Condensation Chemistry and Abundance Measurements in Cloudy Atmospheres

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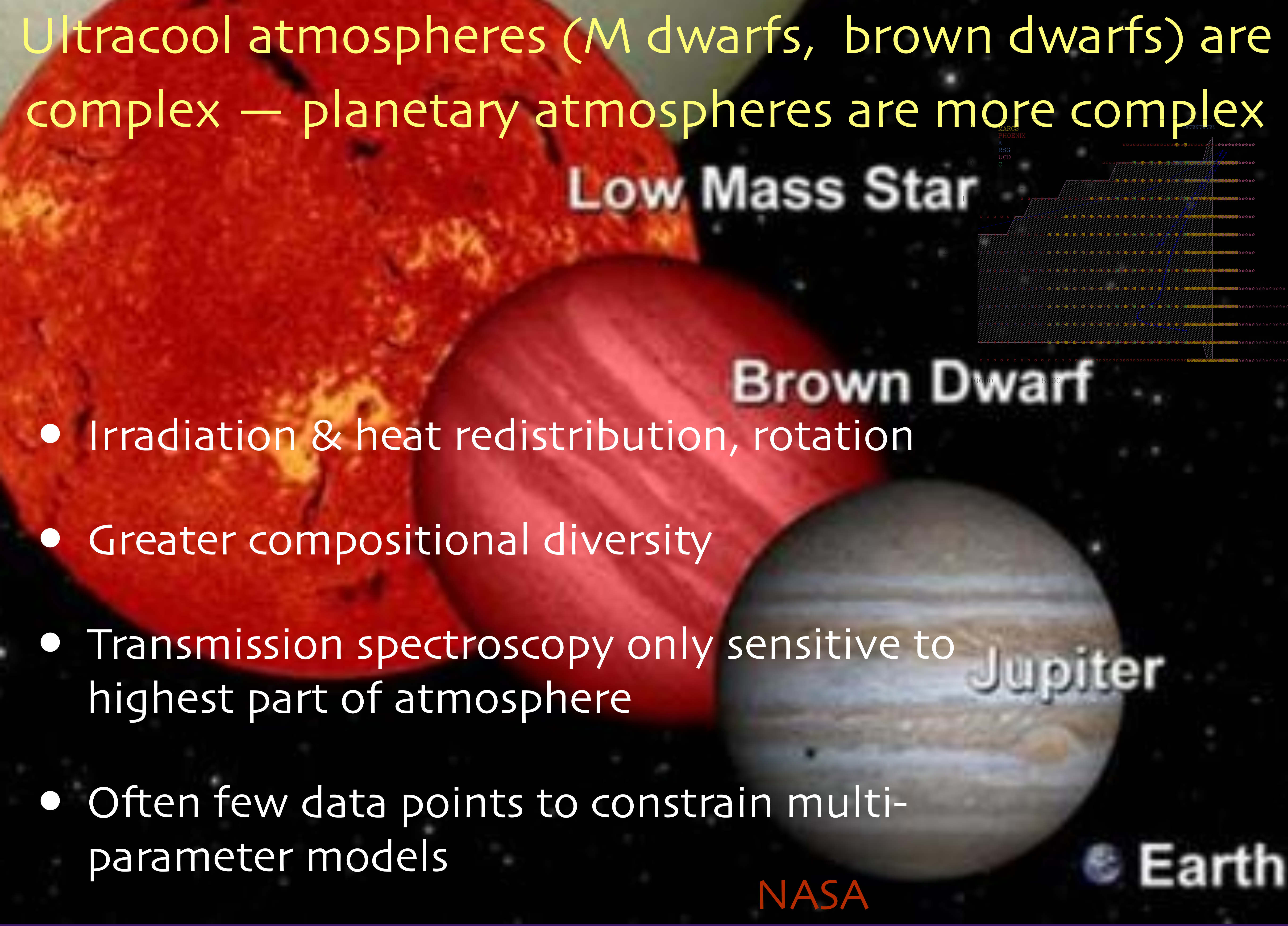
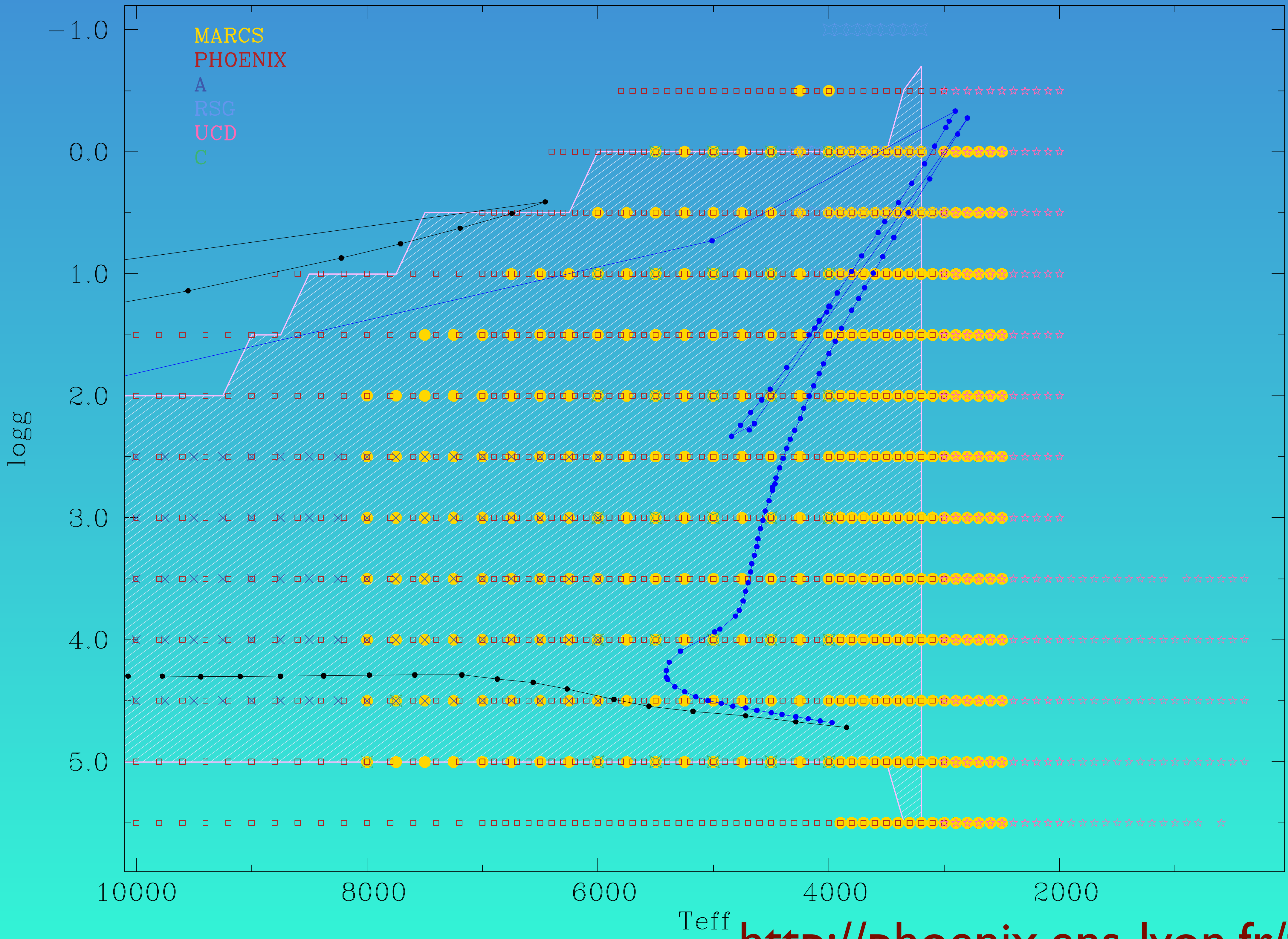
PEPS

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



- Irradiation & heat redistribution, rotation
- Greater compositional diversity
- Transmission spectroscopy only sensitive to highest part of atmosphere
- Often few data points to constrain multi-parameter models

Atmosphere models from supergiants to brown dwarfs — and beyond



Sordo et al. 2011

BP/RP and RVS spectra

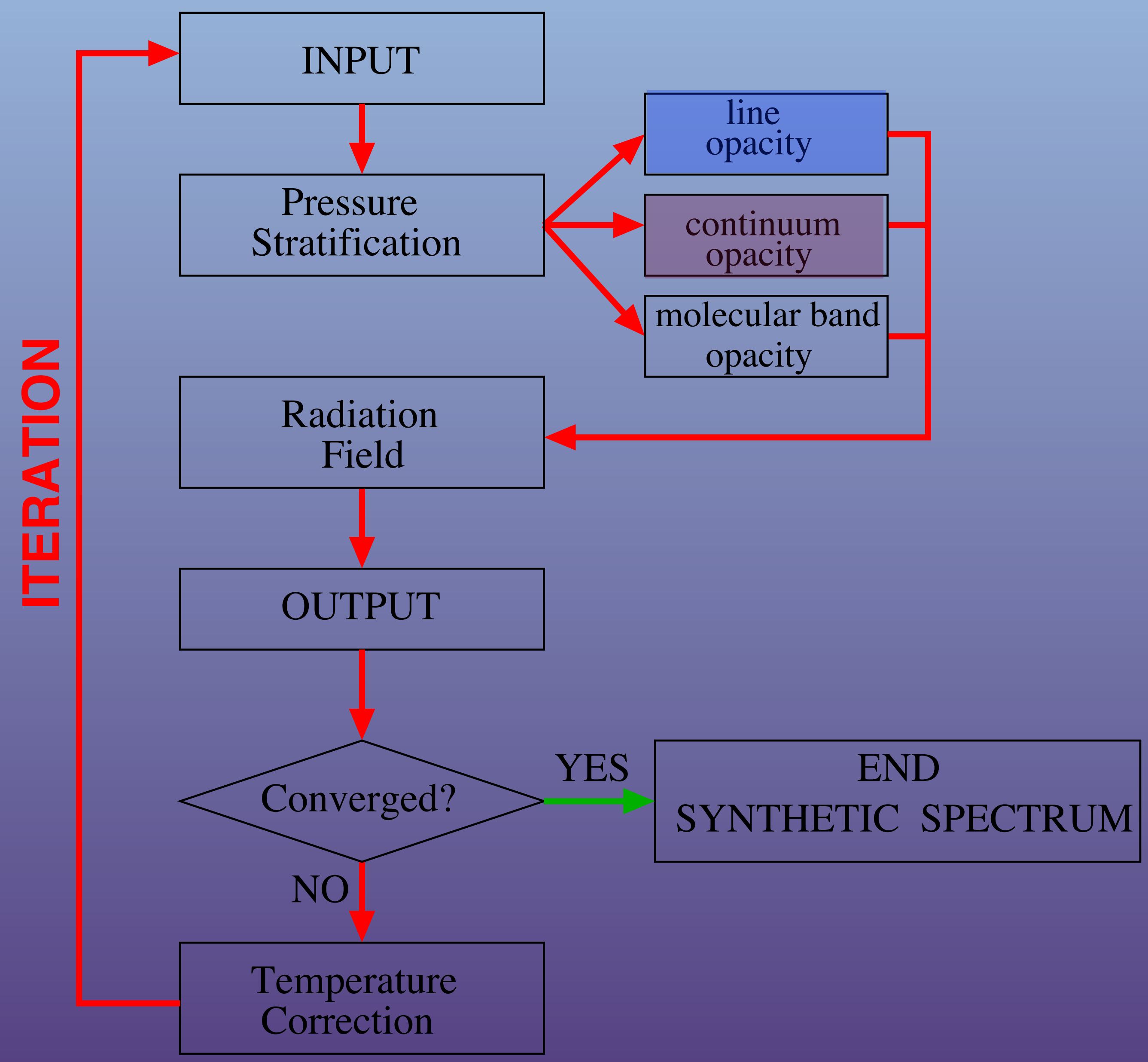
http://phoenix.ens-lyon.fr/fallard/GAIA/

