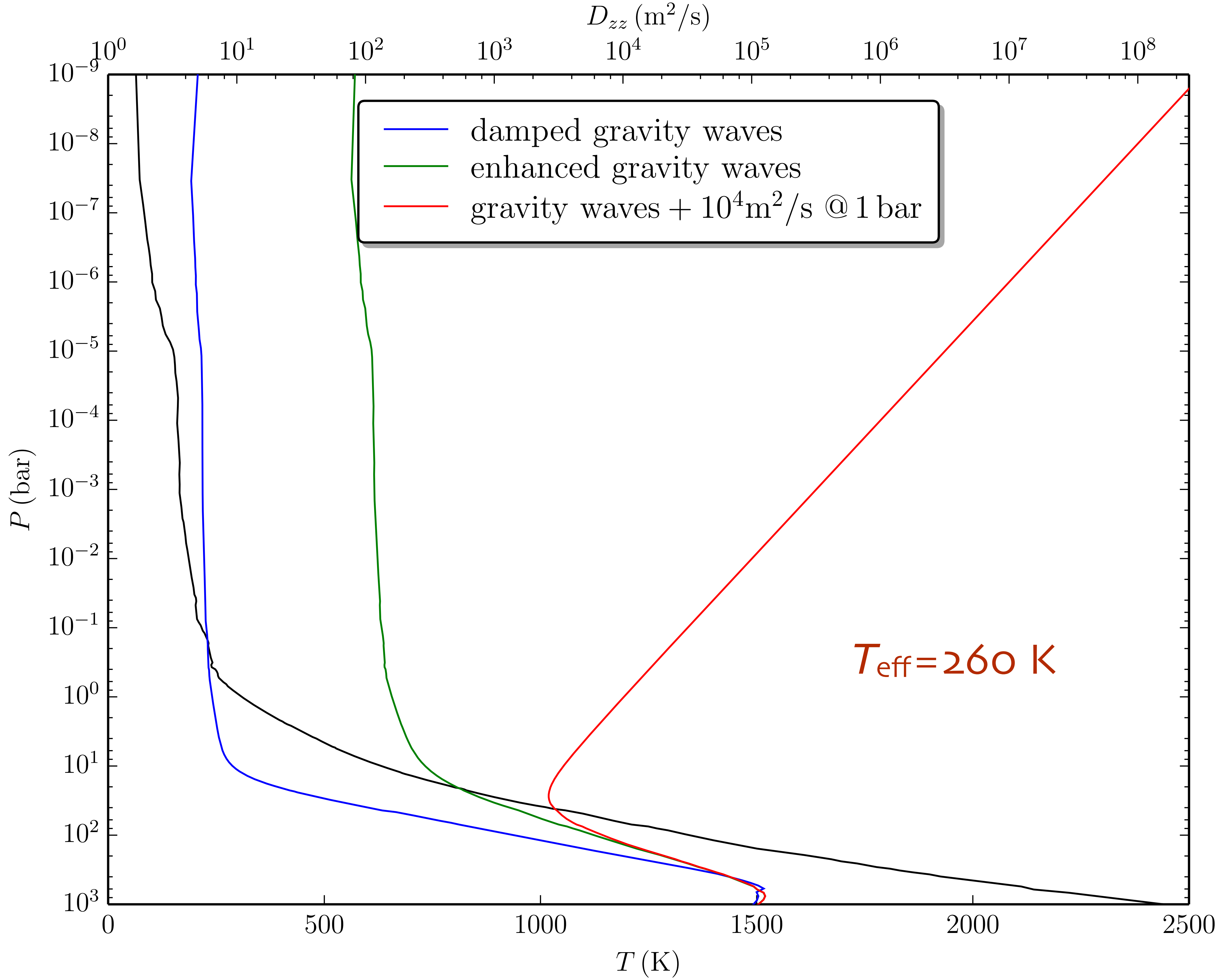
more vigorous mixing supports thicker and higher clouds, less depletion

water ice, ammonium hydrosulphide clouds

quenching of CO, NH_3 in non-CE (cf. Visscher et al. 2010)

