Stellar atmospheres

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Outline

- What is a model atmosphere?
  - Physics/ equations
  - Ingredients
- 1D models
- 3D models
- Models for red (super-)giants
- Stellar parameters : a word of caution

Why we need model atmospheres

We **do not** *measure*, nor *observe*

- L, T_{eff}, R, M, g, chemical composition

- Magnetic field, rotation, velocity fields, ...

- age, mass-loss, ...

We **interpret observations**, using models to compute, e.g., a synthetic spectrum, or a visibility.

What is a model?

-> 1D examples in hydrostatic equilibrium (MARCS, Gustafsson et al. 2008)

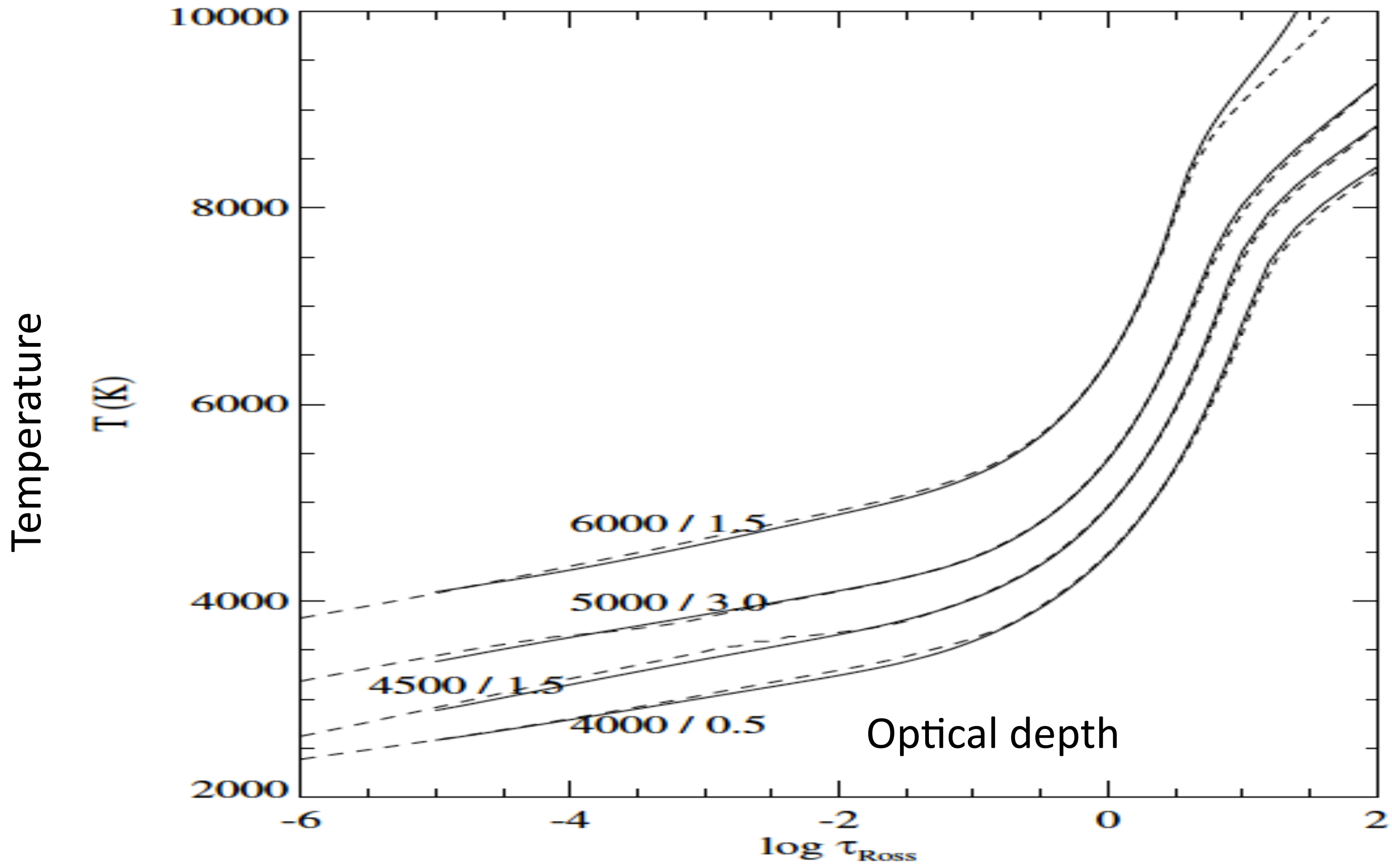
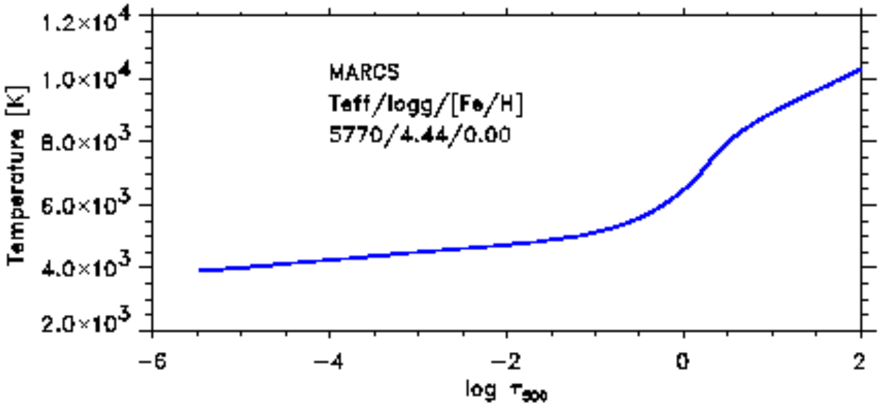
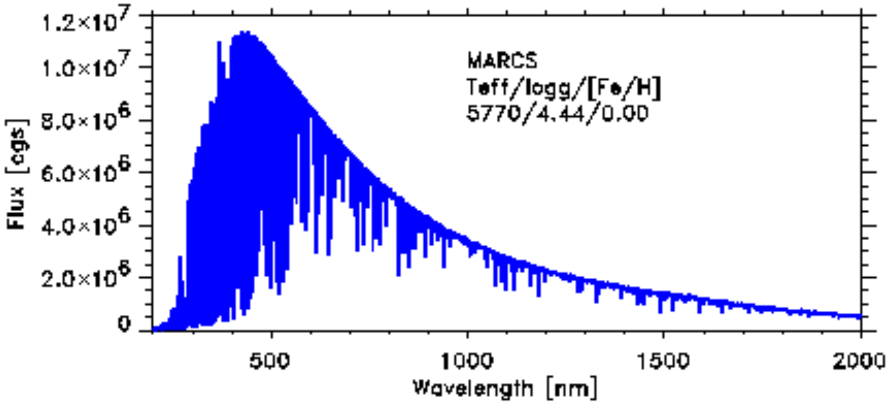


Fig. 17. MARCS model atmospheres for giants and supergiants with [Me/H] = 0.0 (solid) and corresponding models from the recent Castelli & Kurucz grid (dashed). The curves are labelled with relevant values of $T_{\rm eff}$ and log g.

Standard models





- stationary ($\partial/\partial t = 0$), static($\langle v \rangle = 0$)
- Geometry :1D (PP or spherically sym.)
- Statistical equilibrium: $Dn_i/Dt = 0$
- Hydrostatic equilibrium: $dp/d\tau = g/\kappa$
- Radiative equilibrium ($\nabla F_{rad} = 0$) or rad. + convective equilibrium

Simple example:

LTE grey atmosphere($\kappa_\nu = \kappa$) :

$$T^4 = \frac{3}{4} T_{eff}^4 (\tau + 2/3)$$

T and P stratification

- Pressure stratification is ruled by gravity
- Temperature stratification depends on energy flux at the base of atmosphere (T_{eff}), and opacities (+ convection)

Let's look at the simple 1D static case

Hydrostatic pressure equation

$$\frac{dp}{dz} = -\rho g \qquad d\tau_0 = -\kappa_0 \rho \, dz$$

$$\Rightarrow \quad \frac{dp_{tot}}{d\tau_0} = \frac{g}{\kappa_0} \qquad p_{tot} = p_{gaz} + p_{rad} \; (+ p_{magn} + p_{turb} + \ldots)$$

$$\frac{dp_{gaz}}{d\tau_0} = -\frac{dp_{rad}}{d\tau_0} + \frac{g}{\kappa_0} = \frac{g}{\kappa_0}\left(1 - \frac{g_{rad}}{g}\right) = \frac{g_{eff}}{\kappa_0}$$

$$p_{turb} = \beta \, \rho \, \mathrm{v}_{turb}^2 \qquad p_{gaz} \sim \rho \, c_{son}^2$$

Radiative transfer equation (1D, static)

- emission $\quad dI_\nu = j_\nu(s)\, ds$
- extinction $\quad dI_\nu = -\sigma_\nu\, n\, I_\nu\, ds$

  $\alpha_\nu = \sigma_\nu n = \kappa_\nu \rho$
- Optical depth $\quad d\tau_\nu = \alpha_\nu(s)\, ds$
- Source function $\quad S_\nu = j_\nu / \alpha_\nu$

$$\Rightarrow \quad \frac{dI_\nu}{d\tau_\nu} = S_\nu - I_\nu$$

Seemingly simple... BUT $S = S(I)$!

Solution to the transfer equation

- Formal solution

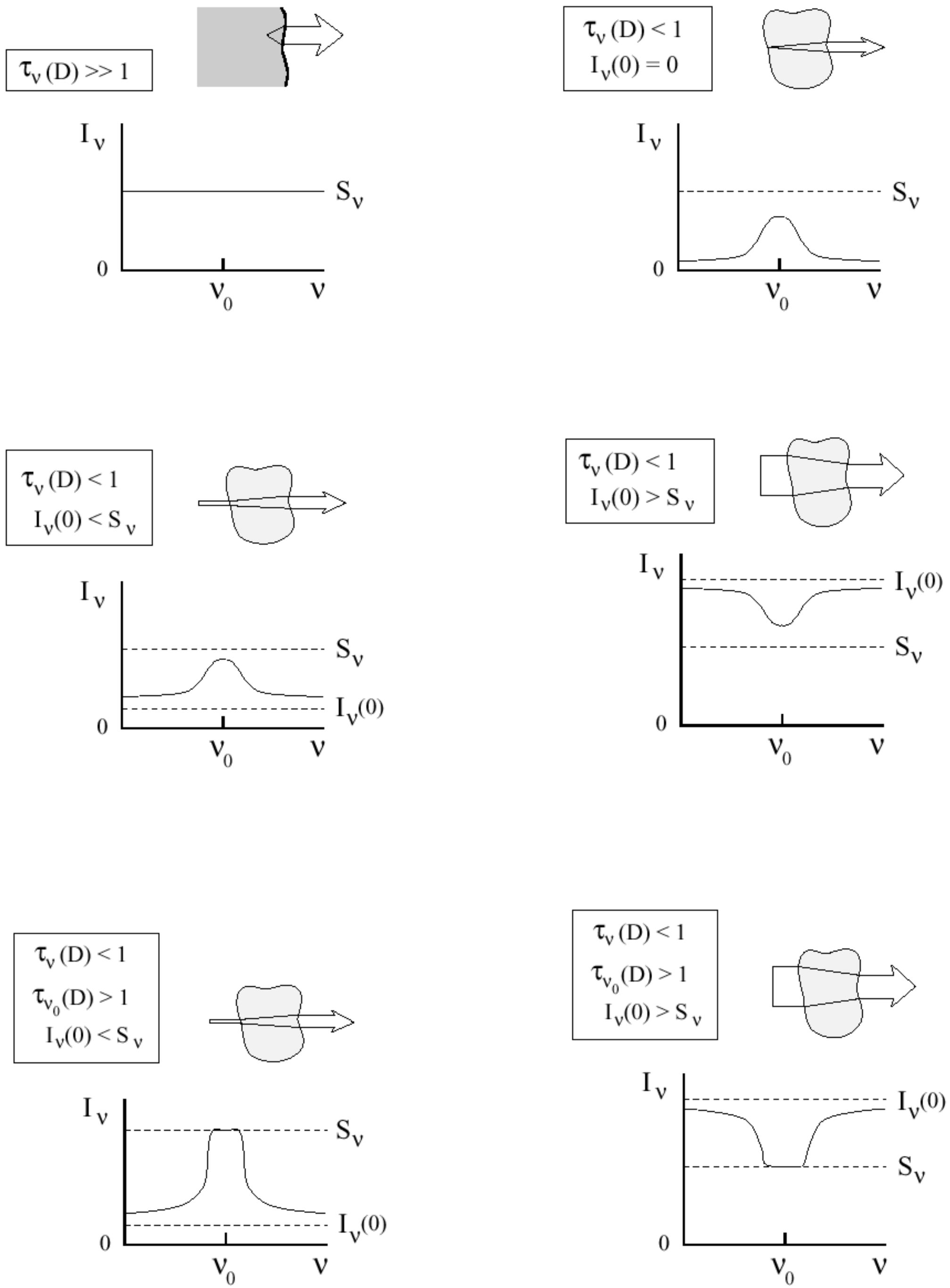
$$I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu} + \int_0^{\tau_\nu} S_\nu(t_\nu)e^{-(\tau_\nu - t_\nu)}dt_\nu$$