(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

Molecular Bands — Methane

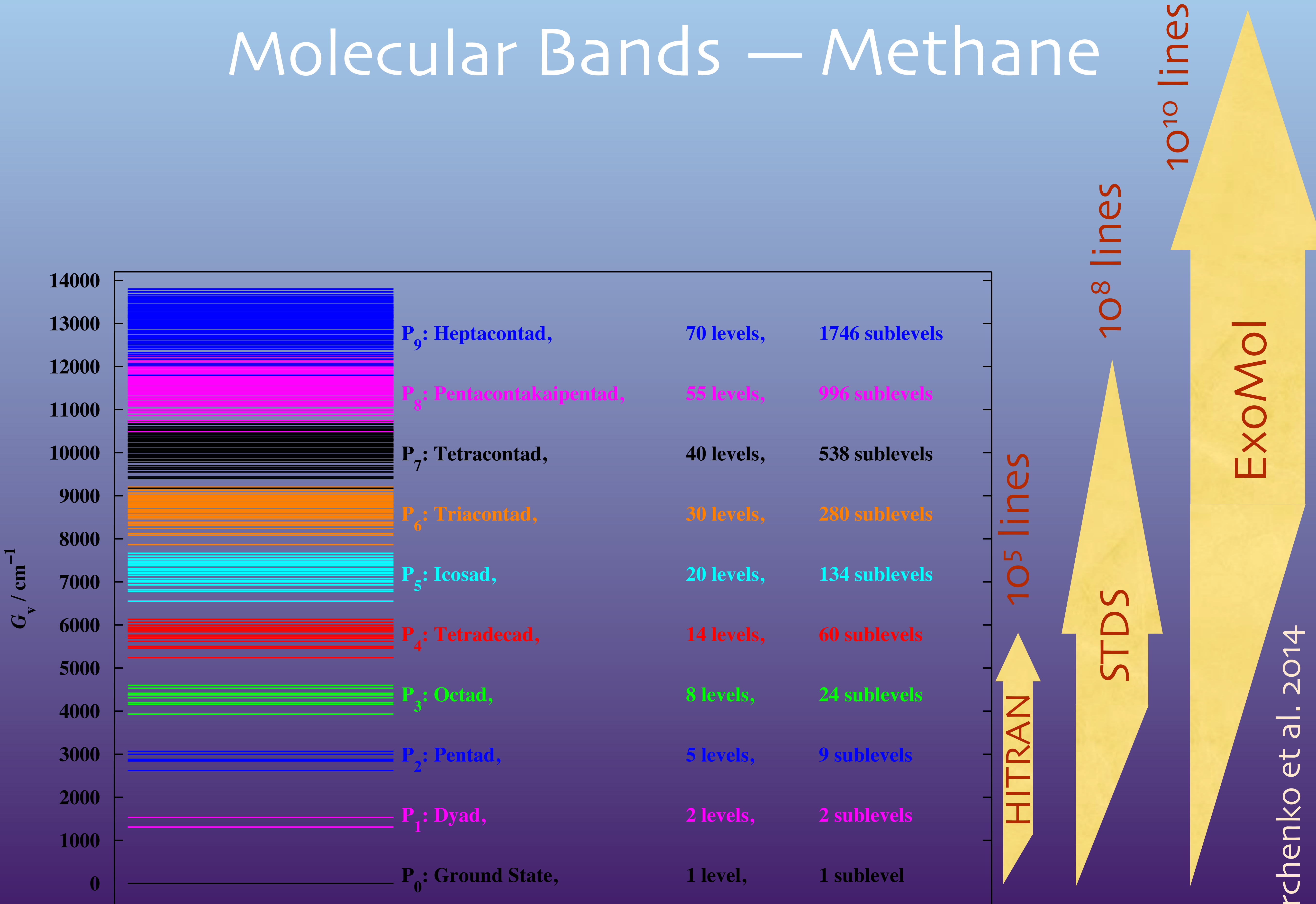
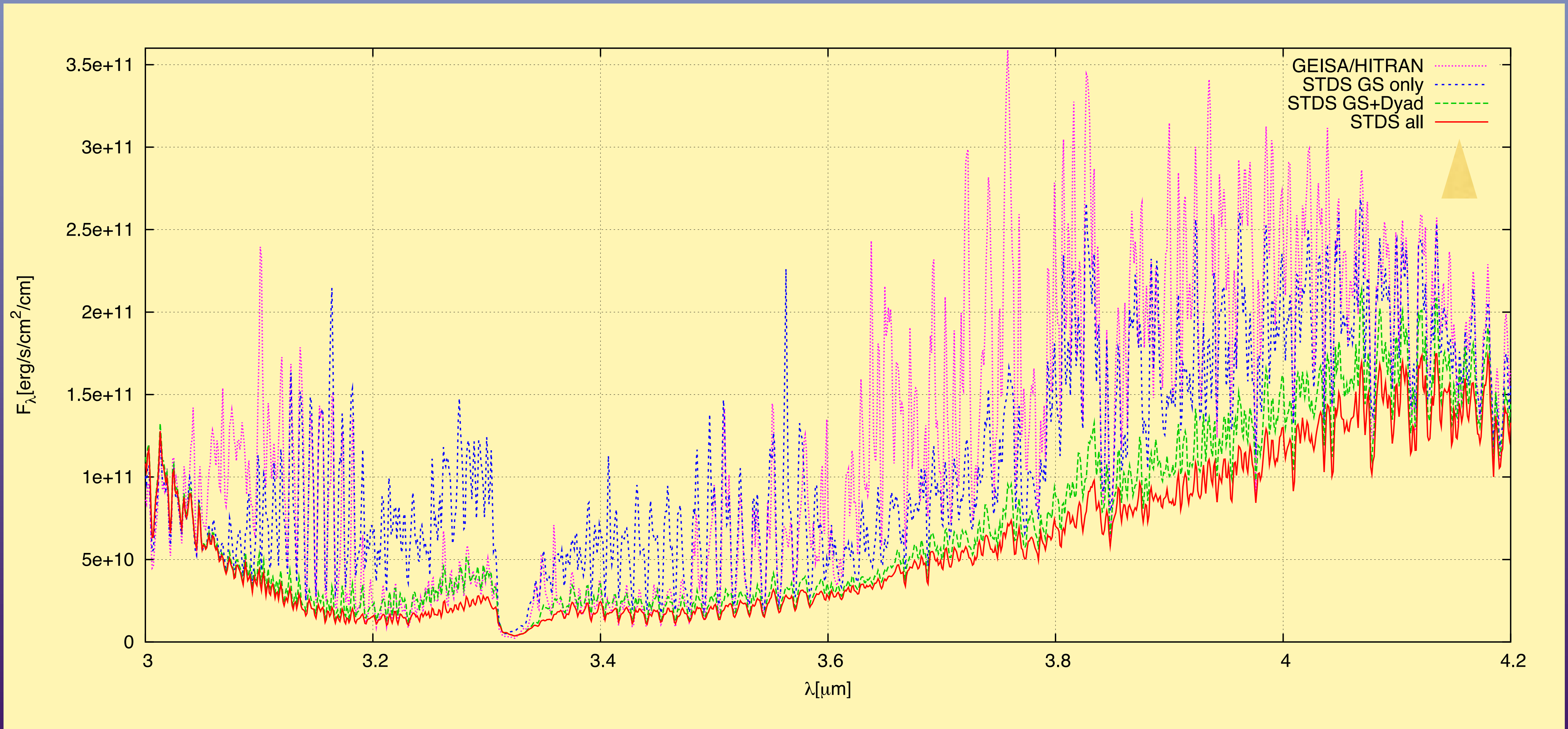


Fig. 2. Polyad energy-level structure for $^{12}CH_4$. Boudon et al. 2006

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)



Molecular Line Profiles - Data

- 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
- Challenges:
  - Most data for Earth and outer planets' atmosphere studies
    → line lists complete only at 296 K
    → damping constants at low temperatures
  - Most experimental measurements for N_2 and O_2 as perturbers
  - Generalisation for large theoretical line lists required

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)

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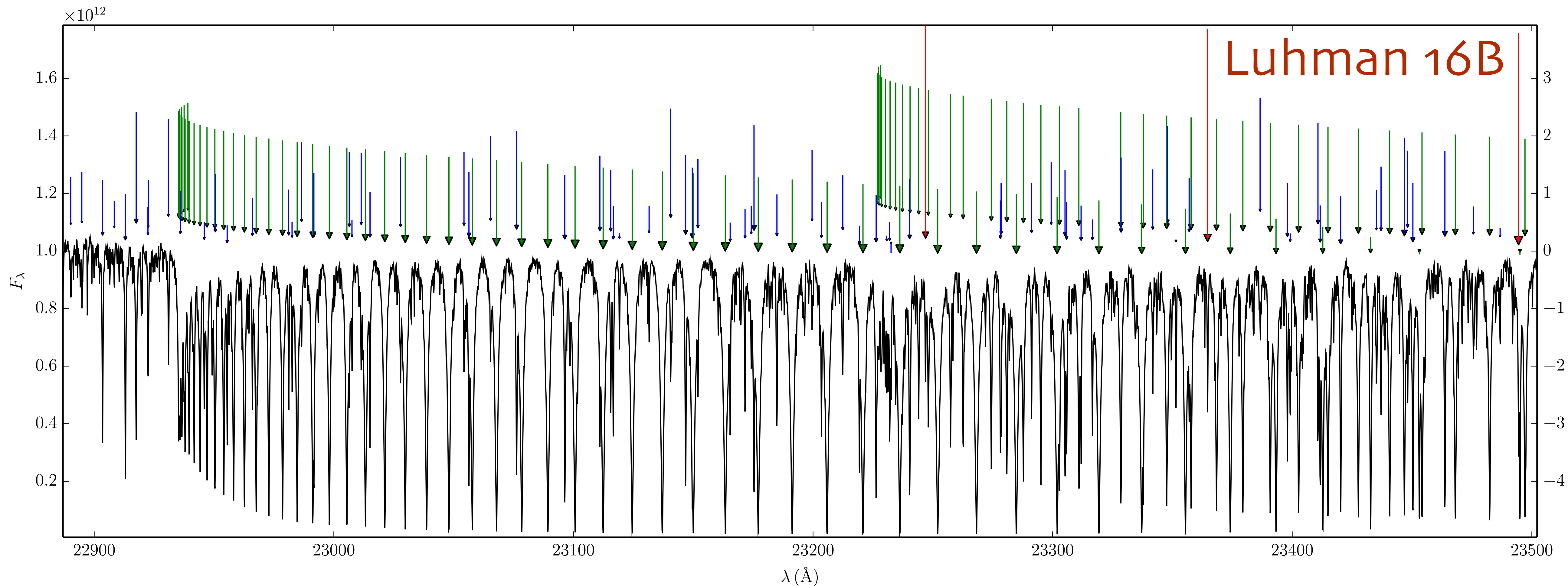
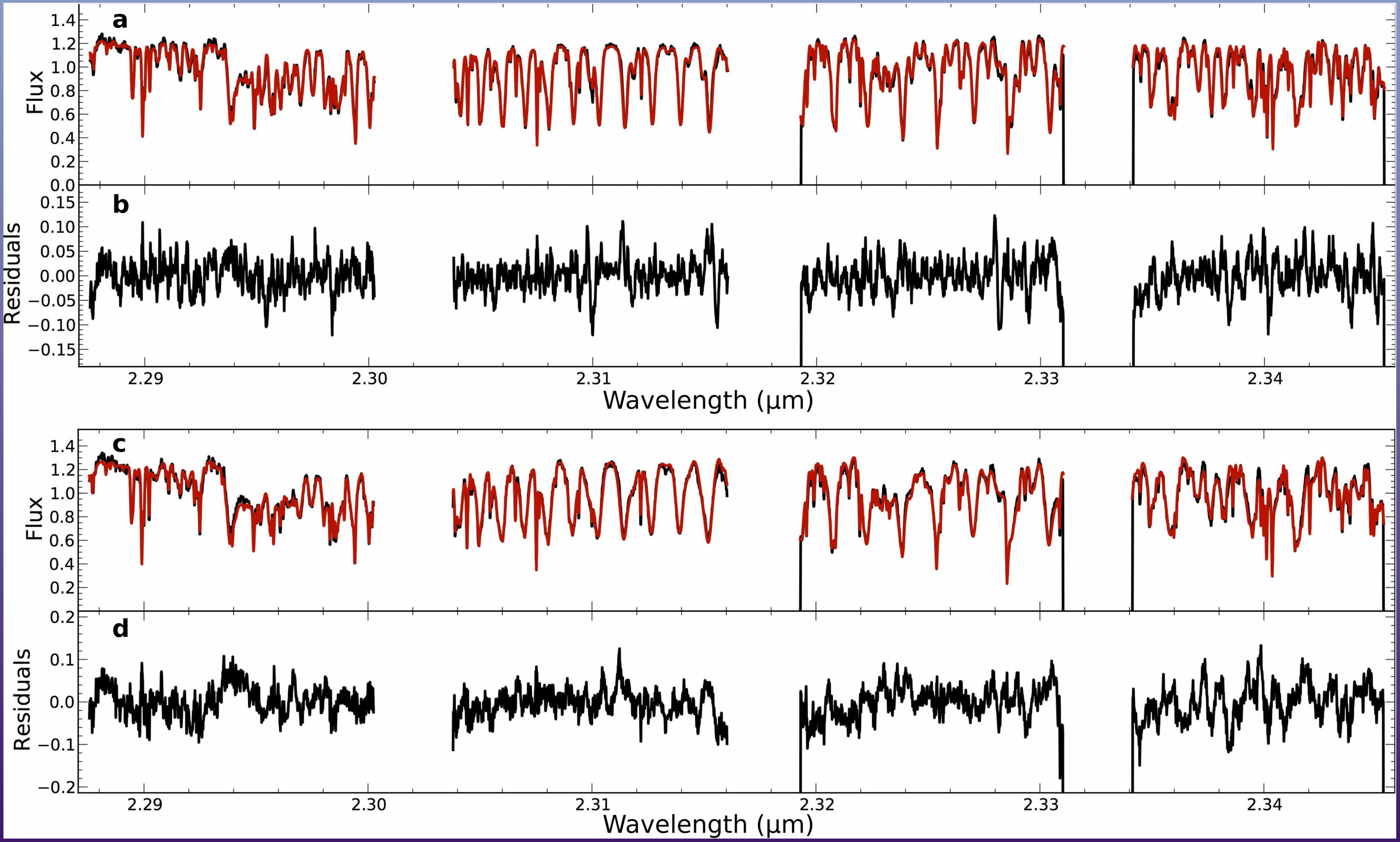