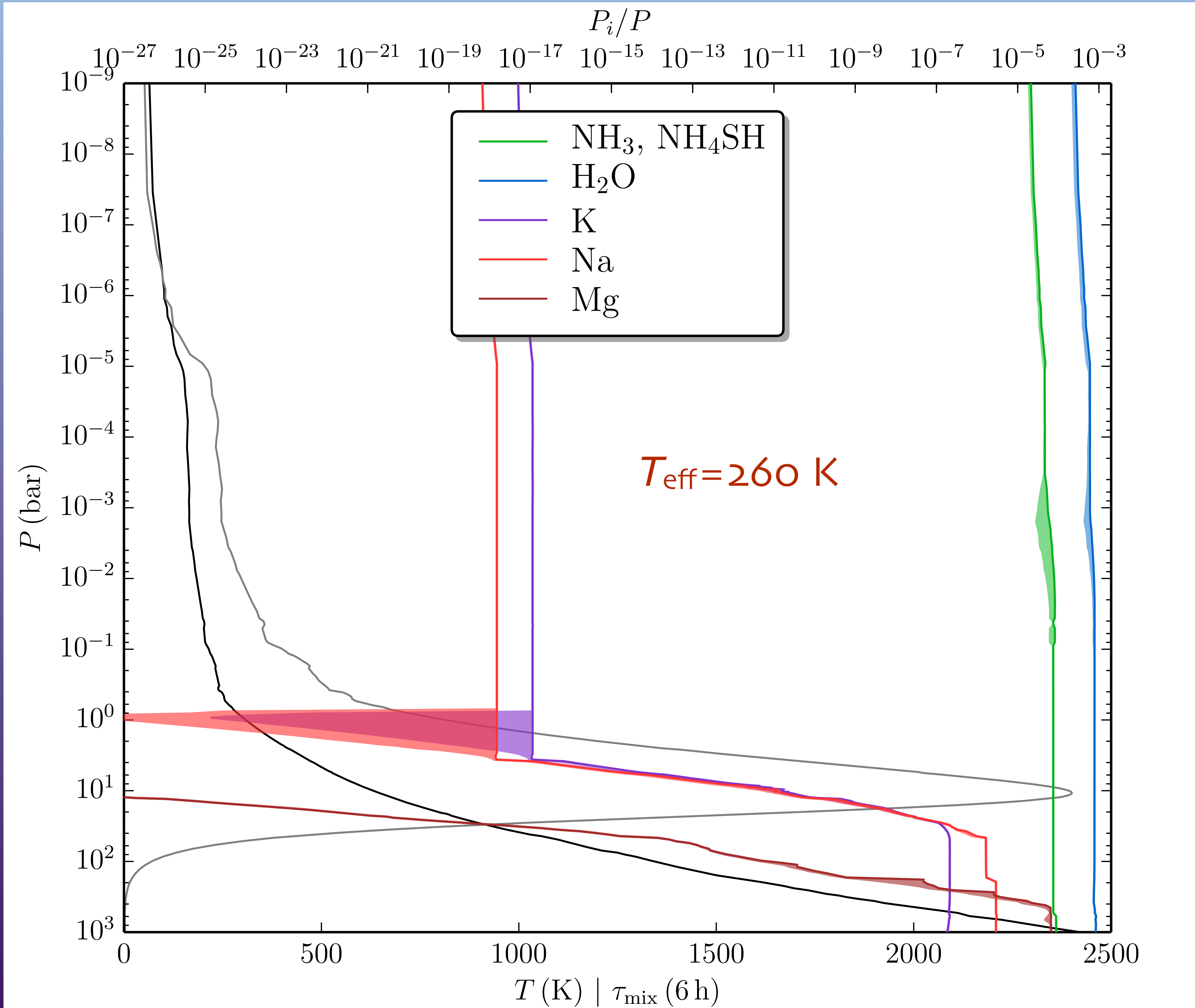
deep silicate clouds

Clouds in Brown Dwarfs and Planets



modelling mixing based on extrapolation of RHD simulations + GCM models (Parmentier et al. Kataria et al.)