- Simple case: homogeneous slab of depth *D*

$$I_\nu(D) = I_\nu(0)e^{-\tau_\nu(D)} + S_\nu(1 - e^{-\tau_\nu(D)})$$

$$\tau_\nu >> 1 \quad \Rightarrow \quad I_\nu(D) \approx S_\nu$$

$$\tau_\nu << 1 \quad \Rightarrow \quad I_\nu(D) \approx I_\nu(0) + \left[S_\nu - I_\nu(0)\right]\tau_\nu(D)$$



τν (D) >> 1
Iν
Sν
0
ν0
ν
τν (D) < 1
Iν(0) = 0
Iν
Sν
0
ν0
ν
τν (D) < 1
Iν(0) < Sν
Iν
Sν
Iν(0)
0
ν0
ν
τν (D) < 1
Iν(0) > Sν
Iν
Iν(0)
Sν
0
ν0
ν
τν (D) < 1
τν0 (D) > 1
Iν(0) < Sν
Iν
Sν
Iν(0)
0
ν0
ν
τν (D) < 1
τν0 (D) > 1
Iν(0) > Sν
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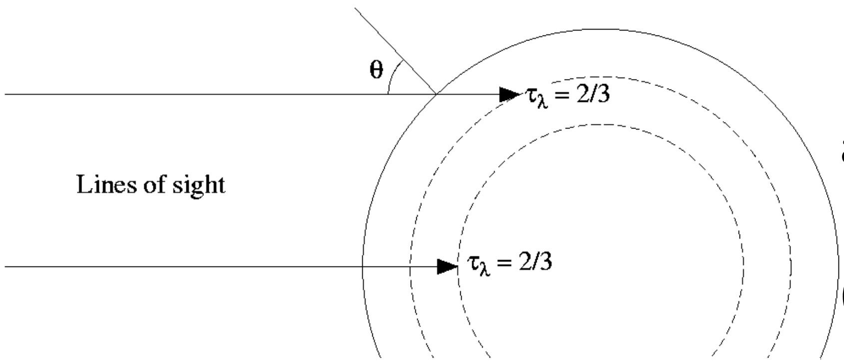
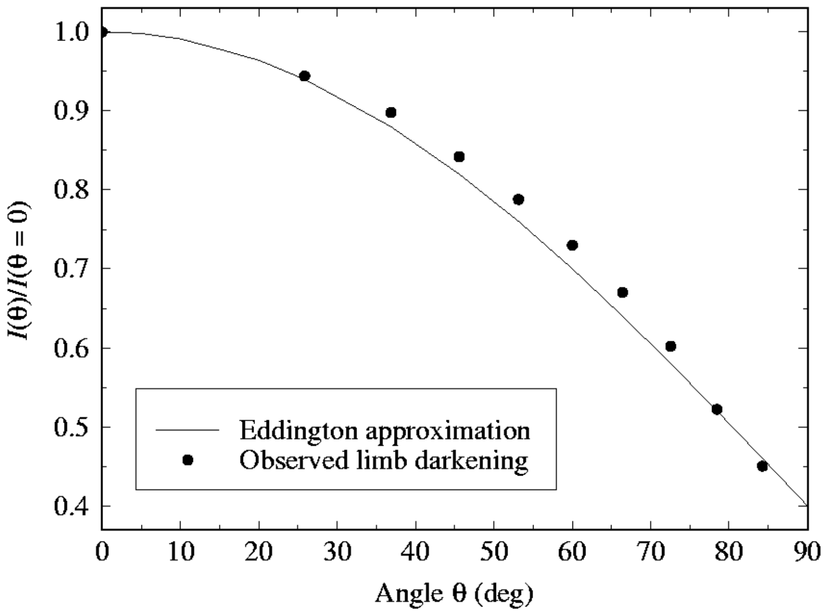
Iν(0)
Sν
0
ν0
ν

From Rutten

A word on limb-darkening





Writing **S = a τ +b**, leads to

I(μ) = S(τ=μ), with μ=cos(θ)

and the flux

F = S(τ=2/3)

(Eddington approx.)

Application :

empirical determination of $S_\nu(\tau)$, T(τ)

⇒ empirical model atmosphere (e.g. Holweger-Müller)

Precious information => Measure it!

K. Schwarzschild (1906) used it to demonstrate that the solar atmosphere is in radiative equilibrium

Effect of lines on the thermal structure

(line blanketing)

At LTE, radiative energy balance requires:

$$q = \int \kappa_\lambda (J_\lambda - B_\lambda) d\lambda = 0$$

At every level in atmosphere

J_λ : radiation from (hotter) deeper atmosphere

B_λ : local (cooler) radiation field

- In the blue $J_\lambda - B_\lambda > 0$ and in the red $J_\lambda - B_\lambda < 0$

=> if an opacity is efficient in upper atmospheric layers, heating (e.g. TiO) or cooling (e.g. H_2O, C_2H_2).

- and backwarming, deeper.

Line blanketing:

Heating in deep layers

Cooling or heating in shallow layers

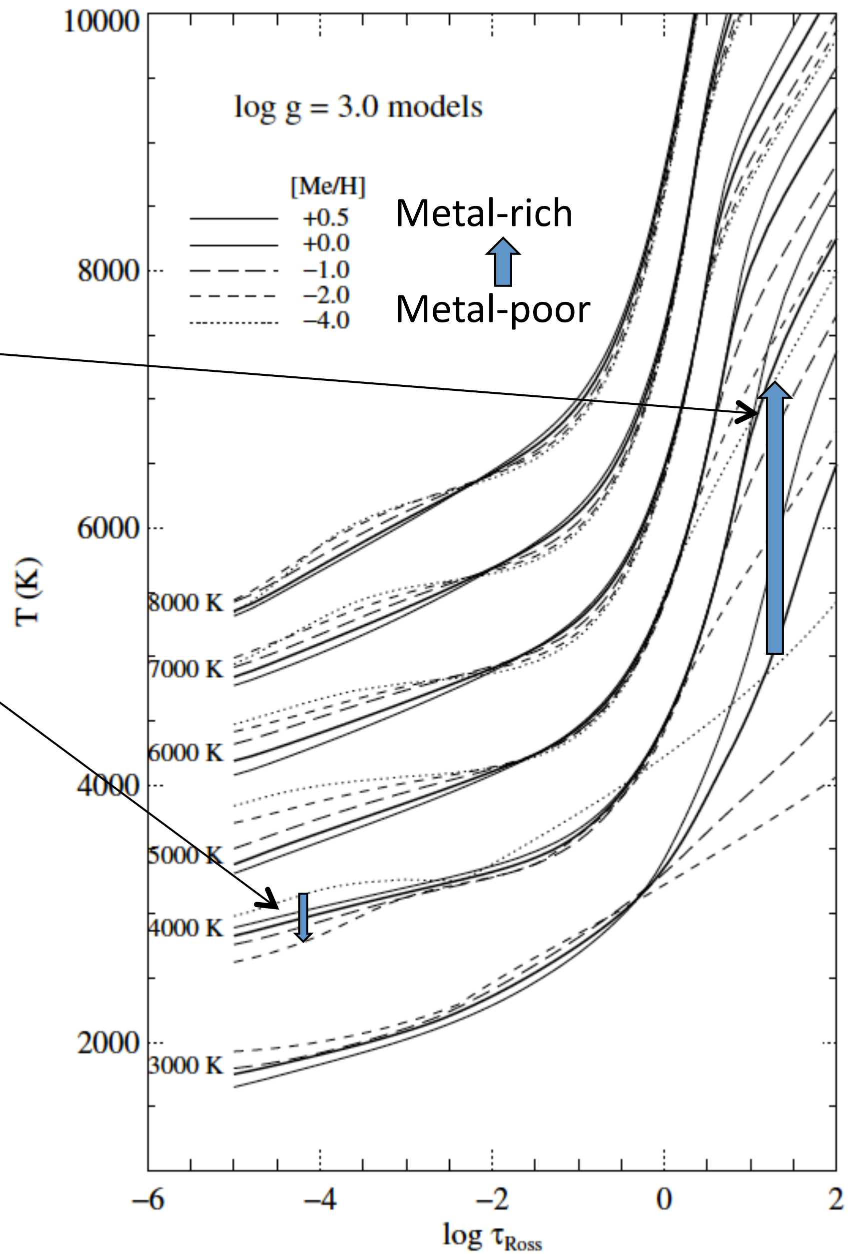
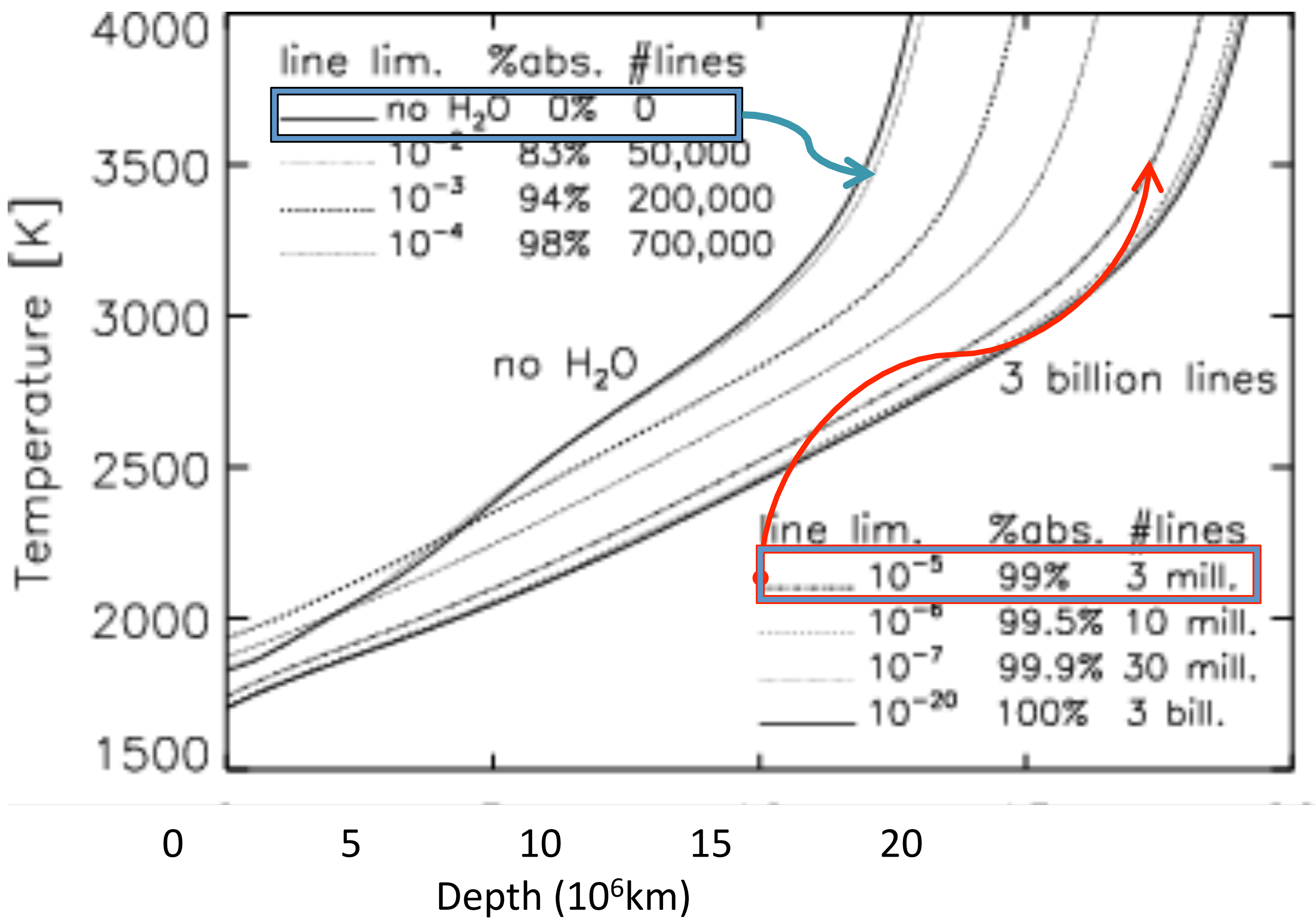


Fig. 2. The temperature structures for a set of model atmospheres with different $T_{\rm eff}$, $\log g = 3$ and different metallicities.

Importance of line list completeness

for the thermal structure (Jørgensen et al. 2001)



Models for different kinds of stars

Hot stars:

- few spectral lines, no convection
- but NLTE, strong wind

Cool stars:

- numerous lines => blanketing (e.g. TiO : 5 isotopes, > 10^7 lines!)
- convection, dust formation, ...