Molecular Line Profiles - Observation

- CO spectrum, testing line positions, strengths, shapes and non-equilibrium chemistry effects



Luhman 16AB Crossfield et al. 2014

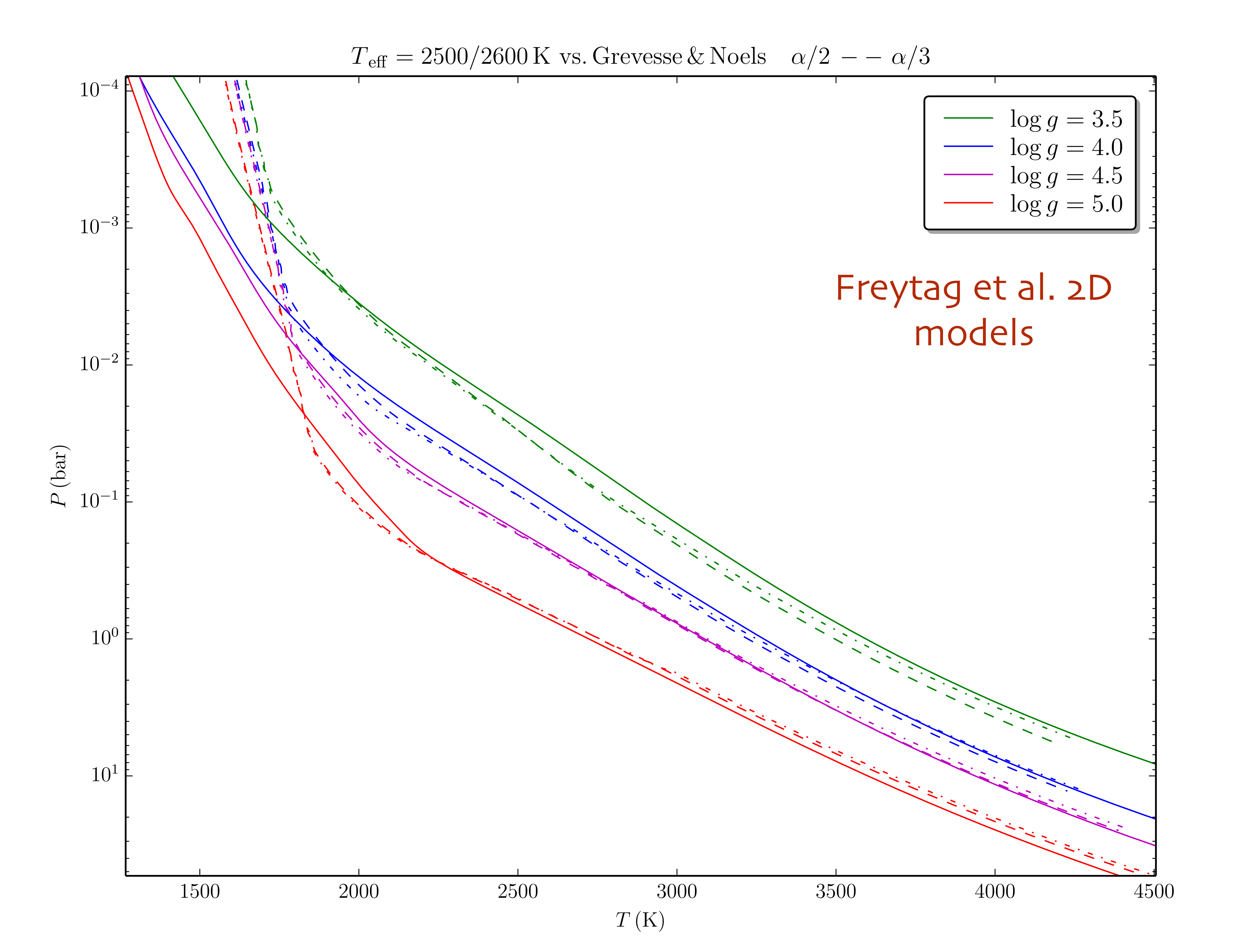
—

model

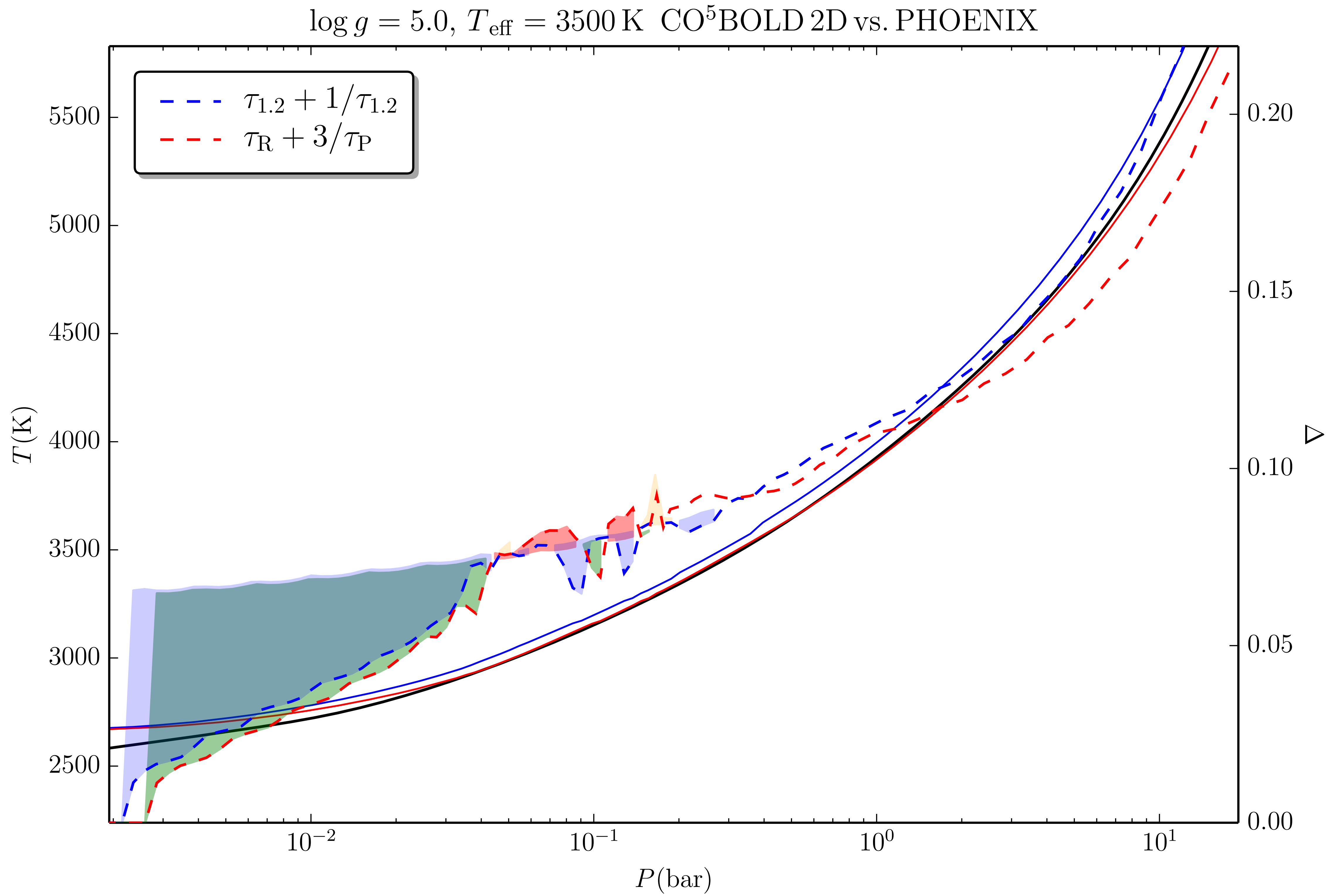
vs.

observation

Modelling convection — calibration of MLT



Modelling convection — calibration of MLT



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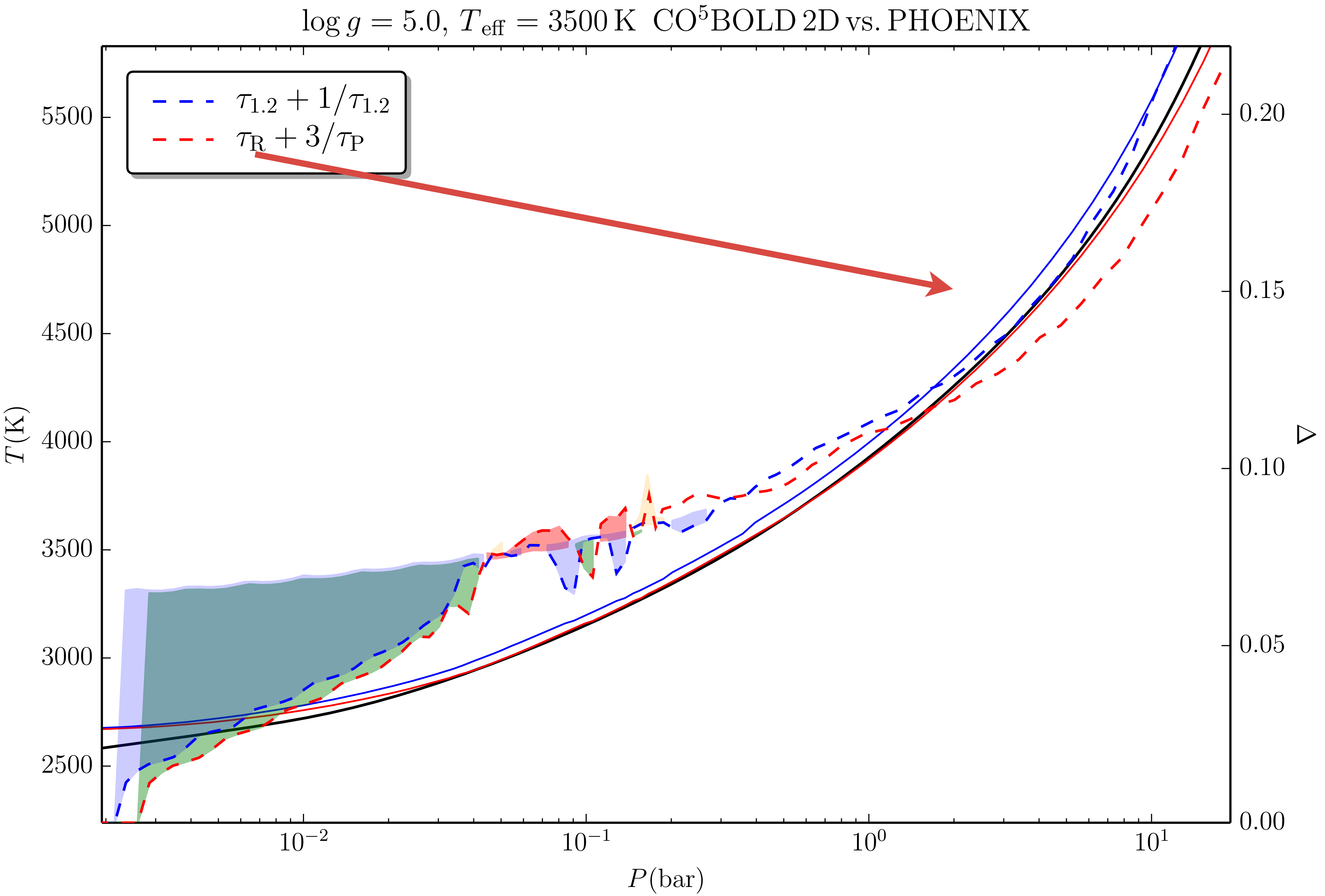