Clouds in Brown Dwarfs and Planets



WISE 0855-0714

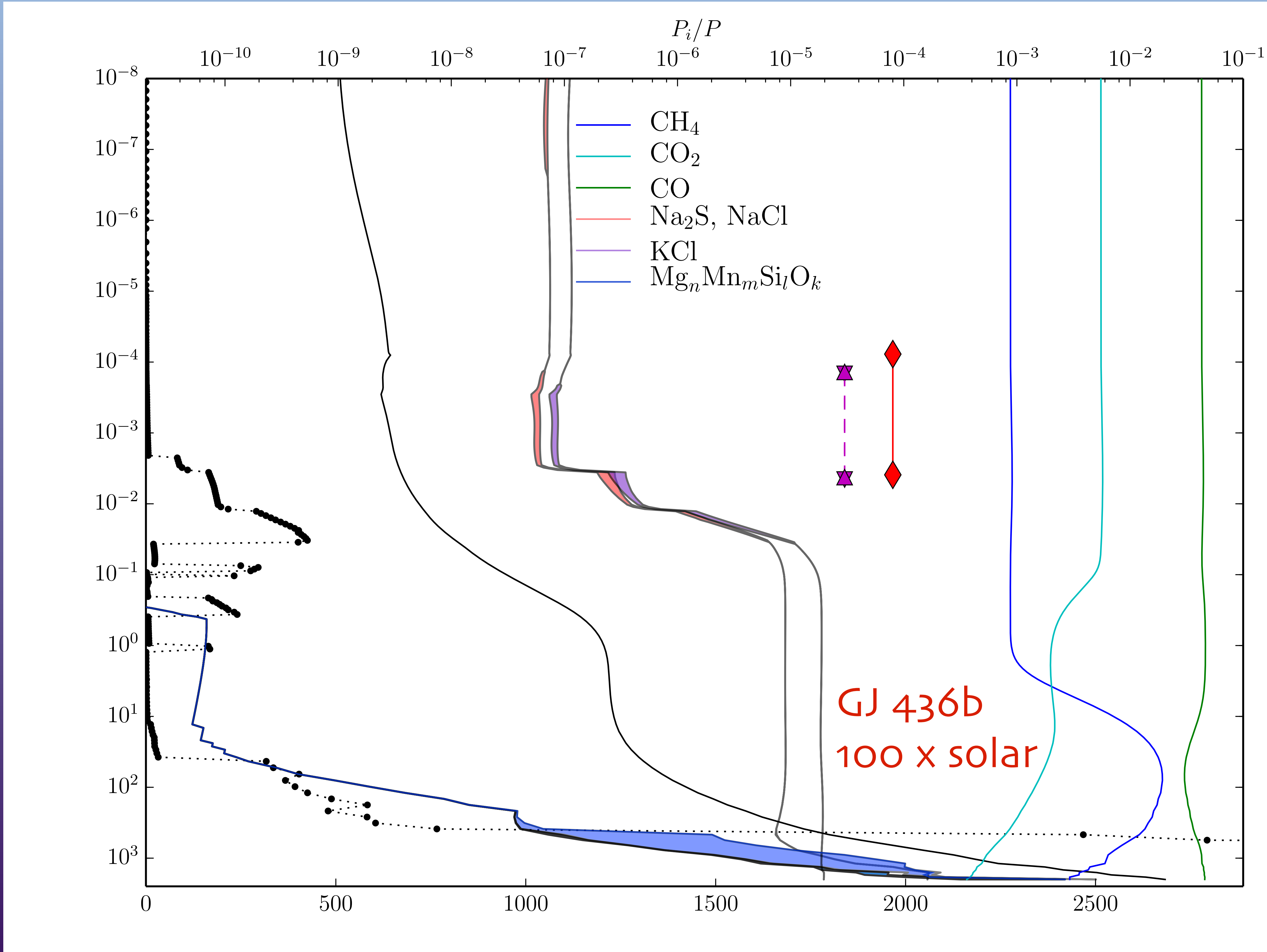
Beamín et al. 2014, poster by H. Boffin