Pulsating stars require radiative hydrodynamics

Classical model atmospheres

“classical” approximations:

- 1-D (PP or SPH)
- LTE (actually : $S_\lambda = \kappa_\lambda B_\lambda + \sigma_\lambda J_\lambda / (\kappa_\lambda + \sigma_\lambda)$)
- hydrostatic
- convection = MLT

works well for most cool stars.

Many successes (Teff-scales, abundances, ...), we will see some limits also!

Three main brands: MARCS, ATLAS, PHOENIX

MARCS 2008

- OS 108000 points
- updated continuous opacities
- updated line opacities, e.g. H_2O, atomic lines with Anstee, Barklem et al.'s collisional broadening, and better H I lines (Barklem & Piskunov, 2003), ...
- more than 10^4 models
- note on computing time :
  - Gustafsson & Nissen 1972 : 25mn for a PP model with 148 λ (25 Balmer lines)
  - 2008 : 10mn for a SPH model with 108000 λ (>10^8 lines)
- Available at **marcs.astro.uu.se**
- Synthetic spectrum code turbospectrum available on

http://asterisk.apod.com/viewtopic.php?f=35&t=28539&hilit=turbospectrum

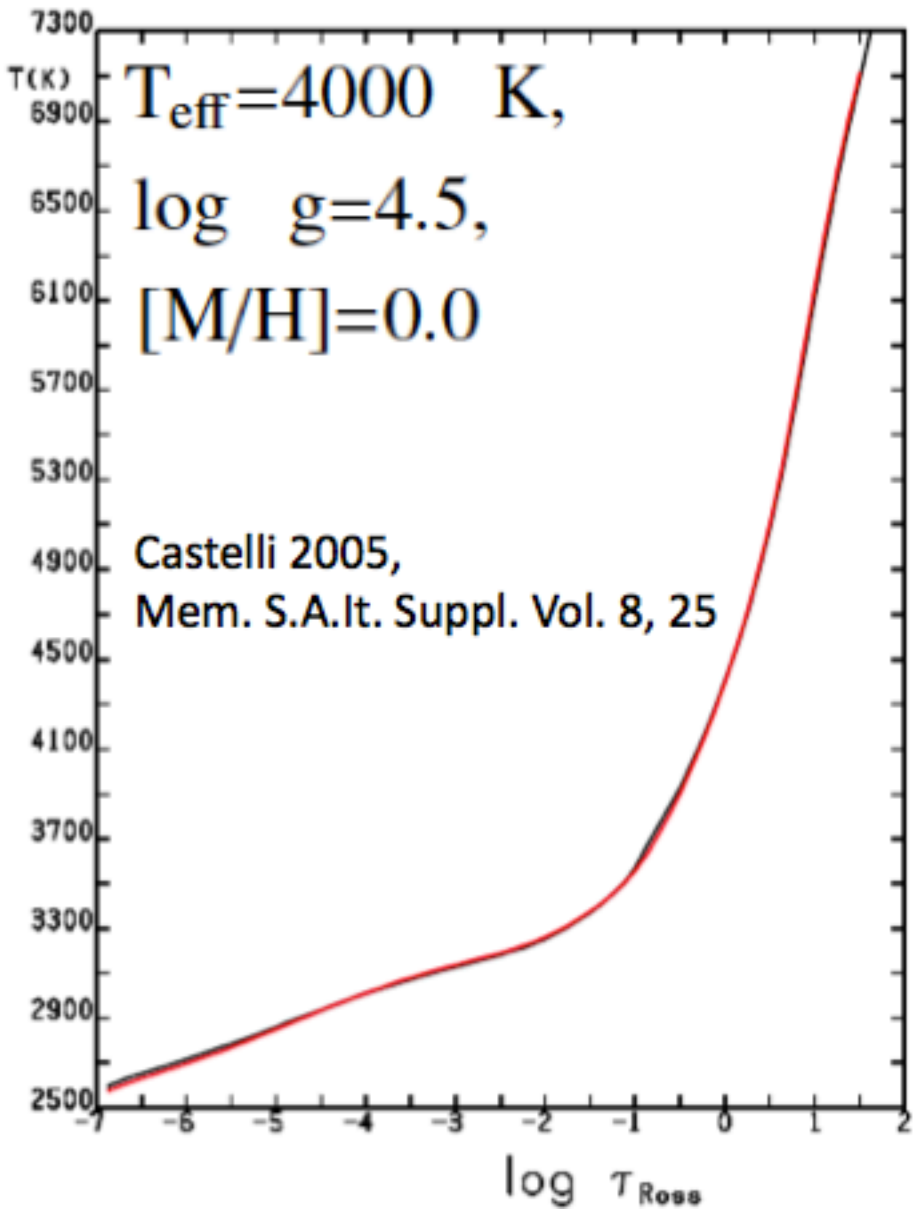
ATLAS

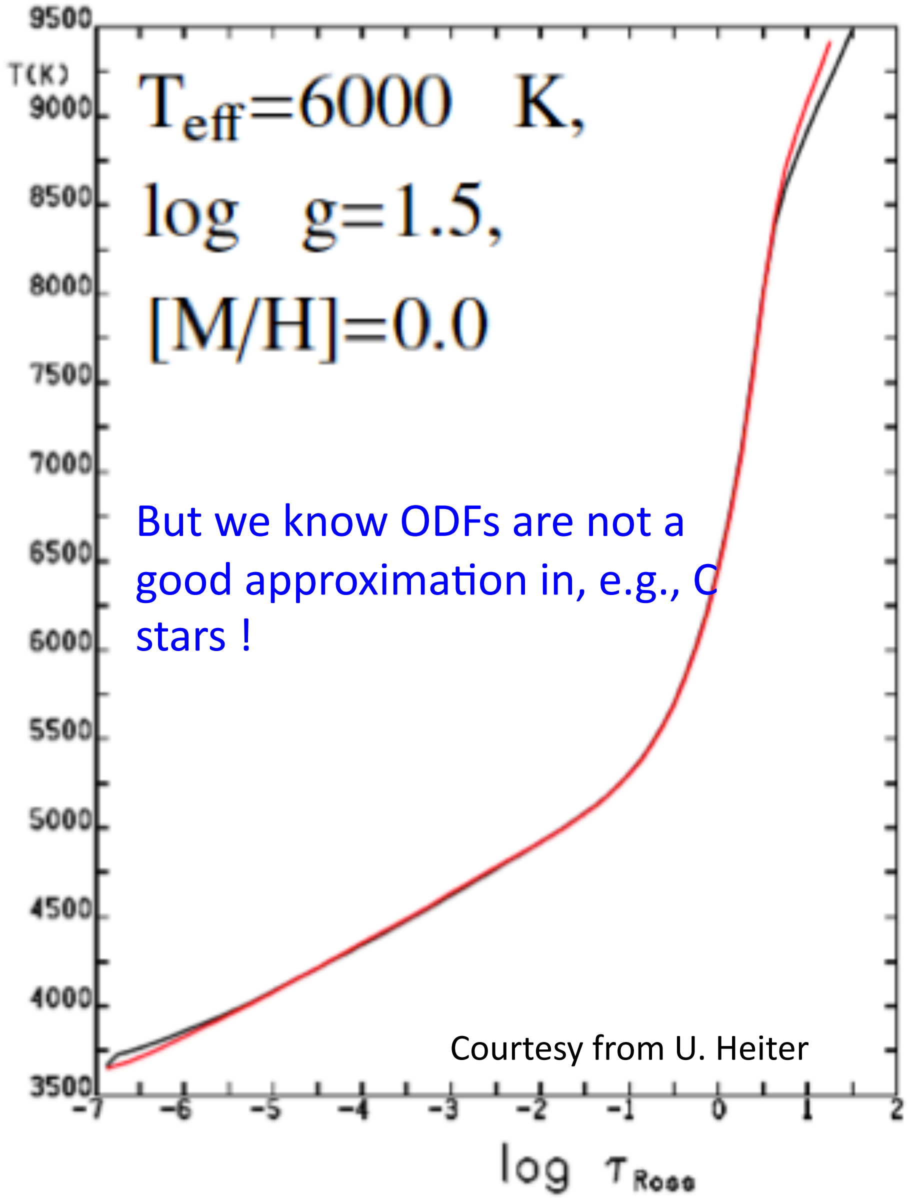
- Kurucz, Castelli, et al.
- Huge data base of atomic lines, computed by Kurucz, supplemented with collected molecular data
- ATLAS9 (1993)
  - Opacity distribution functions (ODFs)
  - pre-tabulated ODF tables for scaled-solar abundances
- ATLAS12 (1993)
  - Opacity sampling
  - compute opacity at every 100th wavelength point (30000 points)
  - sufficient for accurate total flux (?)
  - For individual models with arbitrary abundances

PHOENIX

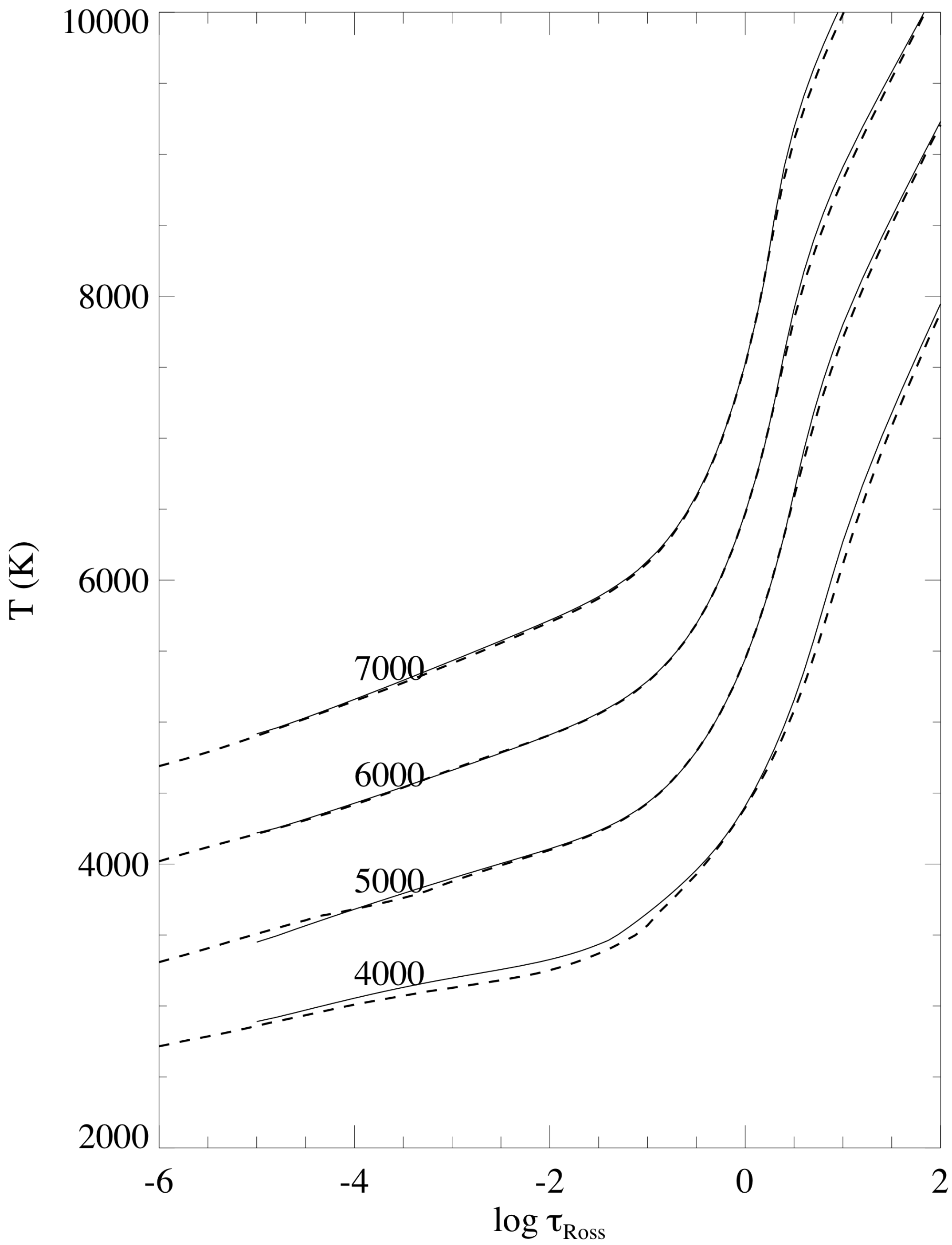
- P. Hauschildt, F. Allard, et al.
- More versatile code : NLTE, winds, relativistic, ..
- Extensive line data, also for very cool stars, but a number of sources different from MARCS