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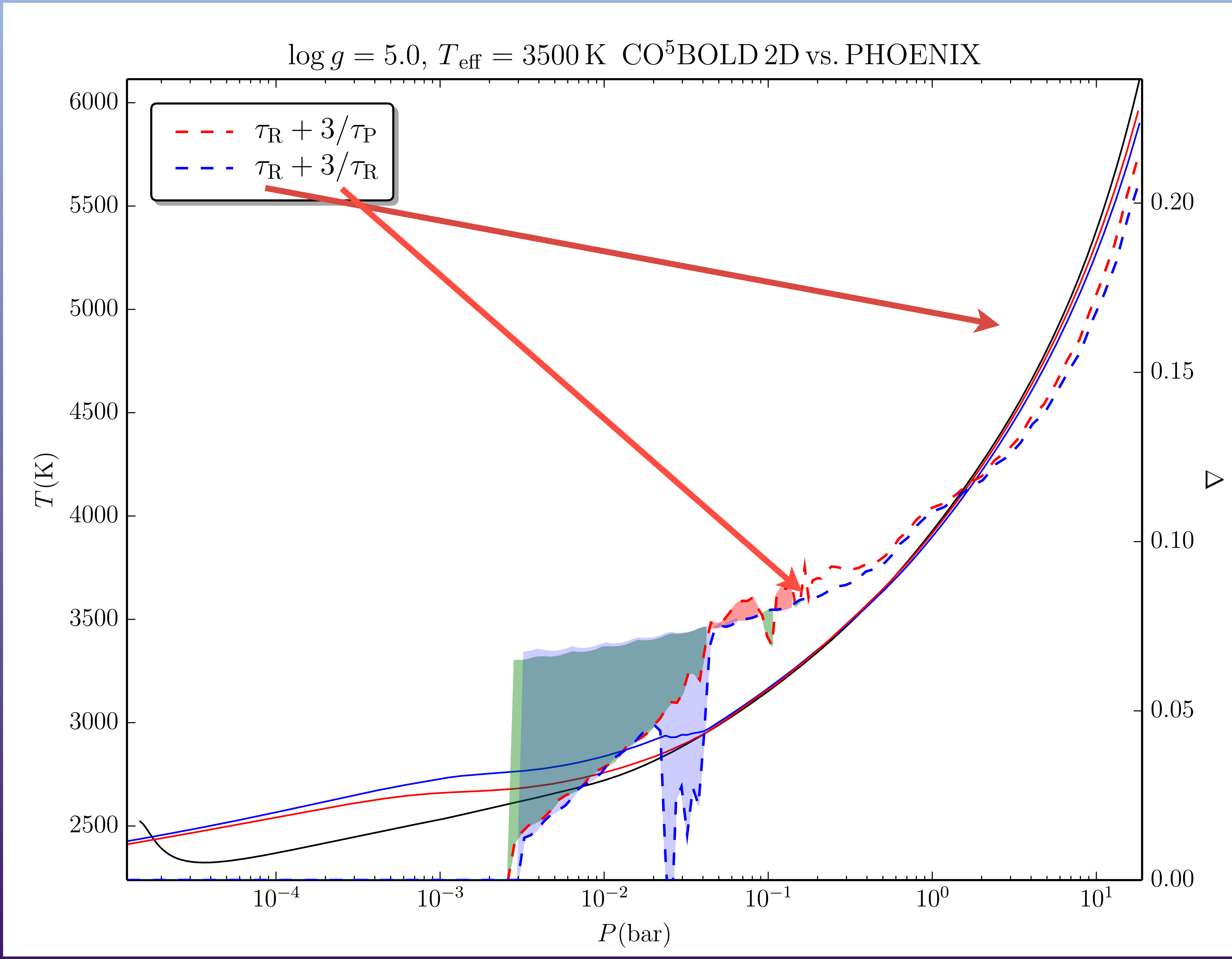

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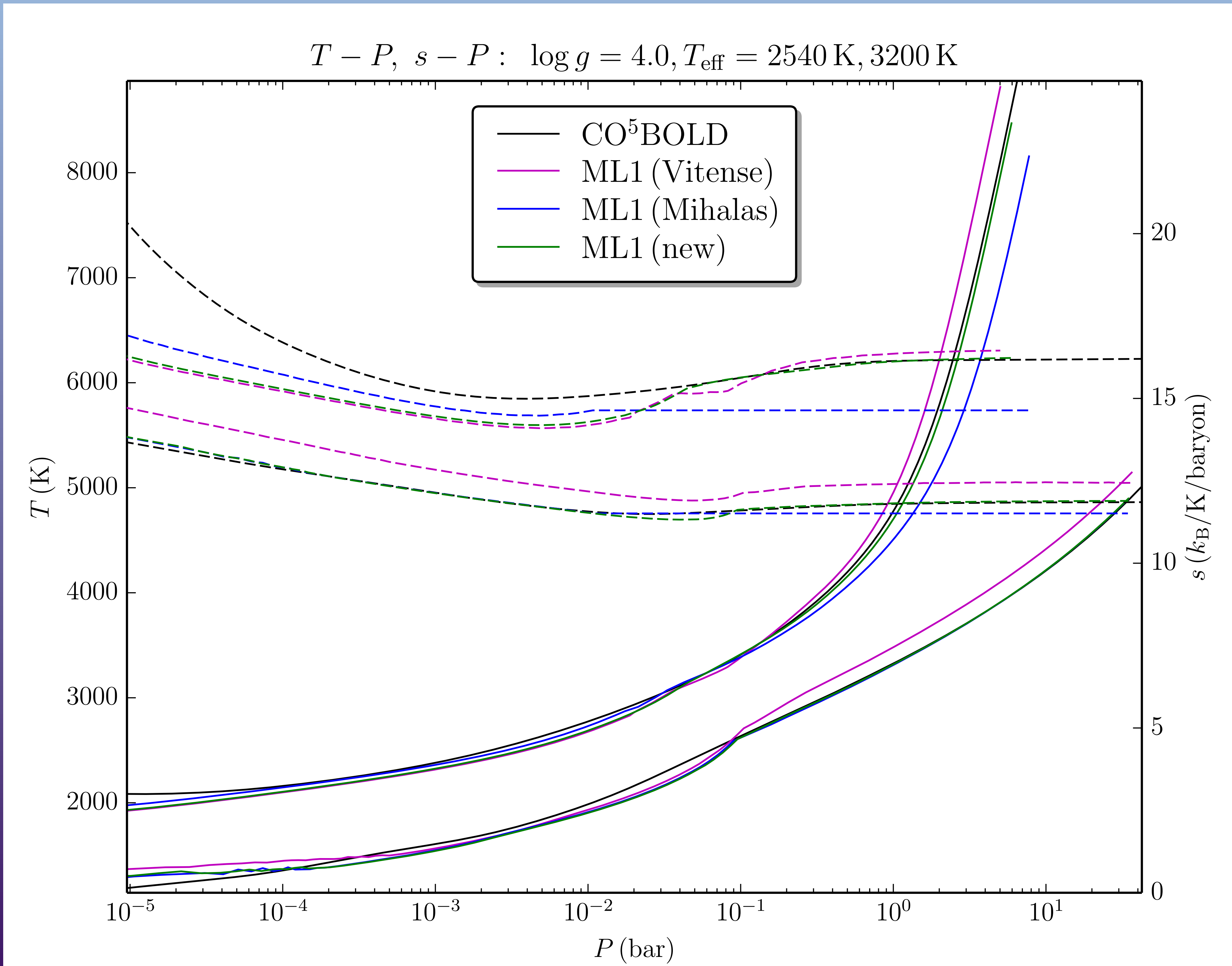
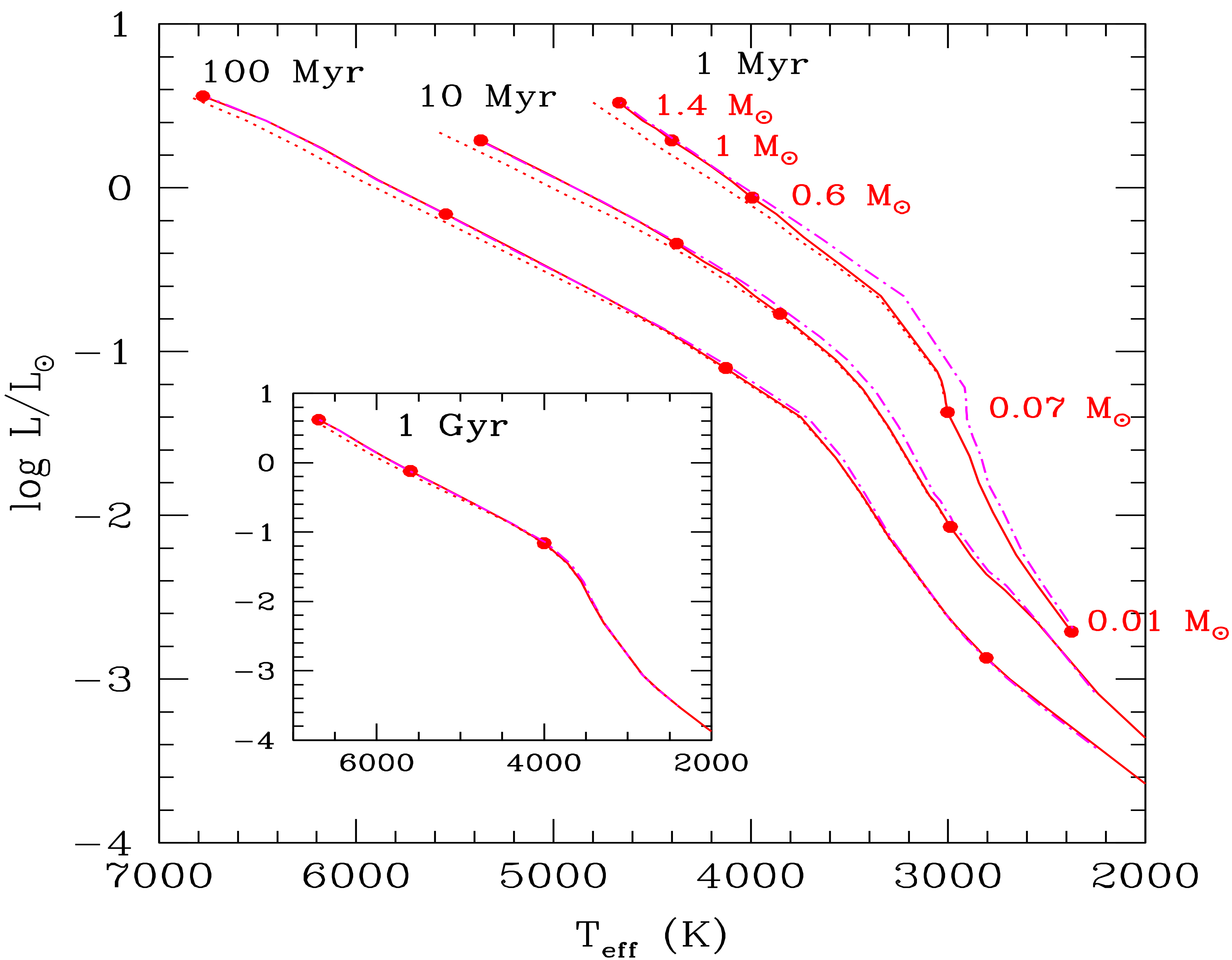