water ice, ammonium hydrosulphide clouds

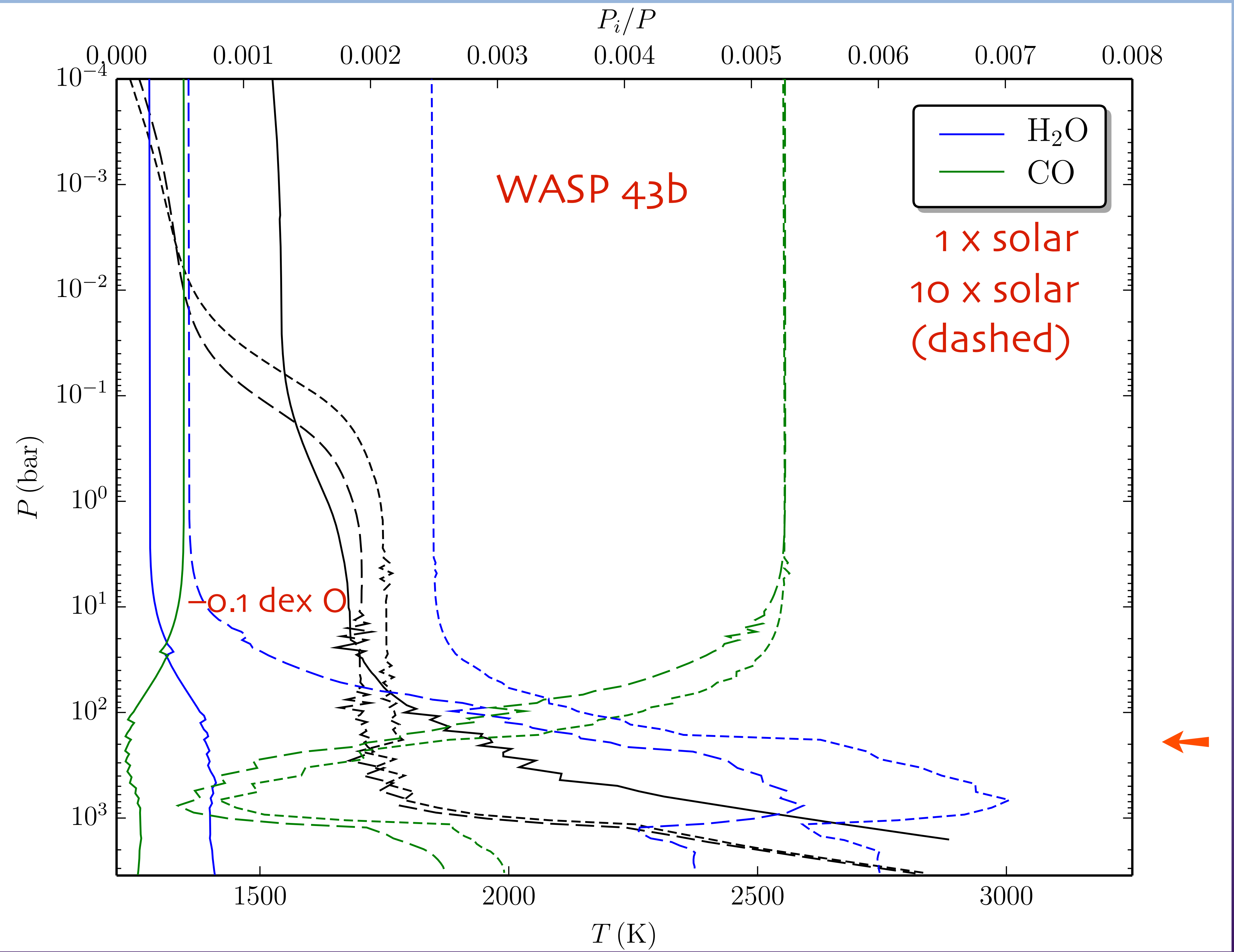
quenching of CO, NH_3 in non-CE (cf. Visscher et al. 2010)