ATLAS9 vs ATLAS12

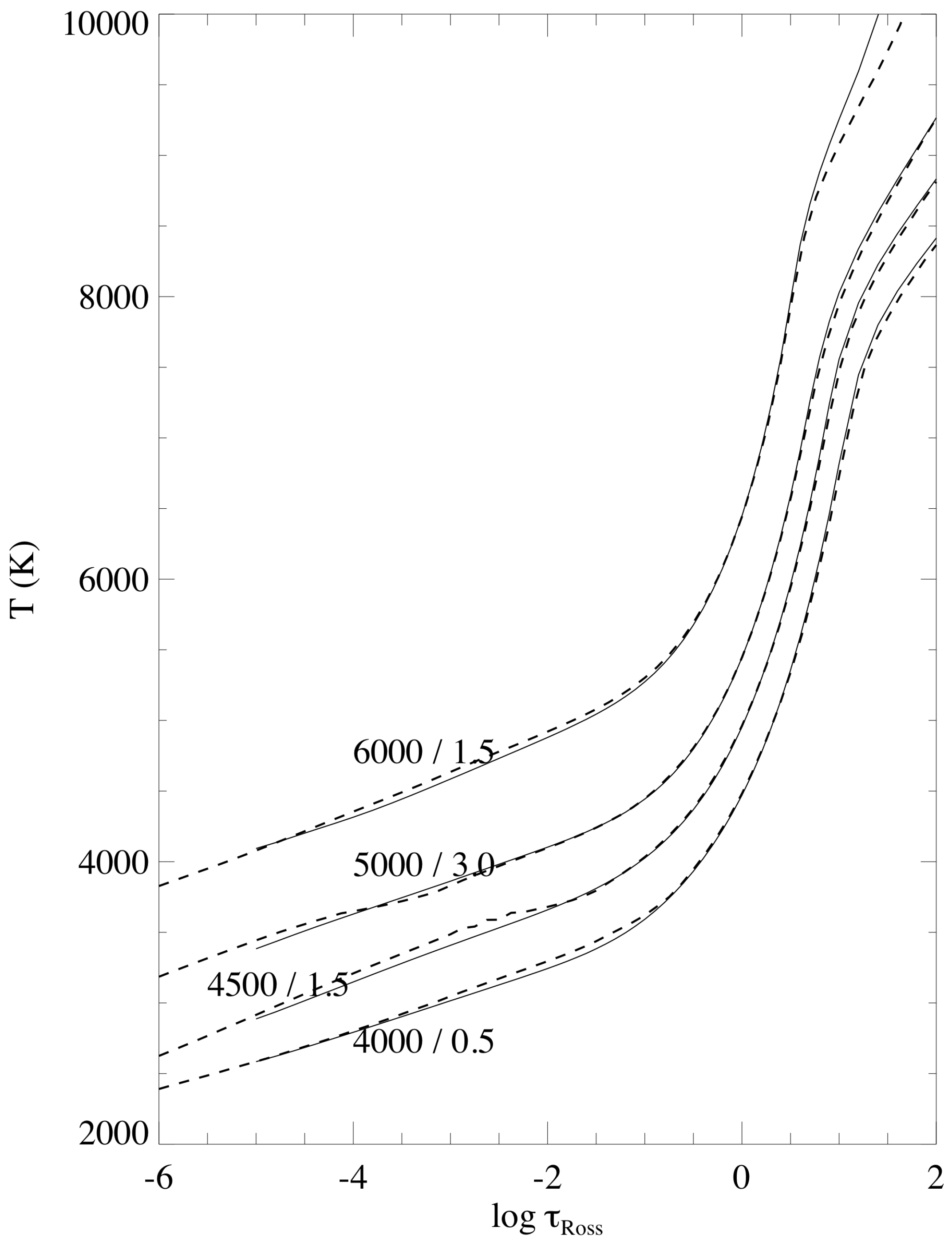




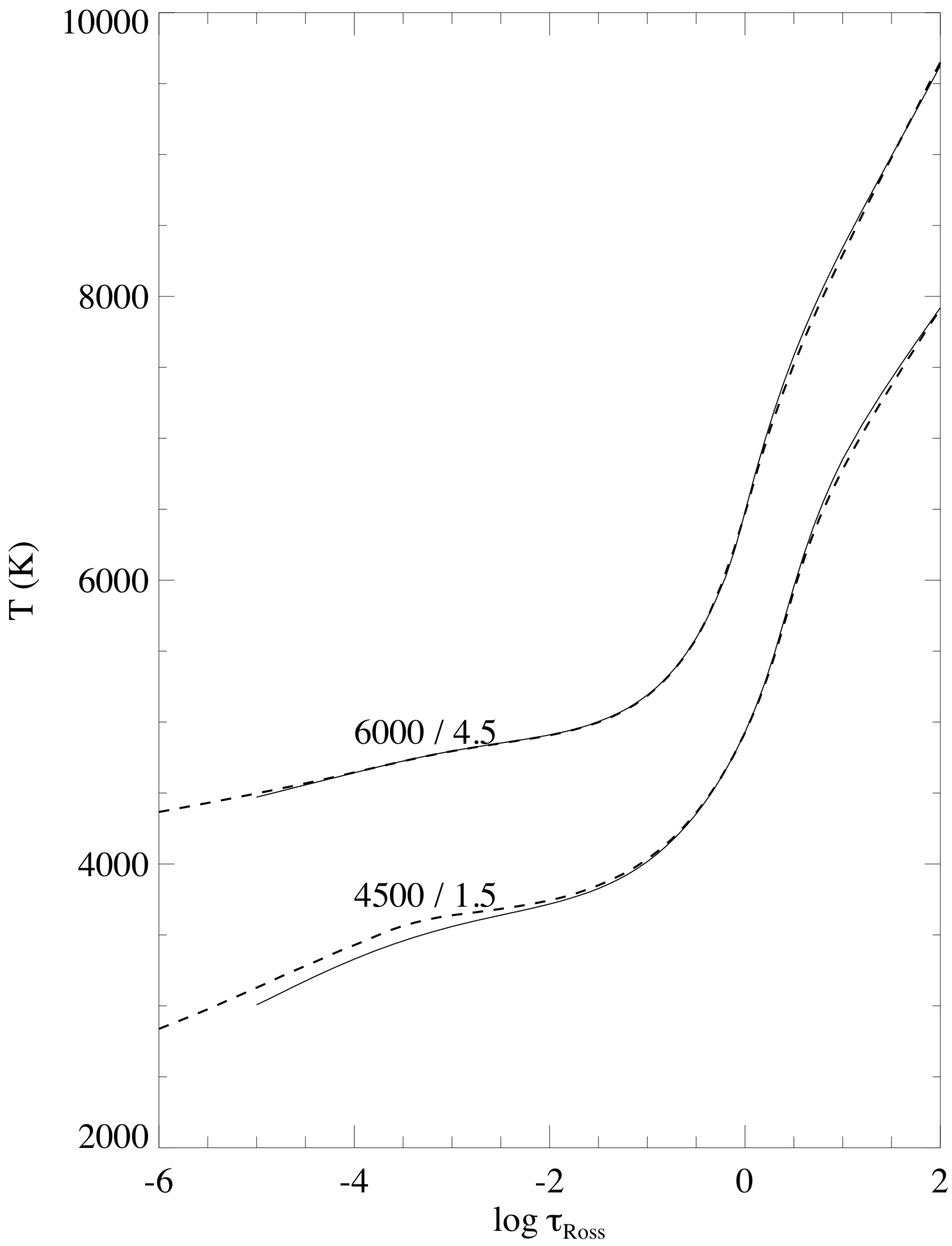
MARCS vs. ATLAS ODFnew, logg=4.5, solar comp



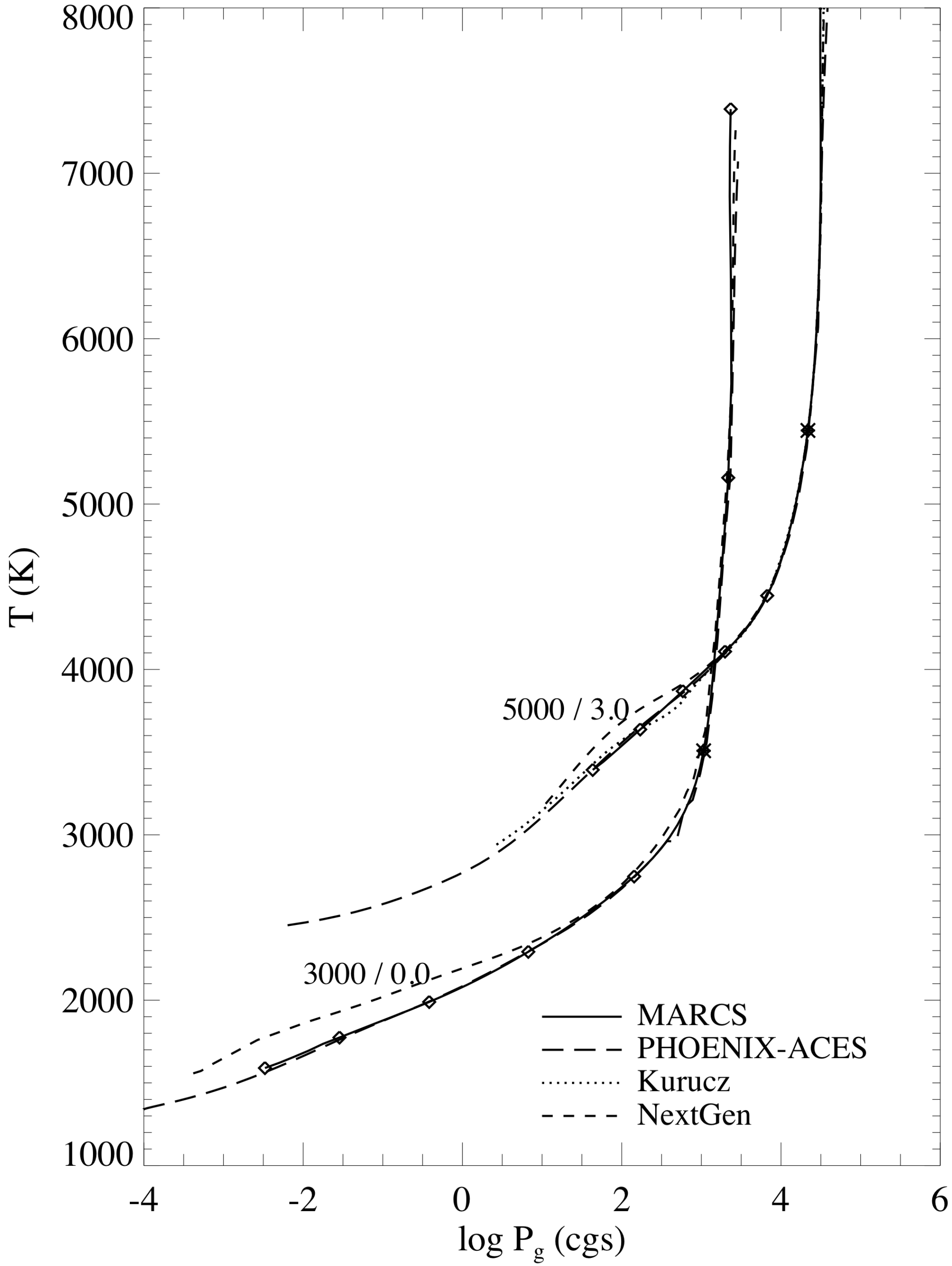
MARCS vs. ATLAS ODFnew giants and SG



MARCS vs. ATLAS [Fe/H]=-2



MARCS +
PHOENIX
(Sph)
ATLAS (PP)



Classical model atmospheres (cool stars)