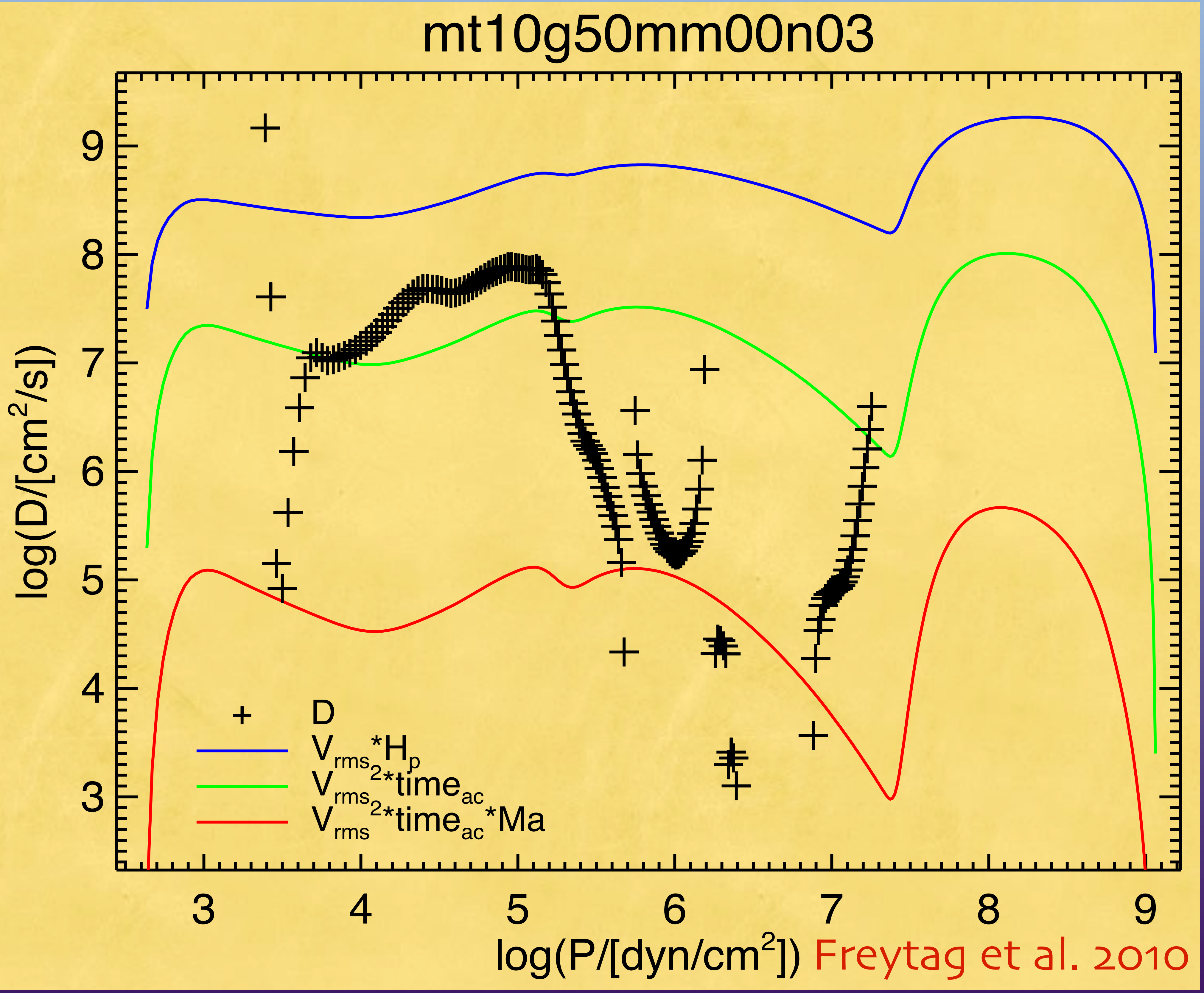
convective structure defines deep thermal profile → boundary condition for evolution!

Modelling convection — calibration of MLT



Baraffe et al. in prep.

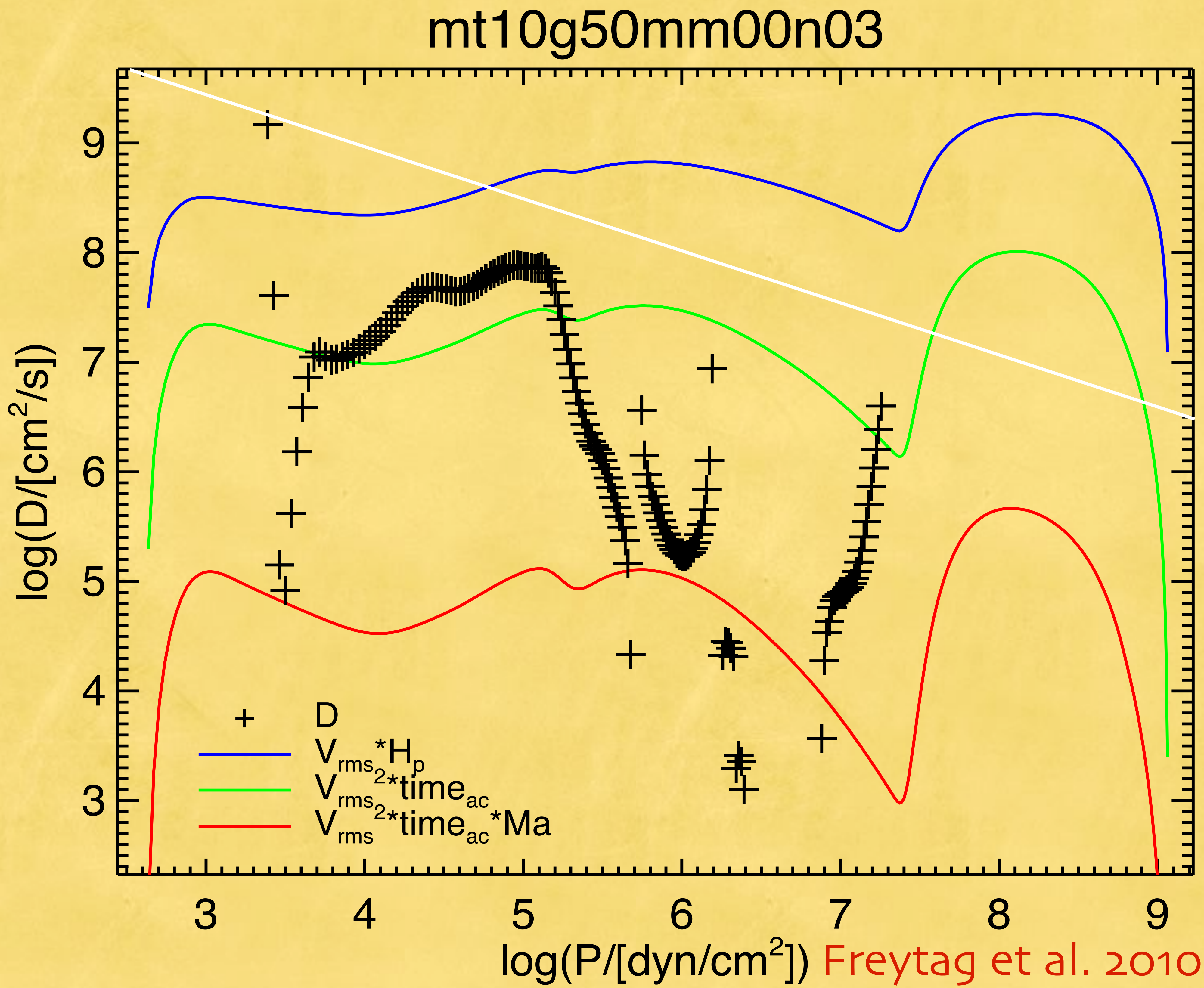
Mixing and Diffusion - a closer Look



Freytag et al. 2010

convective overshoot and gravity wave excitation dominant in brown dwarfs

Mixing and Diffusion - a closer Look



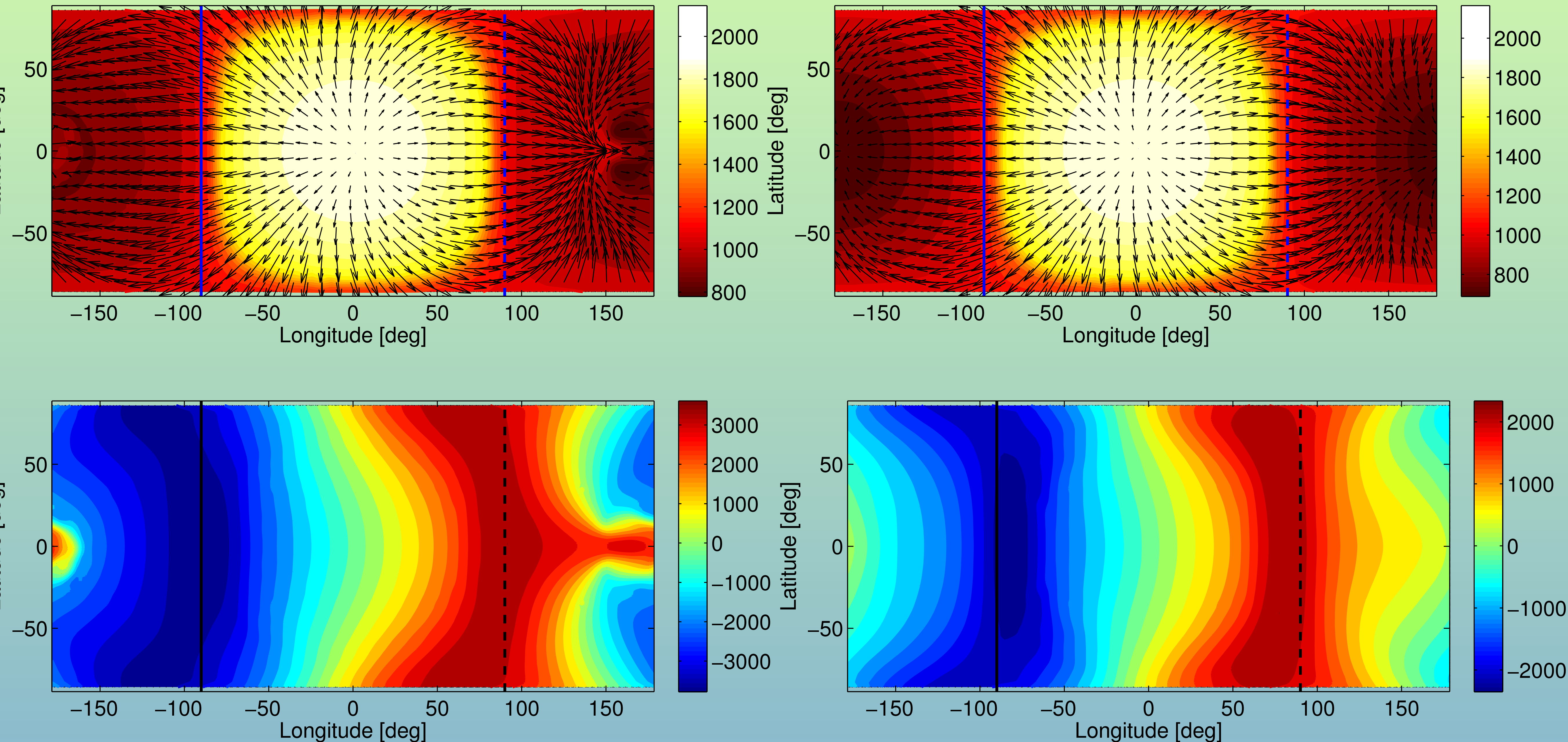
Freytag et al. 2010

convective overshoot and gravity wave excitation dominant in brown dwarfs — but in planets too inefficient (Schwarzschild boundary @ τ ≳ 100

➙

global circulation important!