deep silicate clouds

Clouds in hot Neptunes and super-Earths



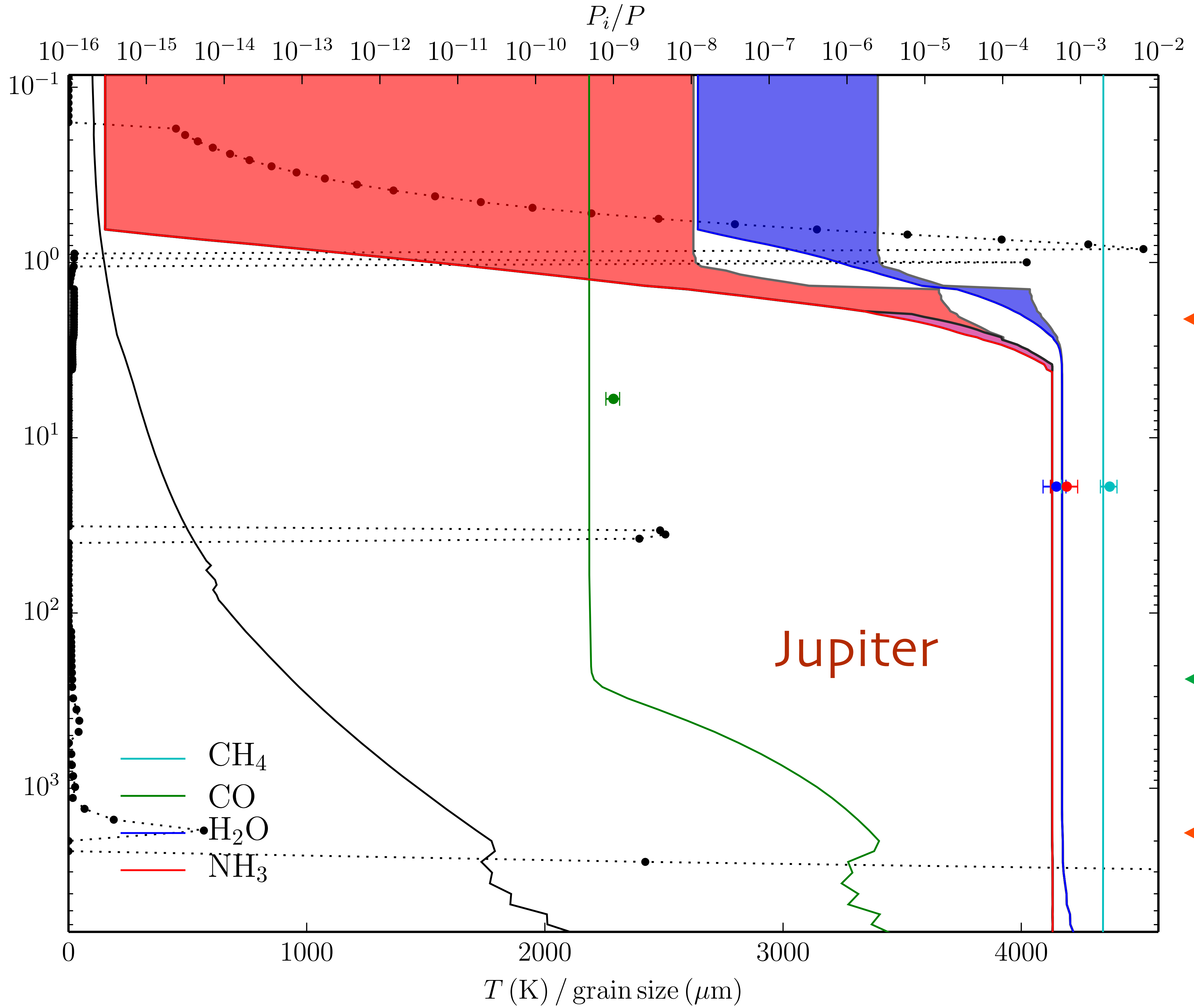
Clouds affect carbon/oxygen chemistry



sequestration of oxygen in deep silicate clouds!