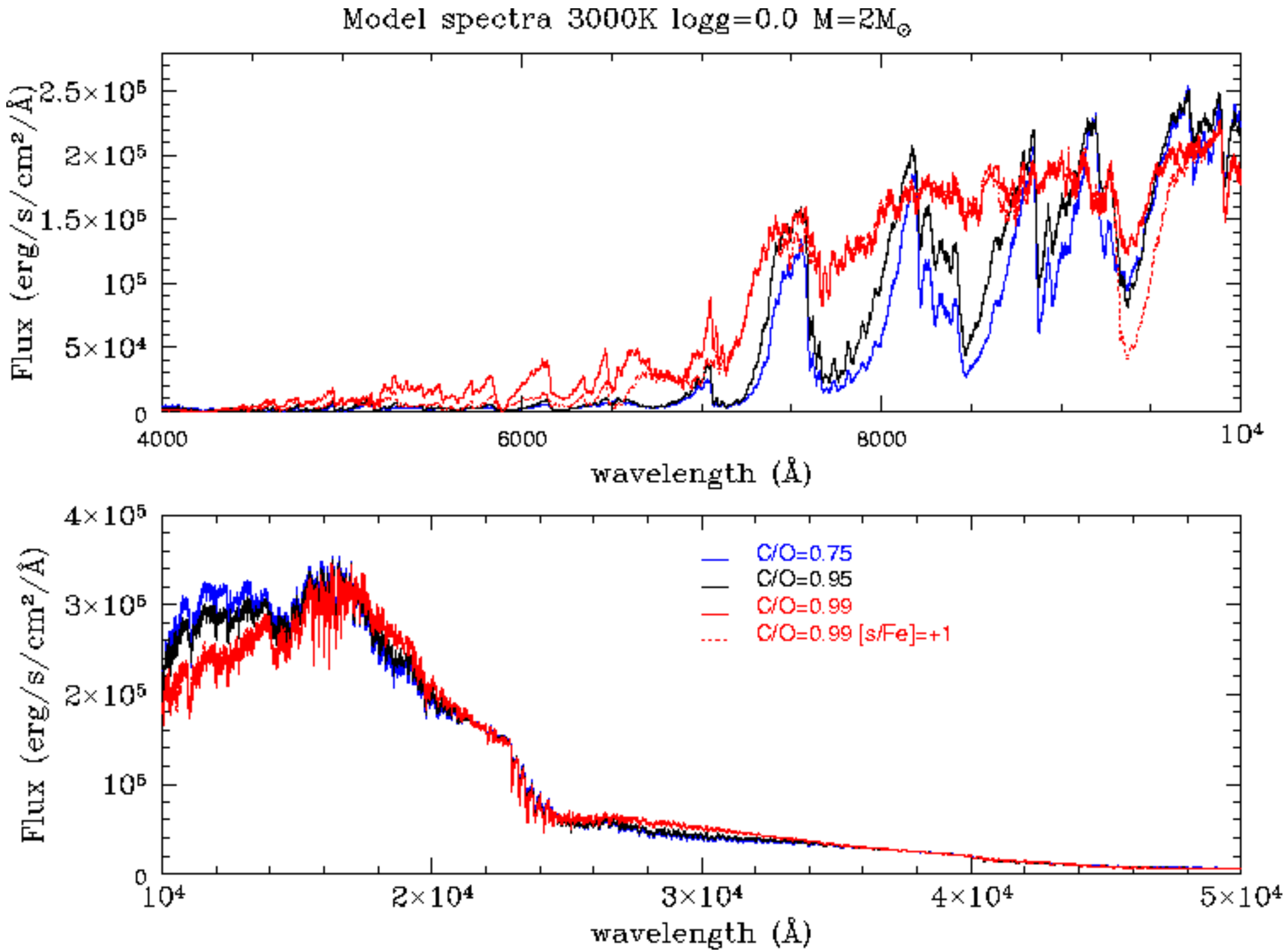
Classical/standard = LTE, 1-D, hydrostatic
Real stars are not "classical" !
But...

• classical models include extremely detailed opacities
• they serve as reference for more ambitious modeling (3-D, NLTE, ...)
• cool star spectra very much affected by molecular lines
... and are thus not yet all studied in detail even with classical models.

Note impressive recent developments : 3D convection (e.g. Ludwig, Freytag, Chiavassa), NLTE (e.g. Hauschildt et al.), pulsation-dust-wind LPVs (e.g. Hoefner et al.).

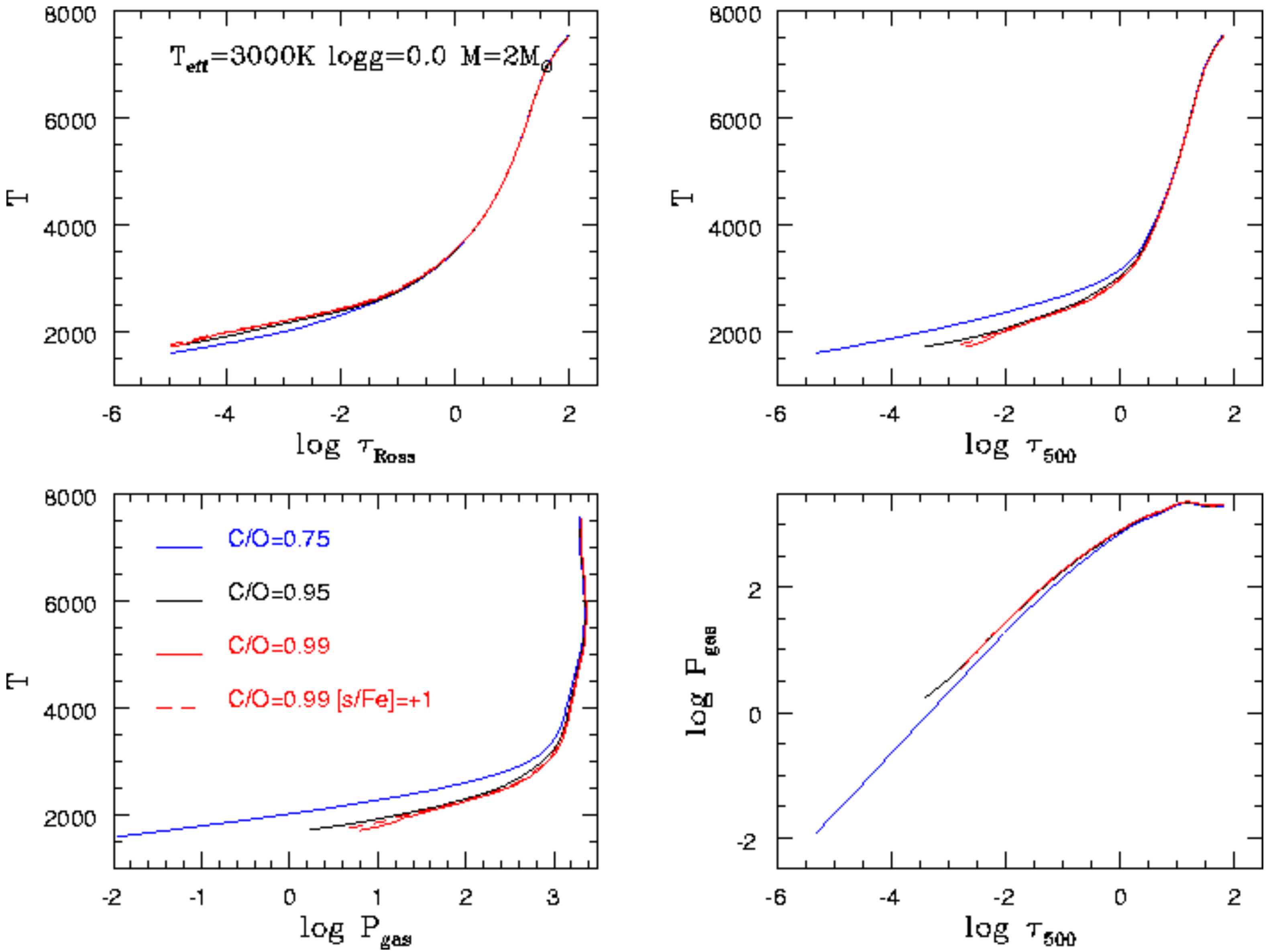
Examples of MARCS 1D models (hydrostatic, LTE)

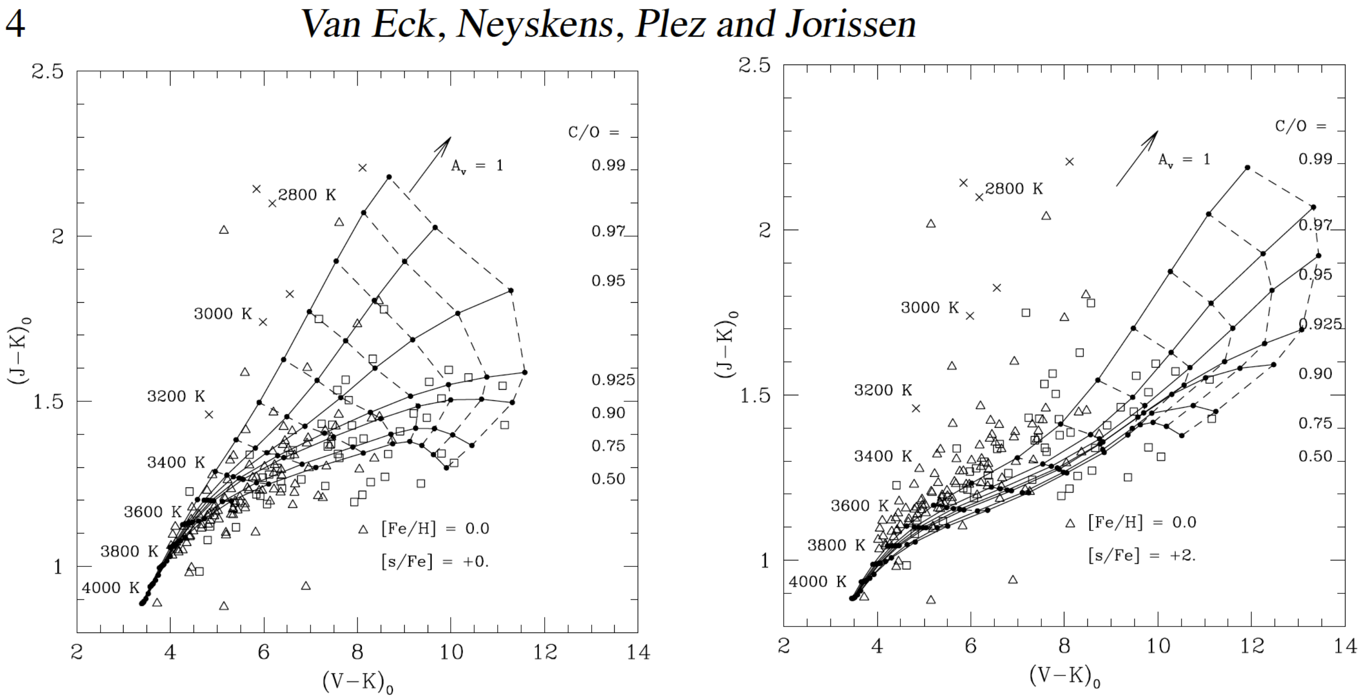
Spectra for S type star mixtures (variable C/O and [s/Fe])



Examples of MARCS 1D models (hydrostatic, ETL)

Thermal structure, opacity effects (NB: 1bar=10^4cgs)

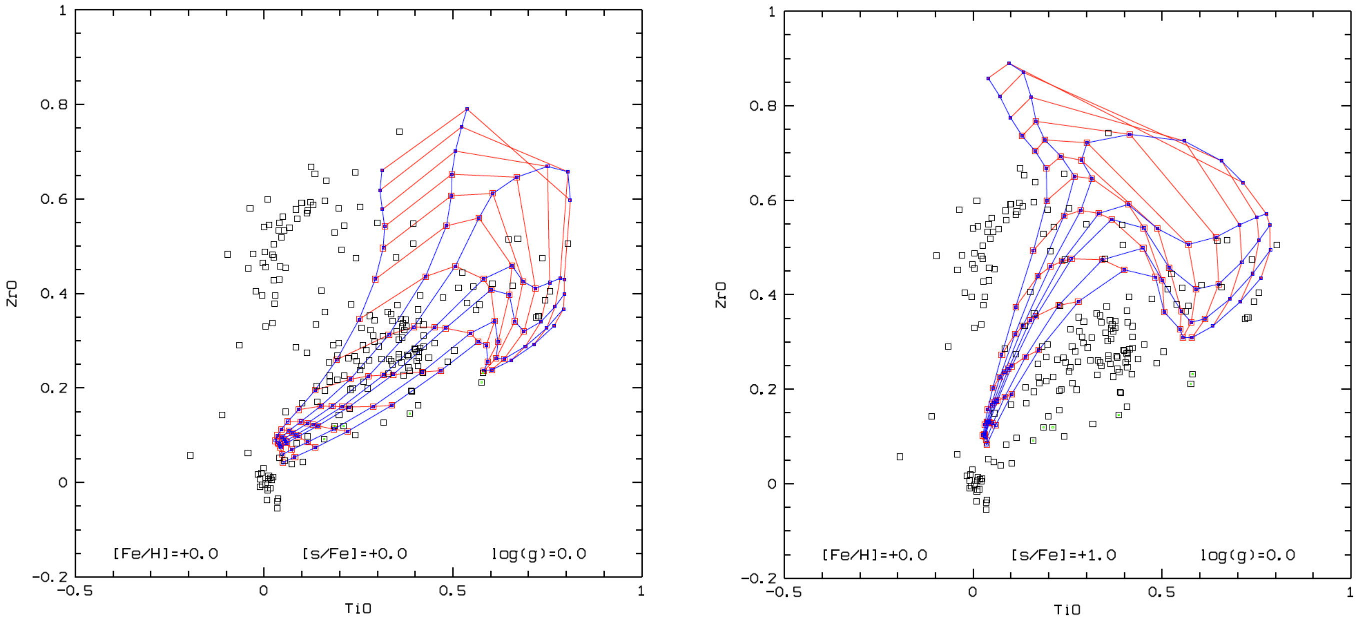




M-S star photometry:

models and observations

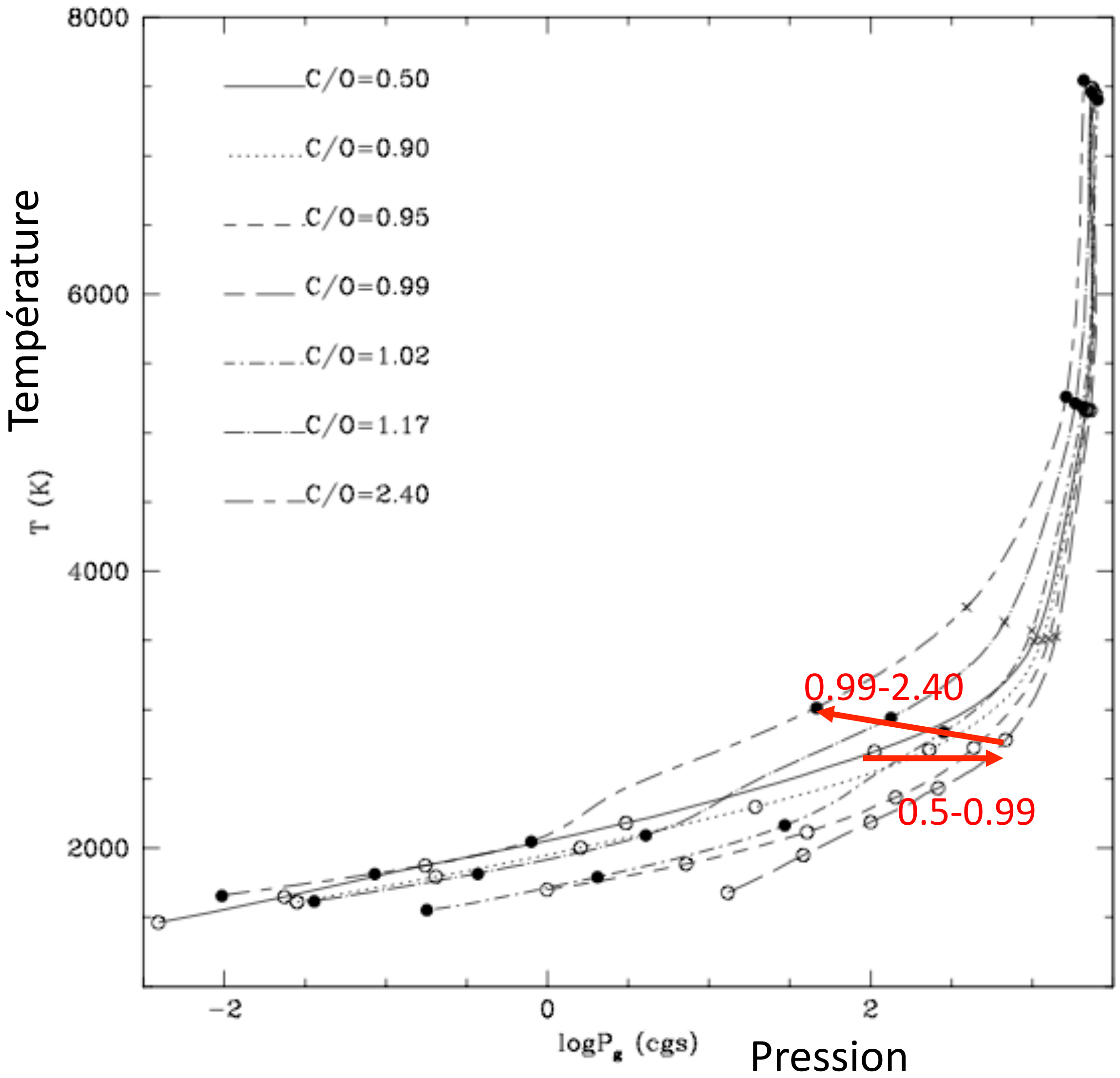
V-K vs. J-K



TiO vs. ZrO index

(VanEck et al. 2010)

Interesting experiments: Effect of C/O in M-S-C models



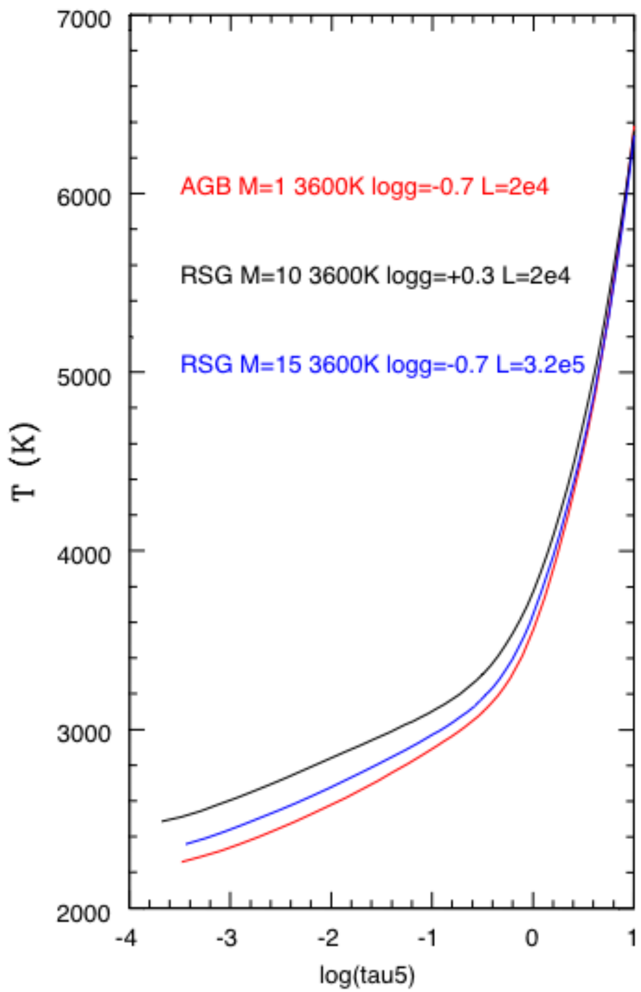
Transition
TiO, H_2O -> C_2, C_2H_2, HCN

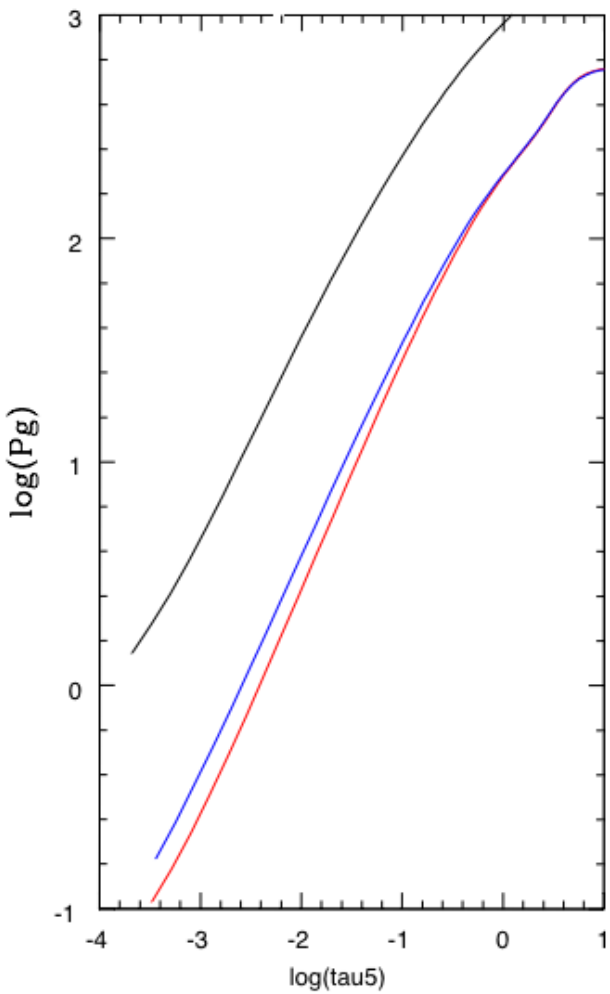
the **CO lock**

C/O<1:
if C/O increases => TiO, H_2O decrease;
Opacity decreases=> higher P

C/O>1
if C/O increases => increase of C_2, C_2H_2, ...
Opacity increases => lower P

Interesting experiments:
Models for RSG and AGB of same L and T_{eff}





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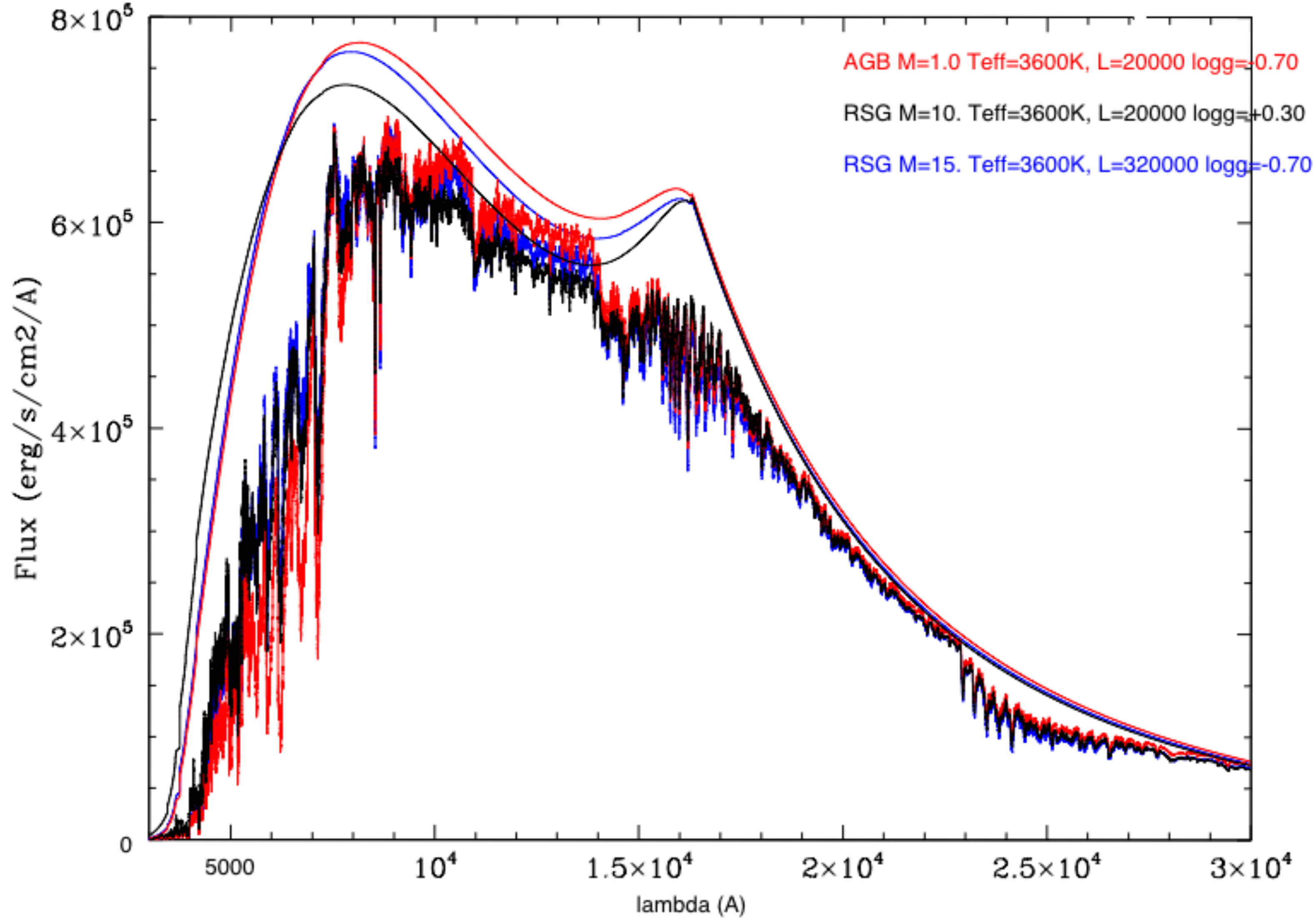
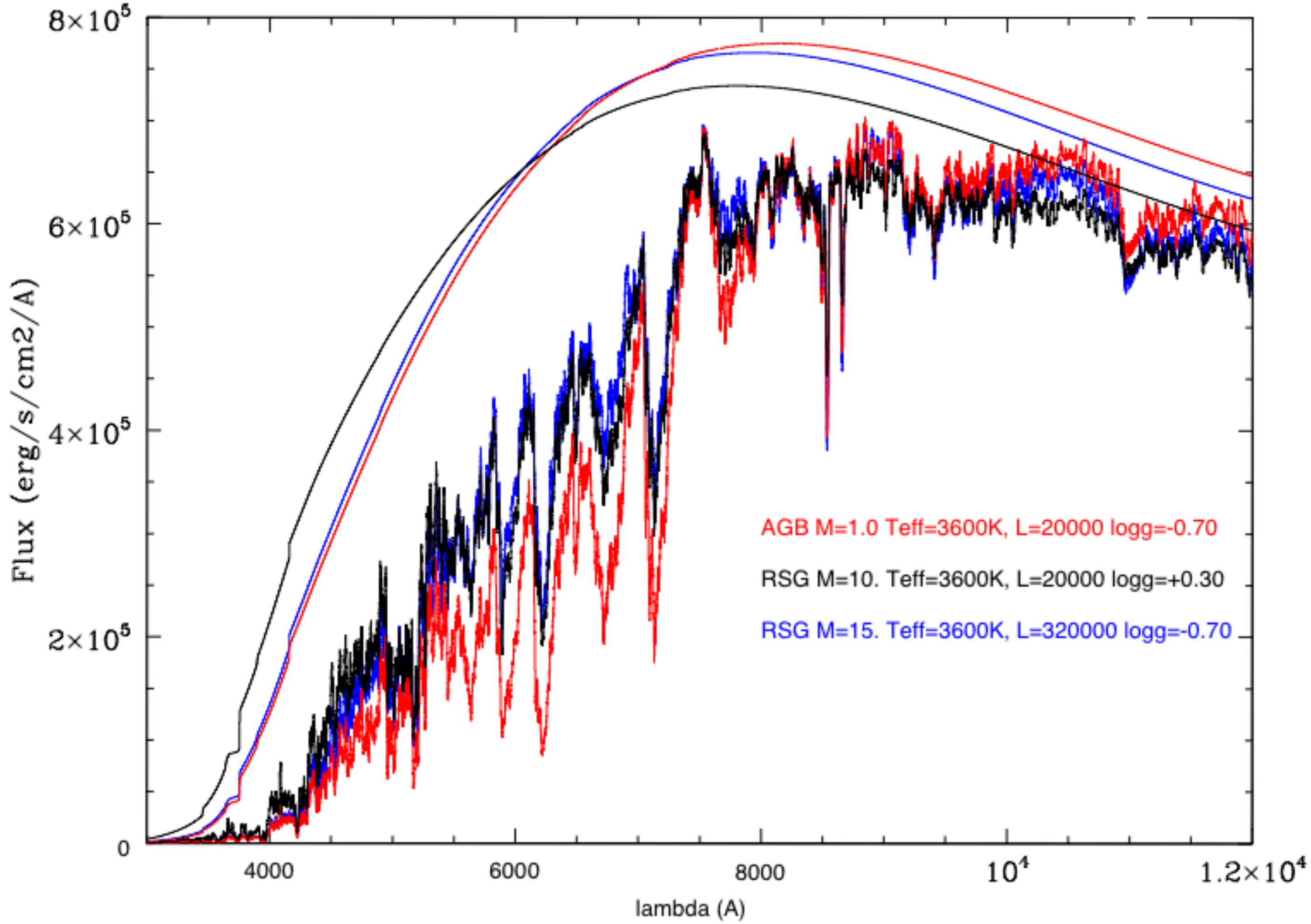
Models for RSG and AGB of same L and T_{eff}