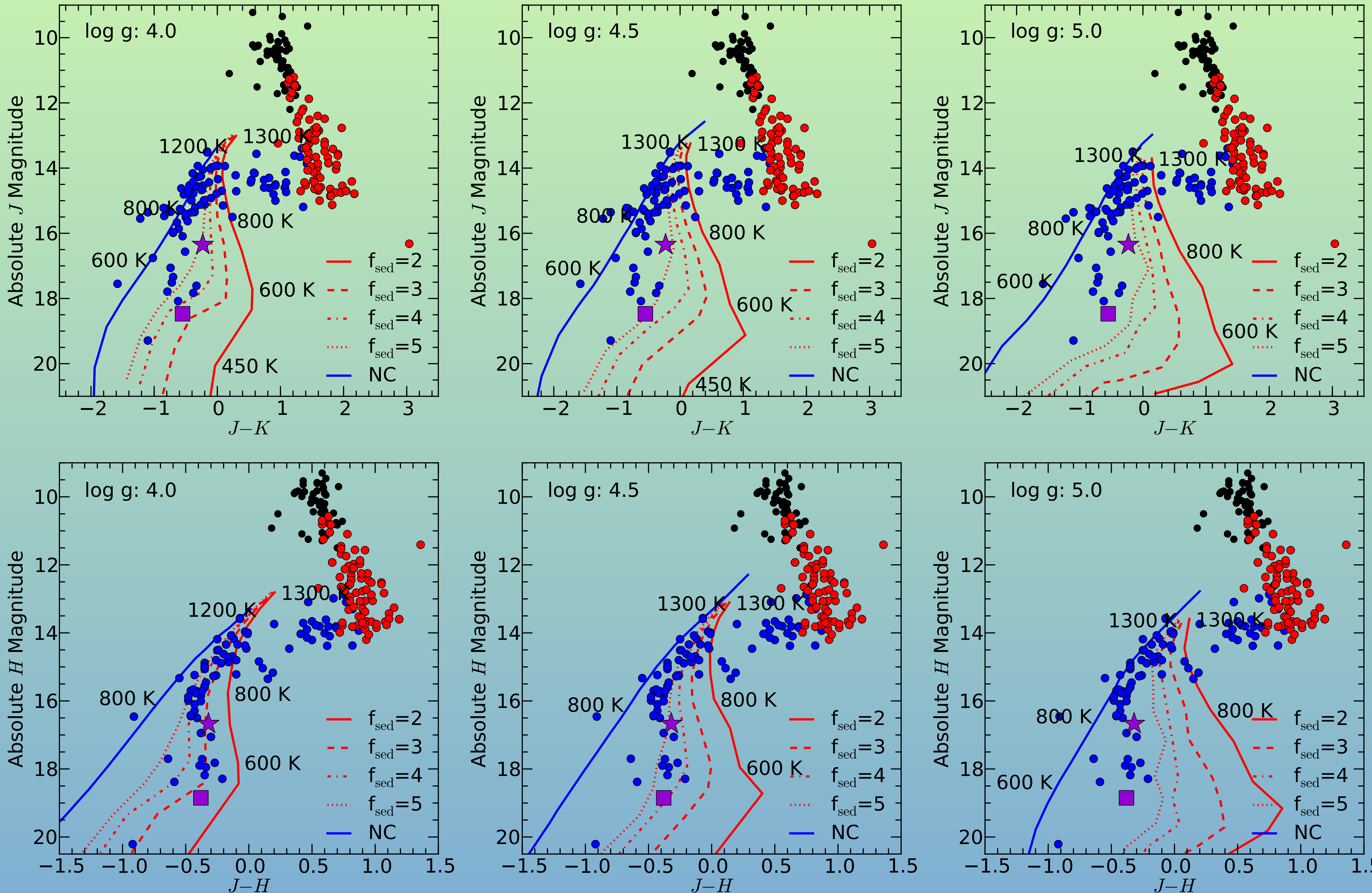
Exoplanets — Irradiation and Circulation



Showman et al. 2013

- Global Circulation models can reproduce temperature redistribution and (observable!) wind patterns
- Strongly non-kartesian (pancake-shaped) grid

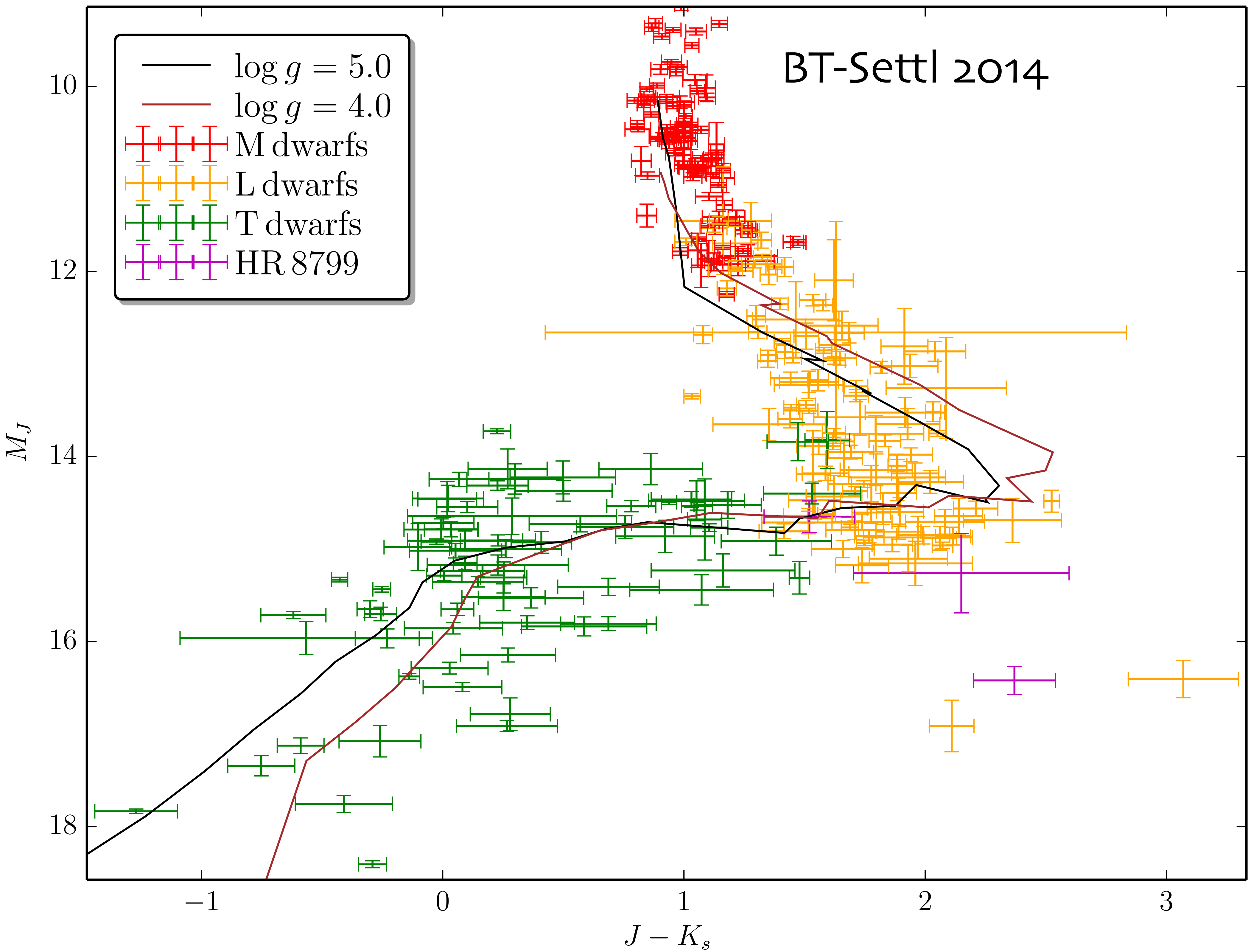
T dwarfs — more clouds



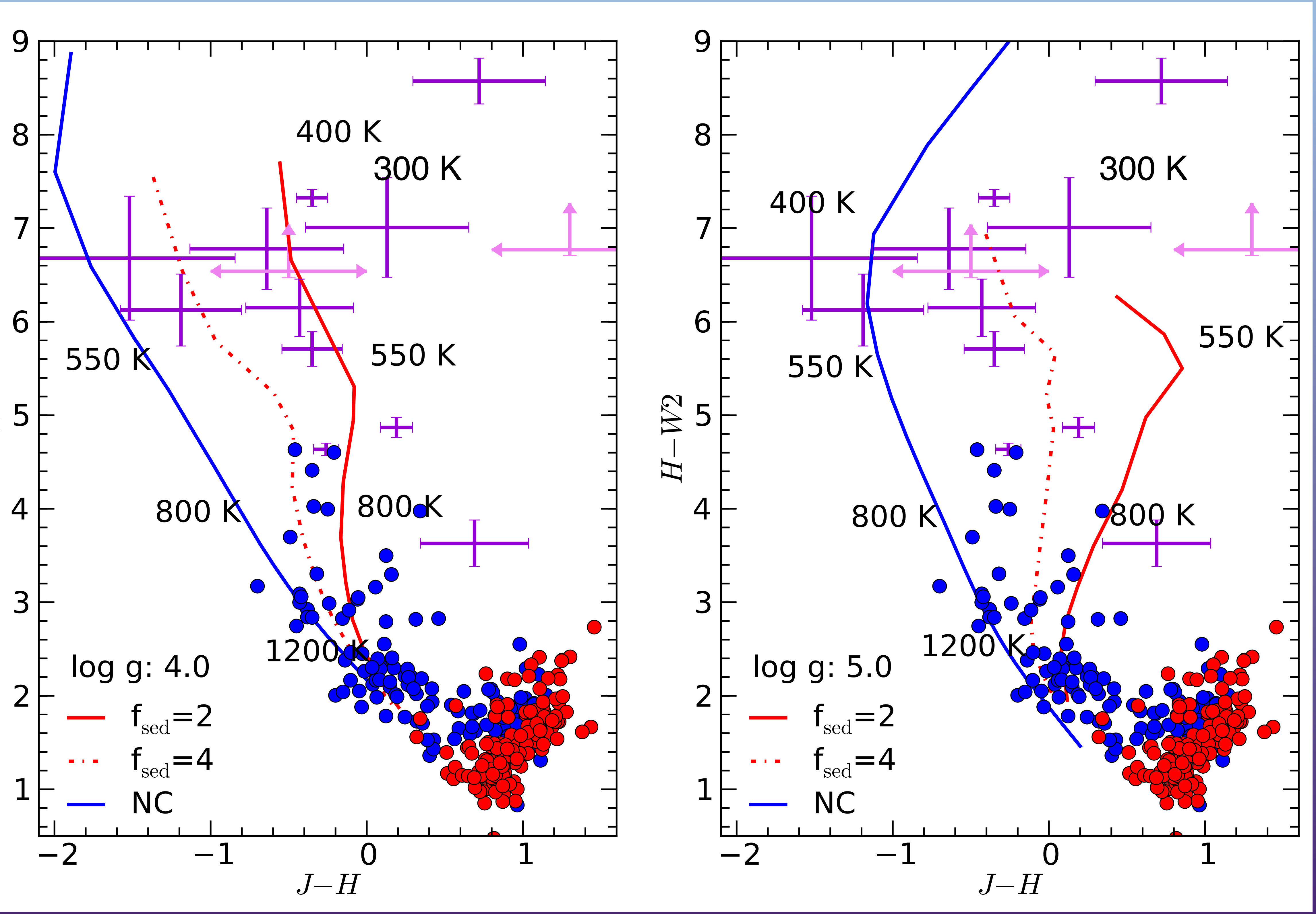
Morley et al. 2012

- Separate cloud setup for low-temperature condensates

Clouds from L to Y dwarfs in a single model



Y dwarfs — yet more clouds



Morley et al. 2012

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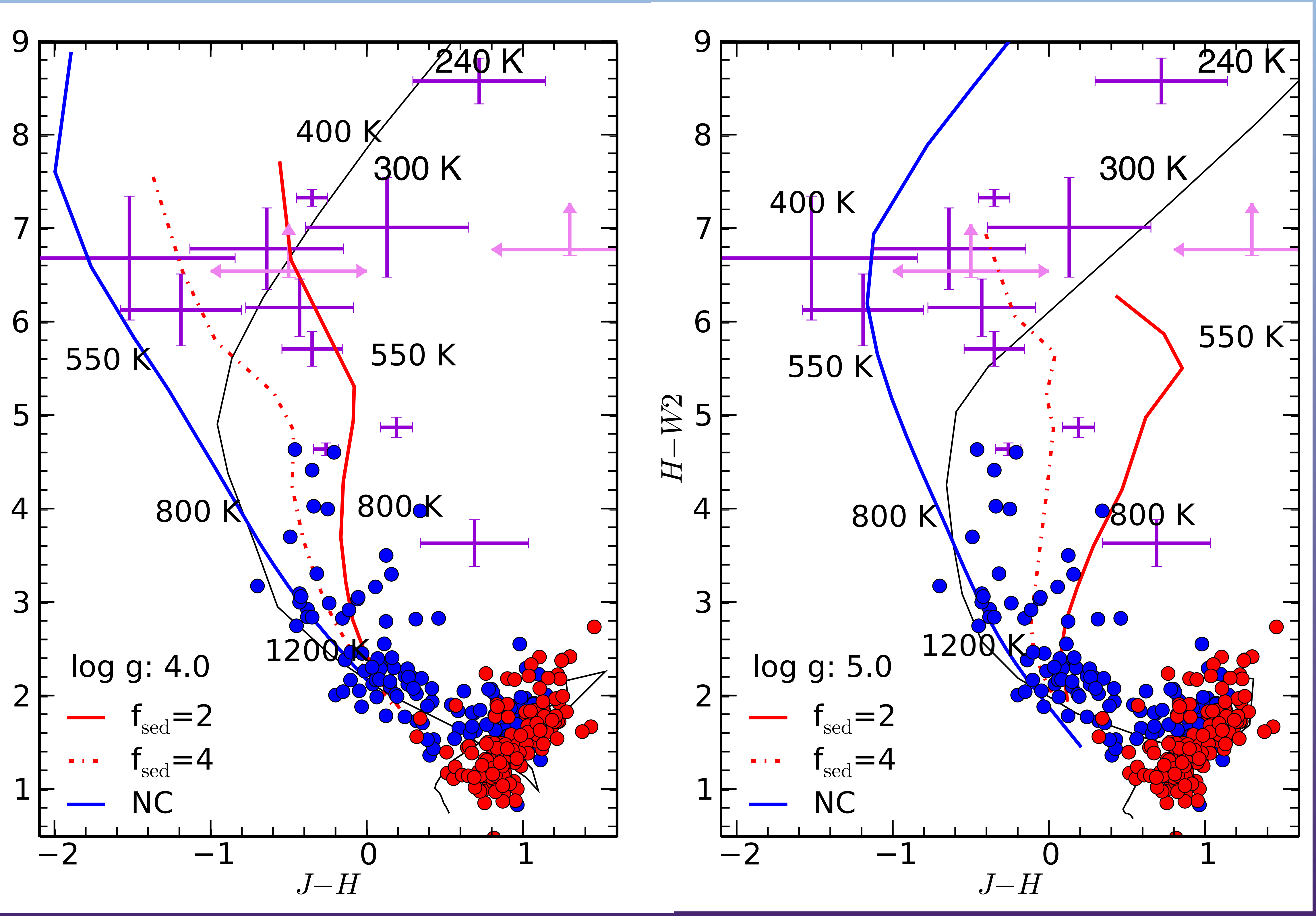