— cf. also talk by T. Kopytova

Clouds in Brown Dwarfs and Planets



water ice, ammonium hydrosulphide clouds

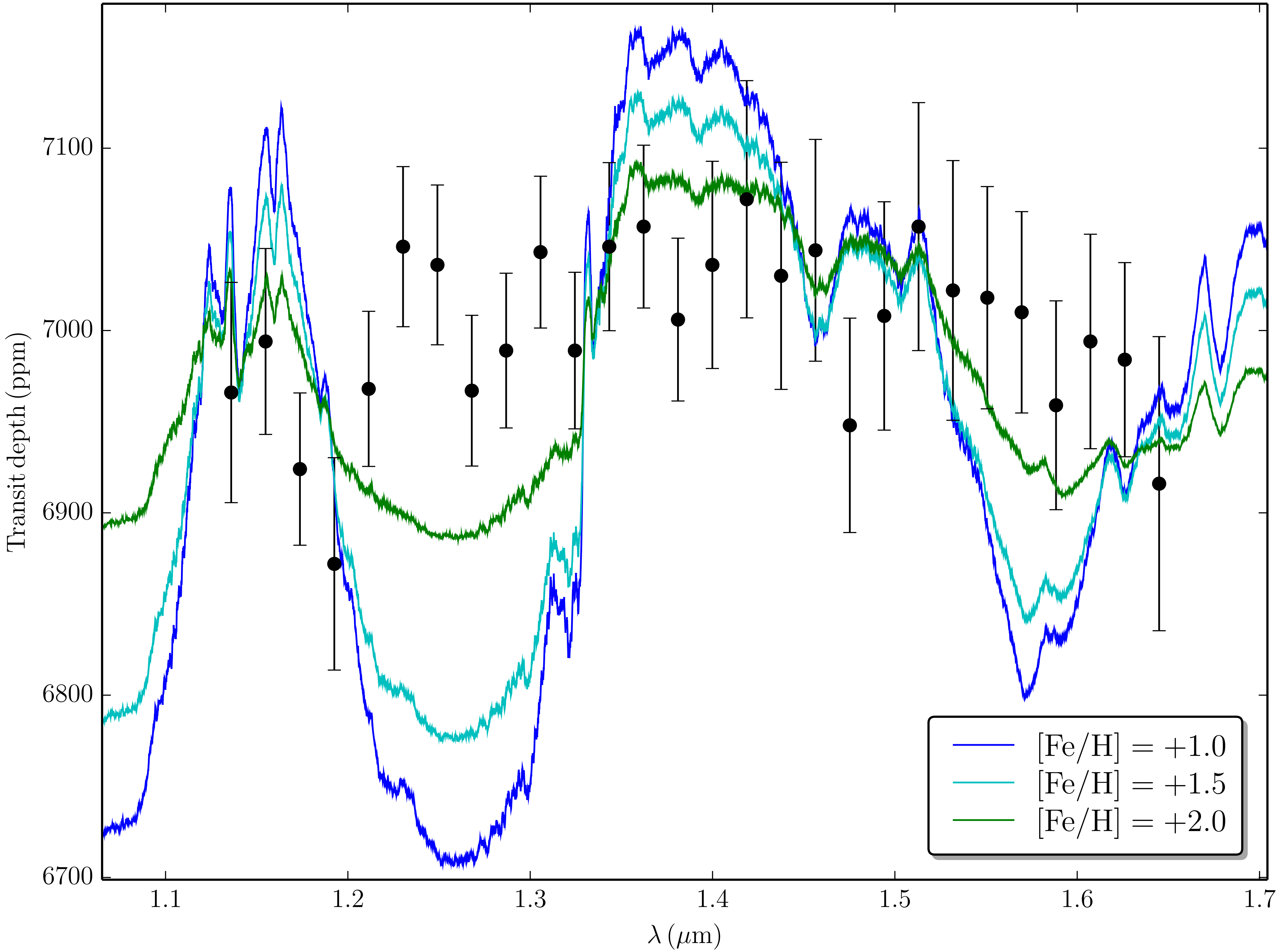
quenching of CO in non-CE (cf. Visscher et al. 2010)