Interesting experiments:

Models for RSG and AGB of same L and T_{eff}

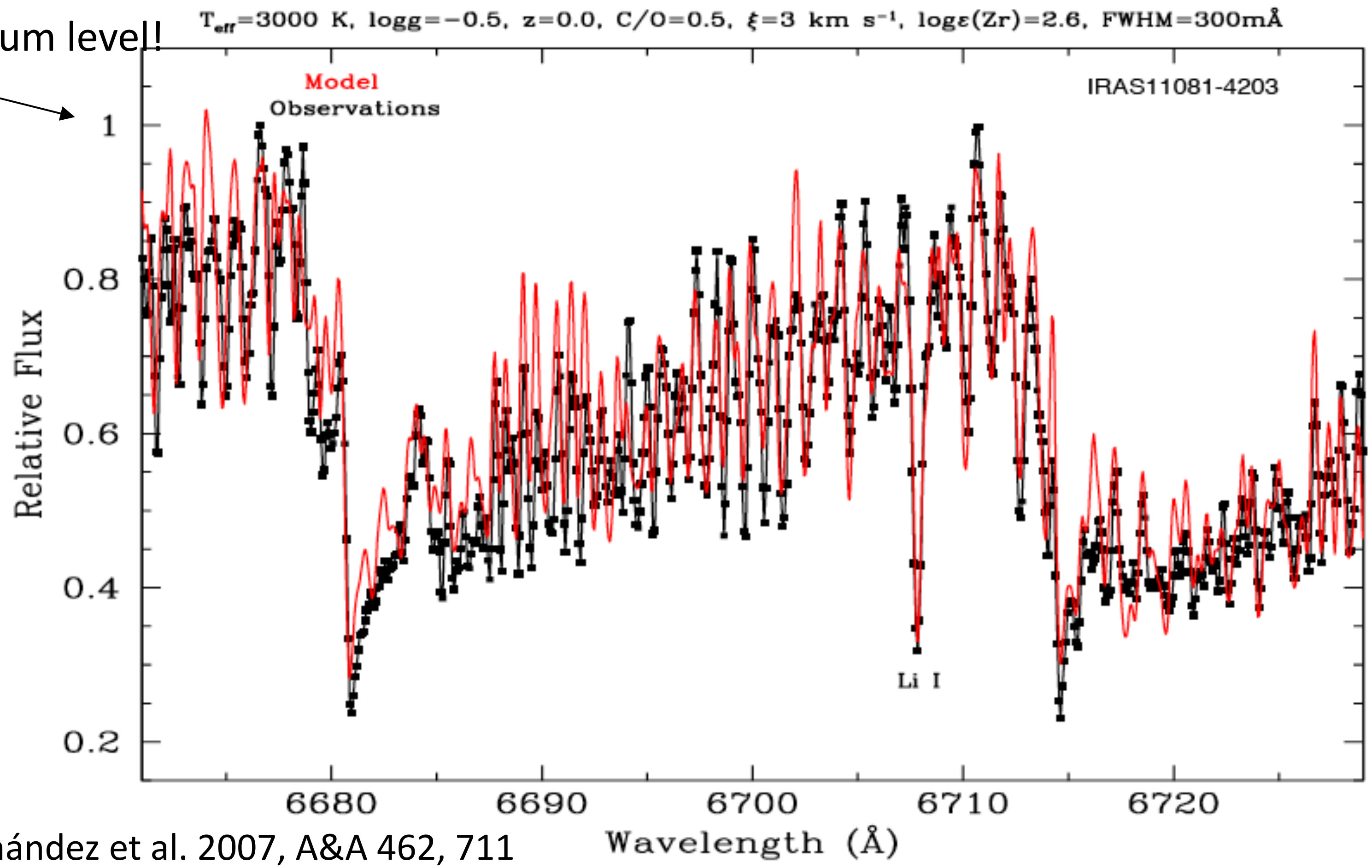


1D models do a good job:

Fit of a very cool red giant spectrum (lines of TiO, ZrO, and atoms)

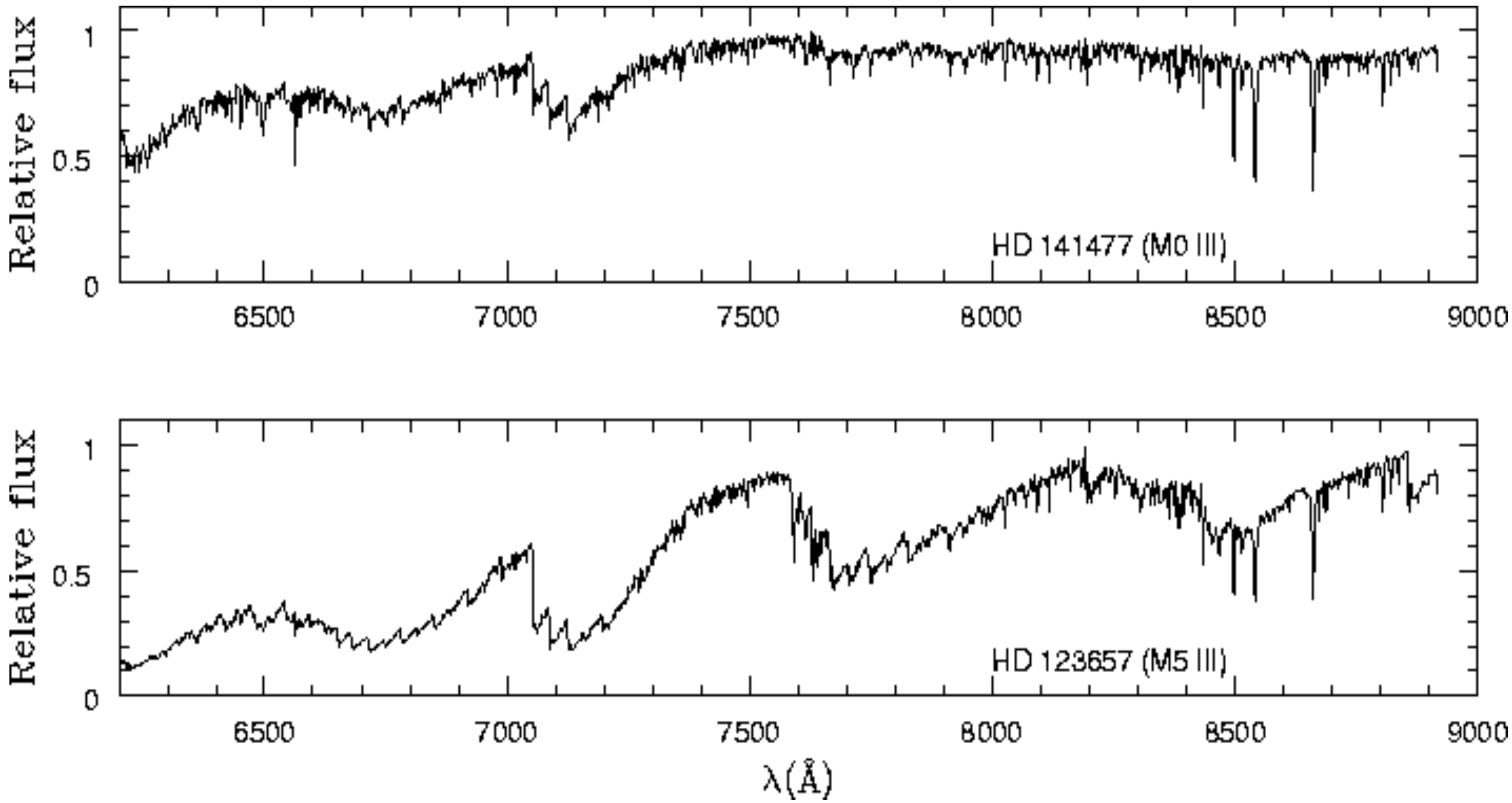
1D model with **obvious physical limitations** in this case of an AGB star, but with **very good line lists**

1 is not the continuum level!