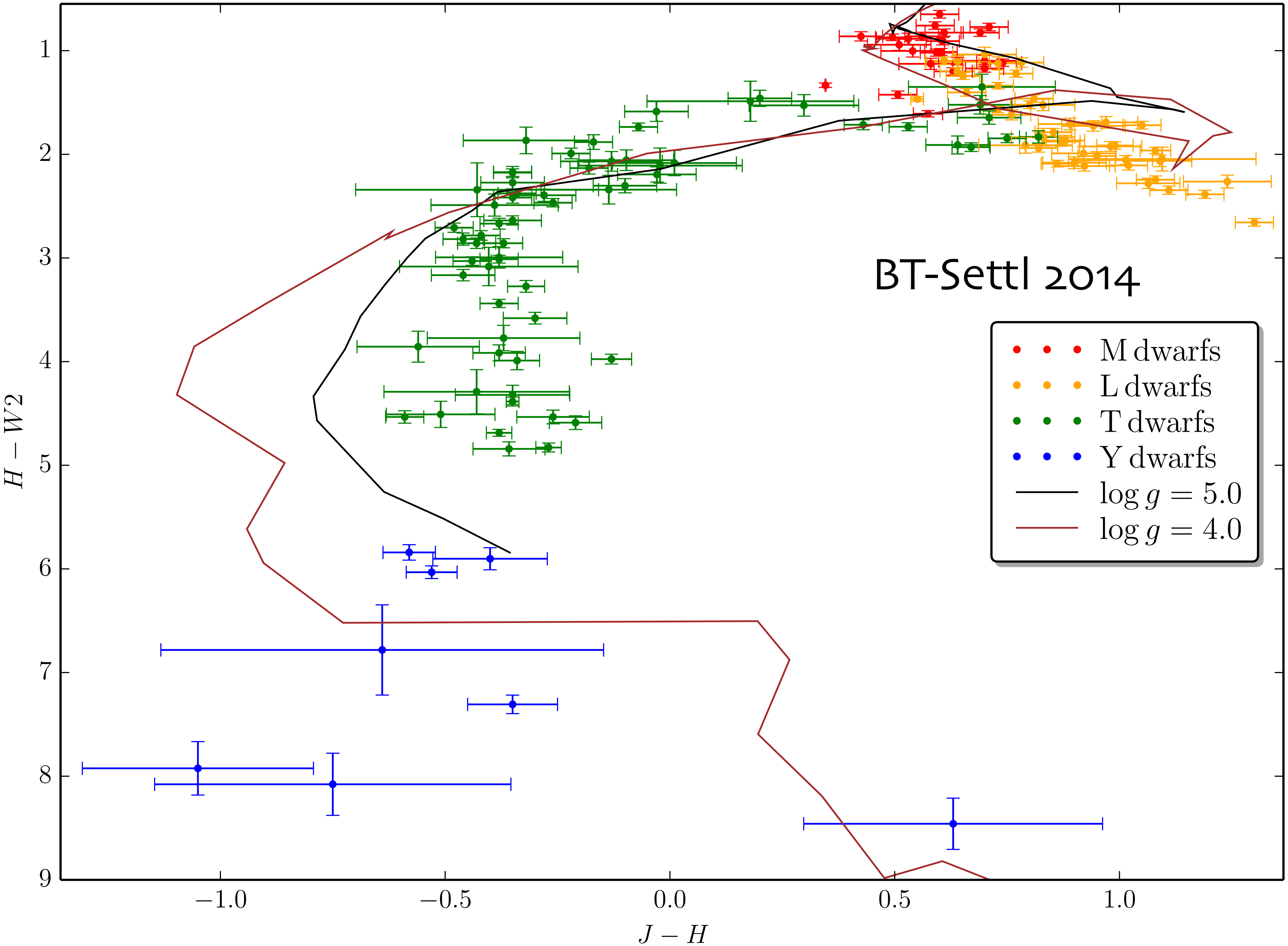
Morley et al. 2012

compared to

BT-Settl 2013

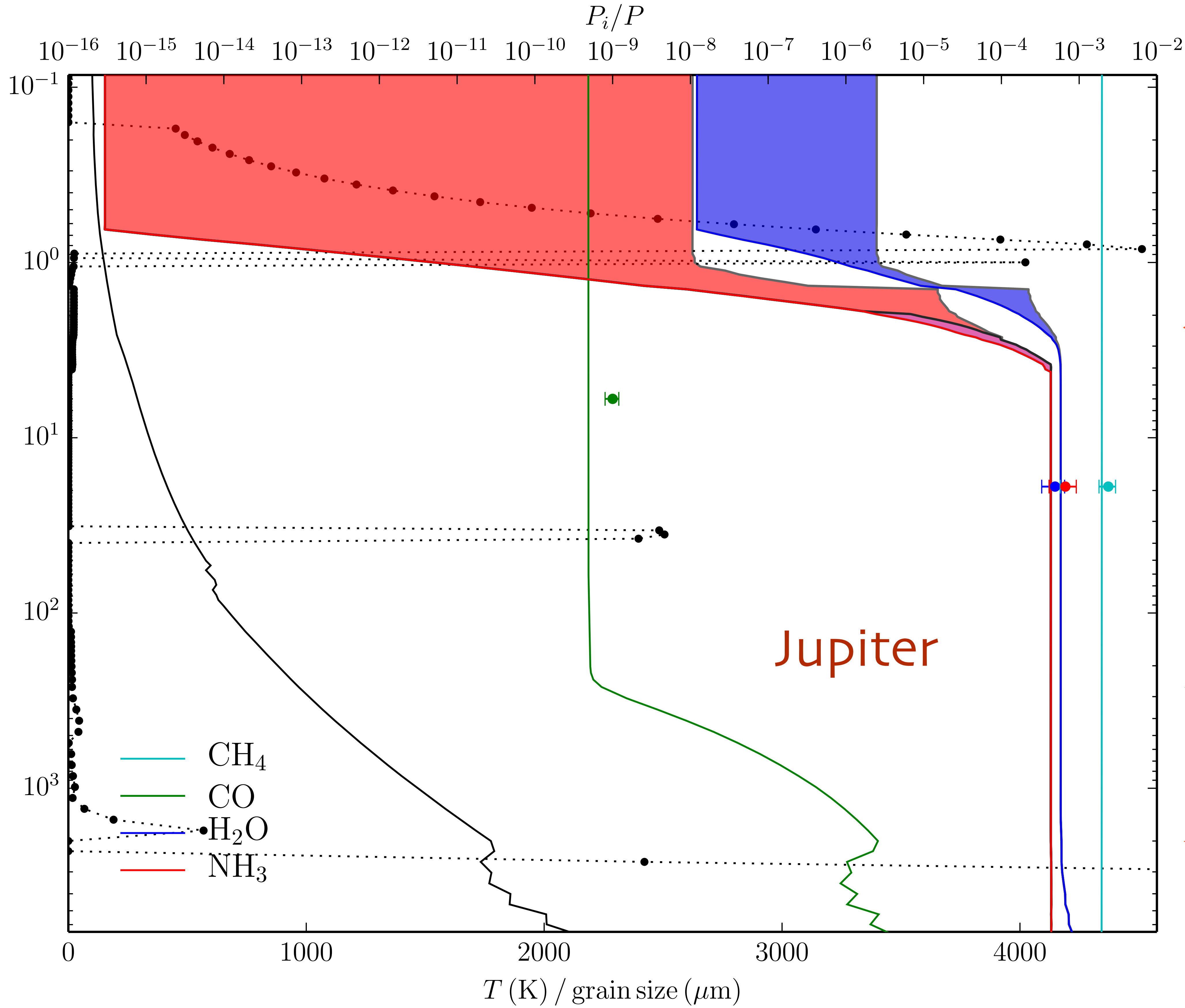
- Water ice clouds appearing between 300 and 400 K

Clouds from L to Y dwarfs



- Water ice clouds appearing between 300 and 400 K

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

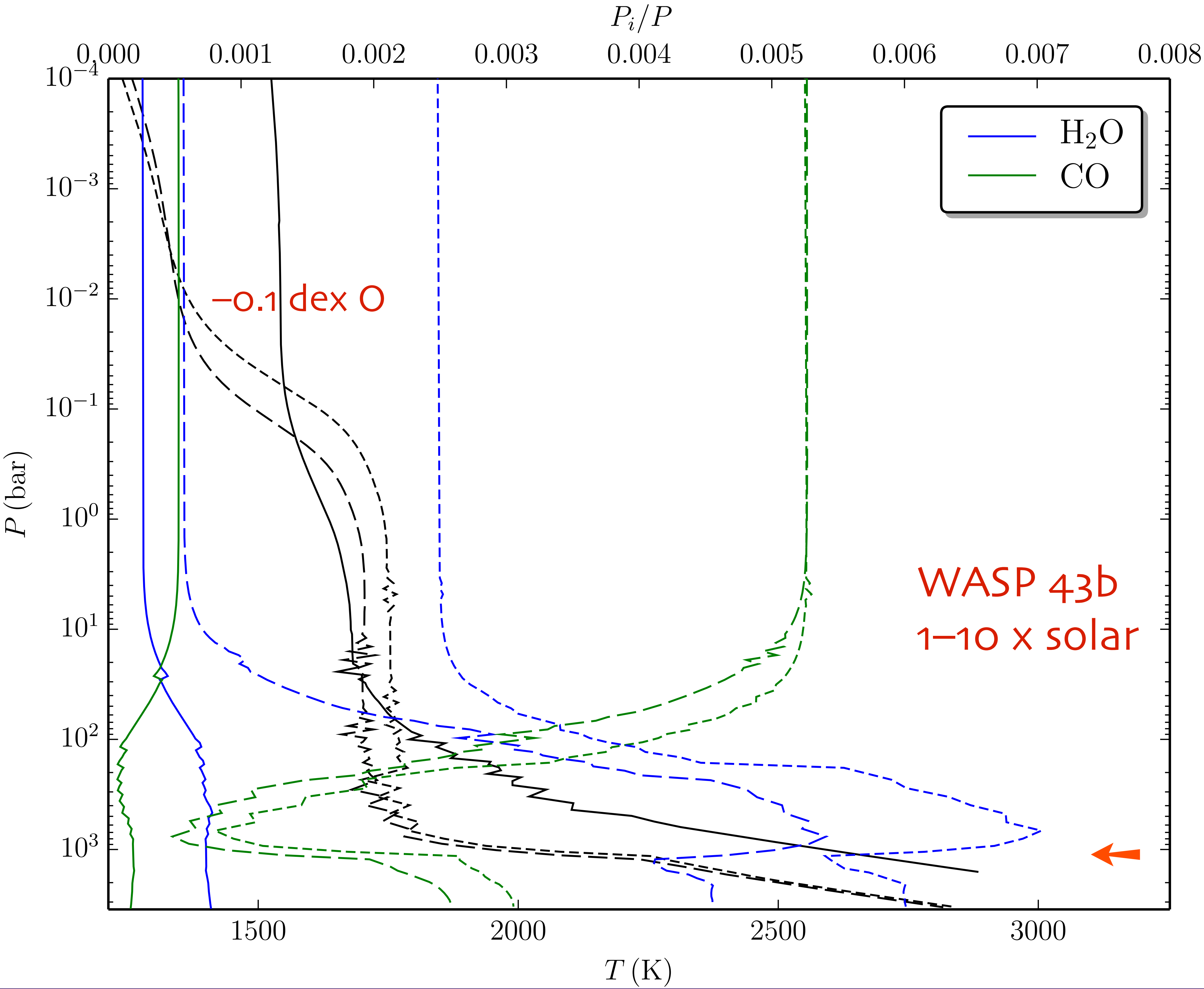
Atmospheric composition

- Metal abundances in general, and carbon and oxygen in particular, can differ from host star
- various degrees of oxygen and carbon depletion can occur depending on location and accretion history in the protoplanetary disk
- “non-solar” C/O, additional impact of cloud condensation
- Ch. Mordasini’s talk;
  cf. also Ch. Helling with I. Kamp et al. 2014