deep silicate clouds

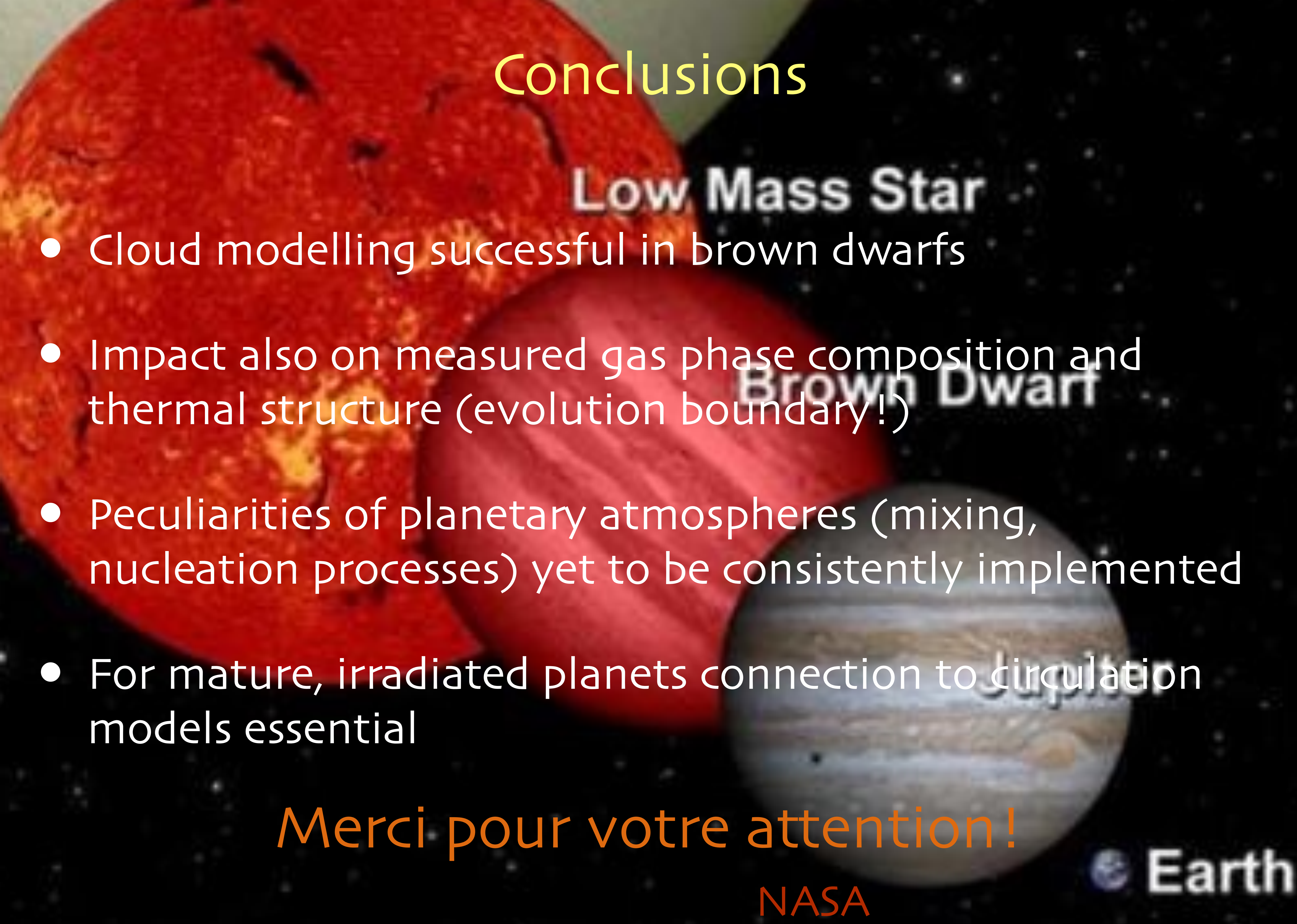
Z 3.5 x solar, O 1.25 x solar!

Clouds in hot Neptunes and super-Earths

GJ 436b transit models and WFC3 observations (Knutson et al. 2014)



Conclusions



- Cloud modelling successful in brown dwarfs
- Impact also on measured gas phase composition and thermal structure (evolution boundary!)
- Peculiarities of planetary atmospheres (mixing, nucleation processes) yet to be consistently implemented
- For mature, irradiated planets connection to circulation models essential

Merci pour votre attention !

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