  (Life, in press)

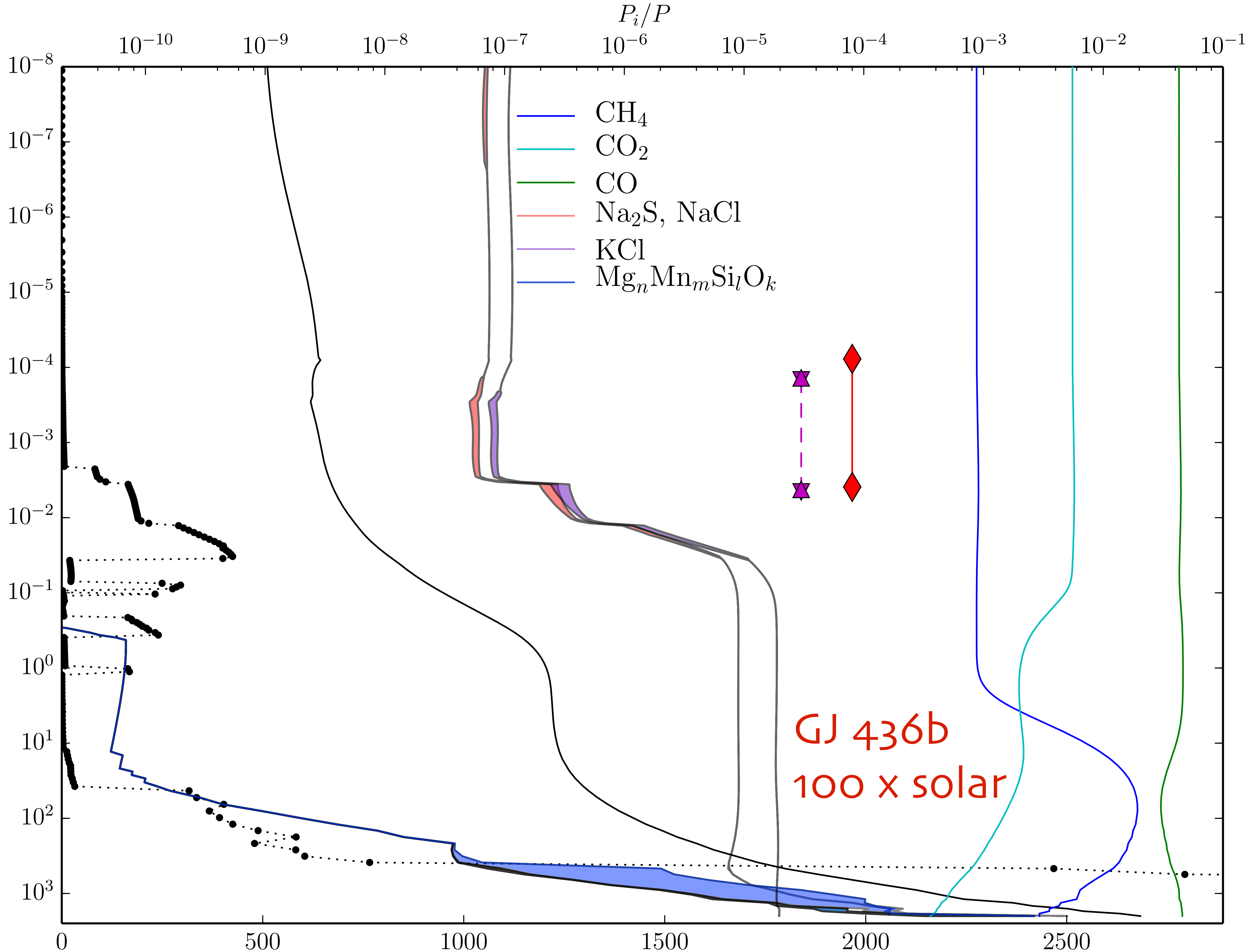
→ try arXiv:1403.4420 ?

Clouds affect carbon/oxygen chemistry



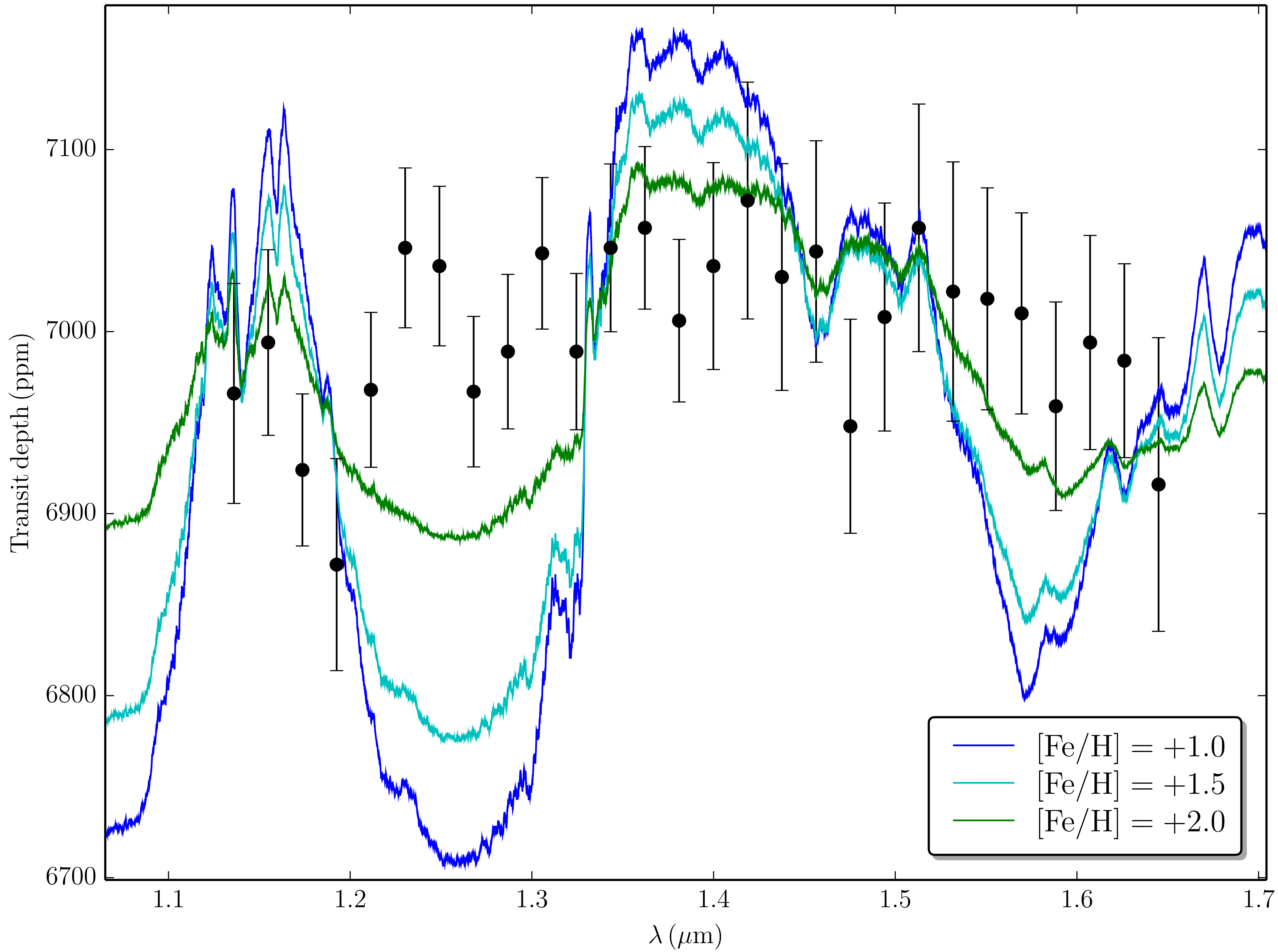
sequestration of oxygen in deep silicate clouds!

Clouds in hot Neptunes and super-Earths

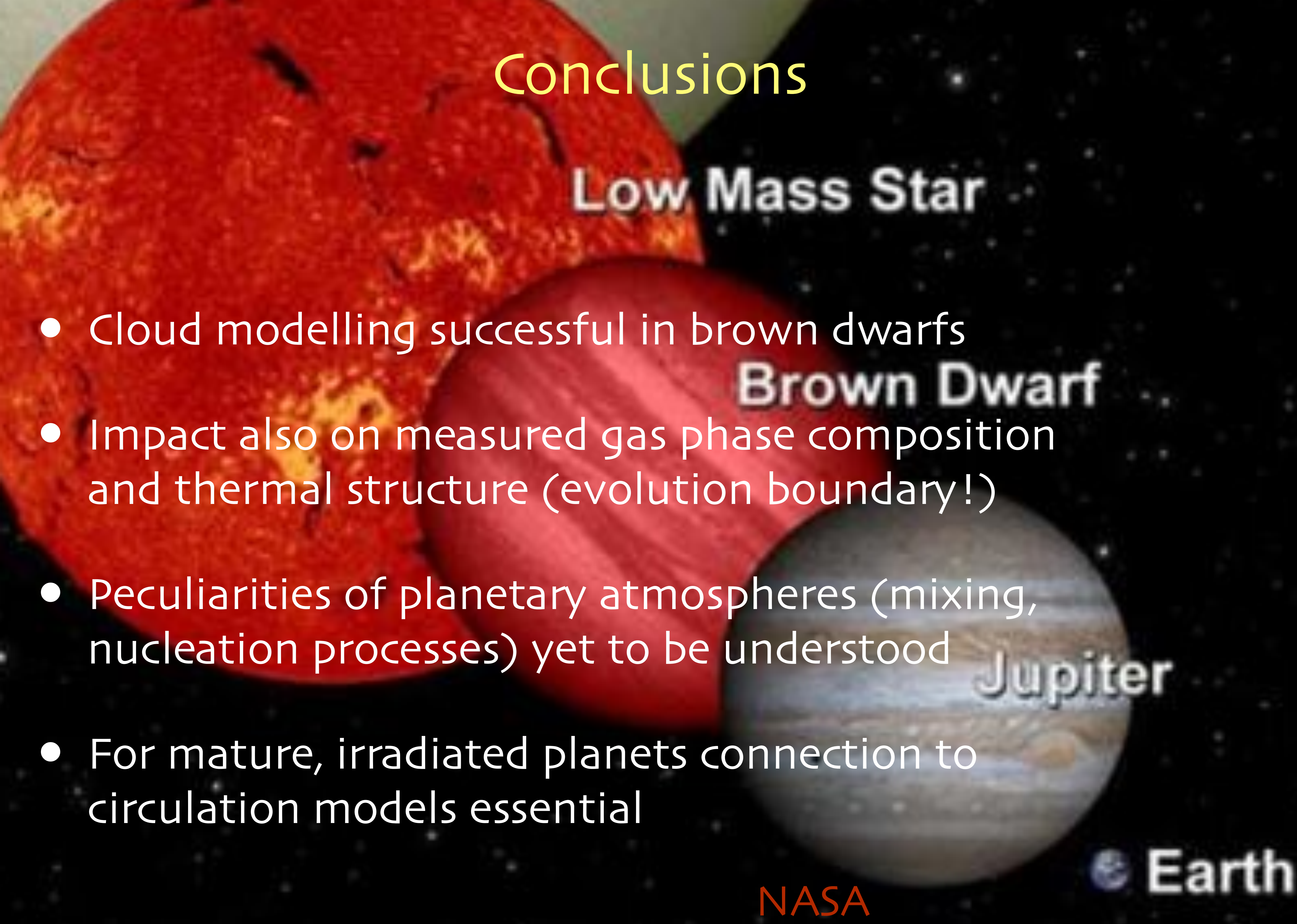


Clouds in hot Neptunes and super-Earths

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 understood
- For mature, irradiated planets connection to circulation models essential