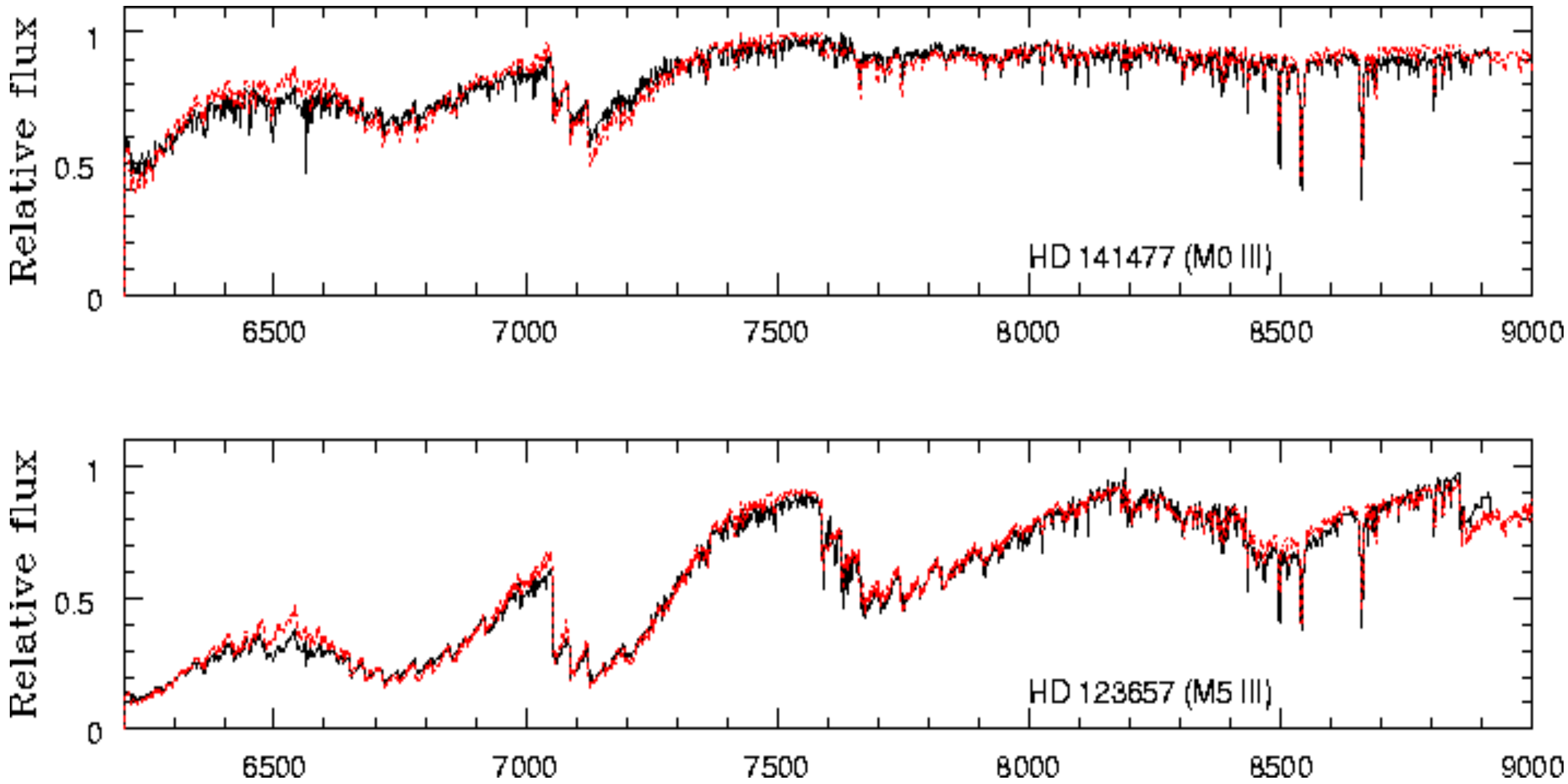


From García-Hernández et al. 2007, A&A 462, 711

Other example



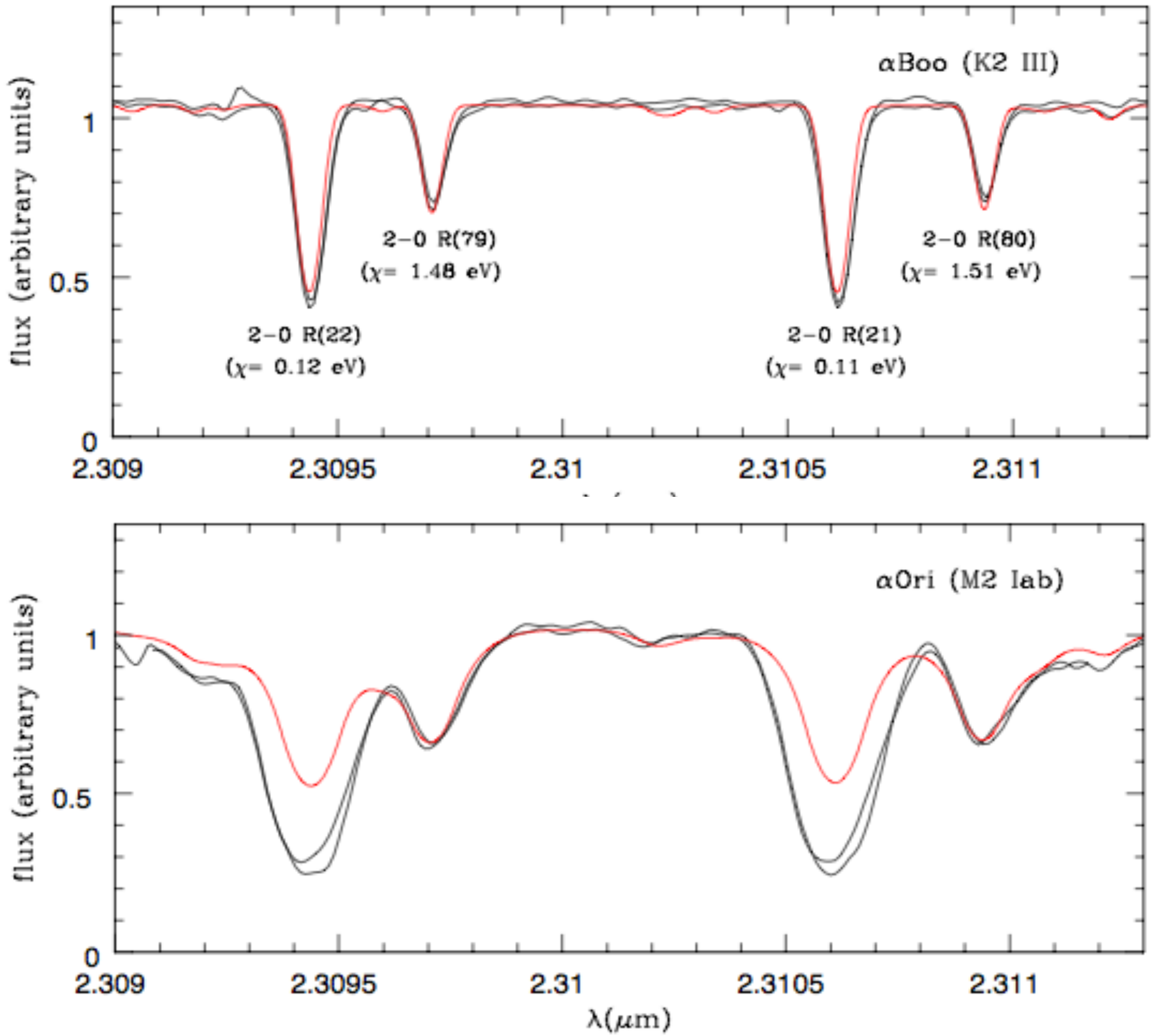
Observed spectra of M giants (Serote-Roos et al. 1996, A&AS, 117, 93)



Observed spectra of M giants (Serote-Roos et al. 1996, A&AS, 117, 93), and MARCS model spectra (from Alvarez & Plez 1998, A&A 330, 1109)

Some problems:

CO vib-rot lines in the K band -> circumstellar material, molspheres?



FTS spectra
Wallace & Hinkle
1996

MARCS model
spectra

Some limitations are intrisic to the methods

- We may improve opacities, input data, ...

BUT

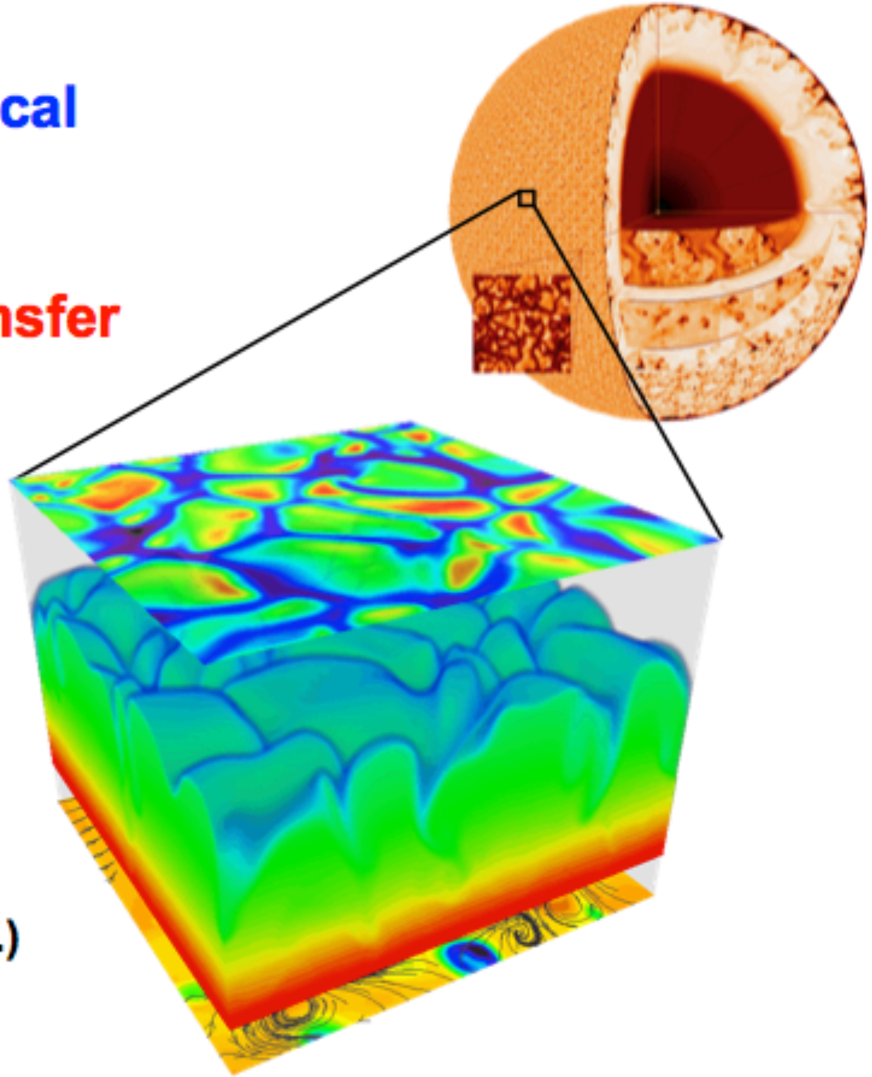
- LTE / NLTE
- 1D static / 3D dynamic
- ...

3D stellar atmosphere models

Ingredients:

- Radiative-hydrodynamical
- Time-dependent
- 3-dimensional
- Simplified radiative transfer
- LTE

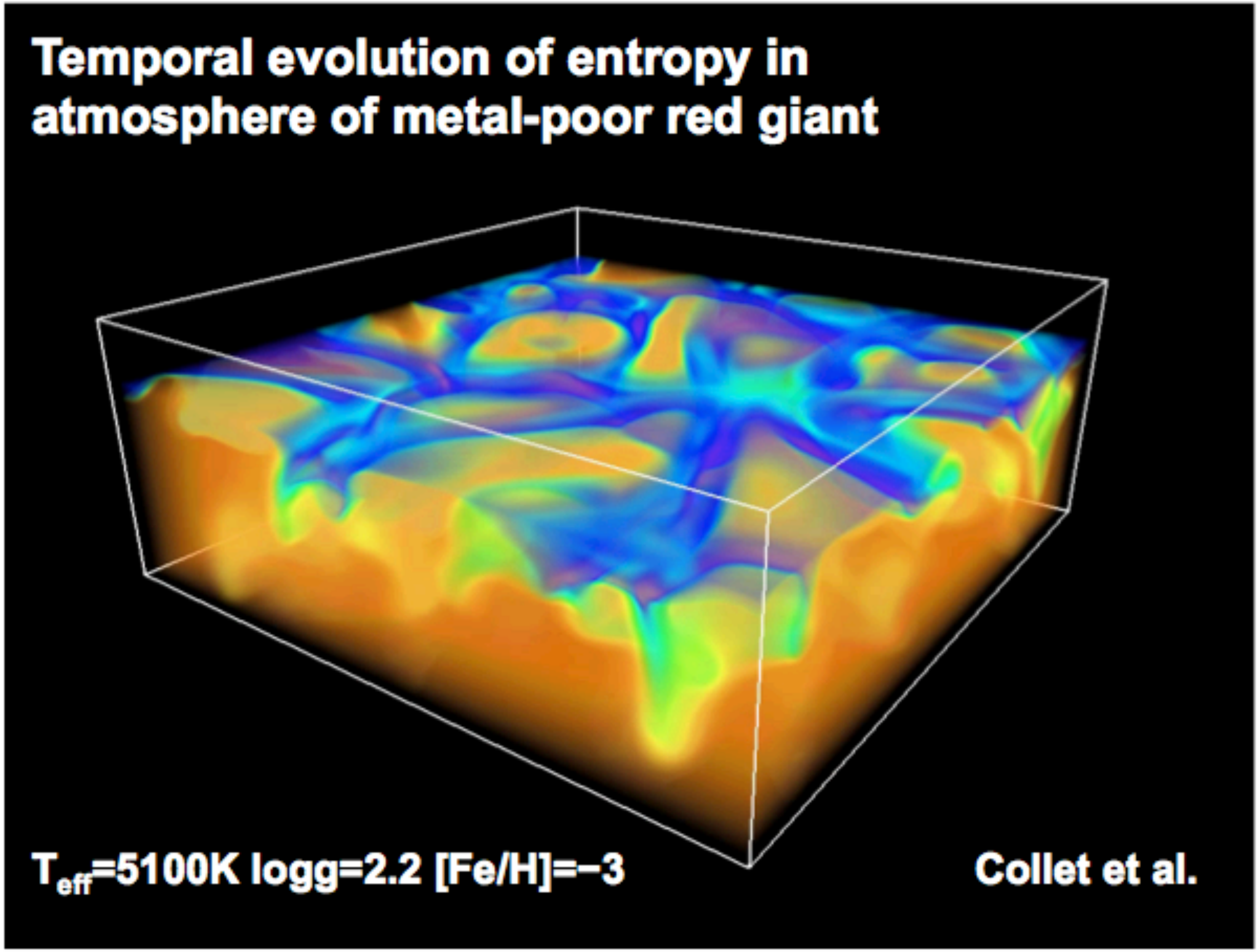
Essentially parameter free



For the aficionados:
Stagger-code (Nordlund et al.)
MHD equation-of-state (Mihalas et al.)
MARCS opacities (Gustafsson et al.)
Opacity binning (Nordlund)

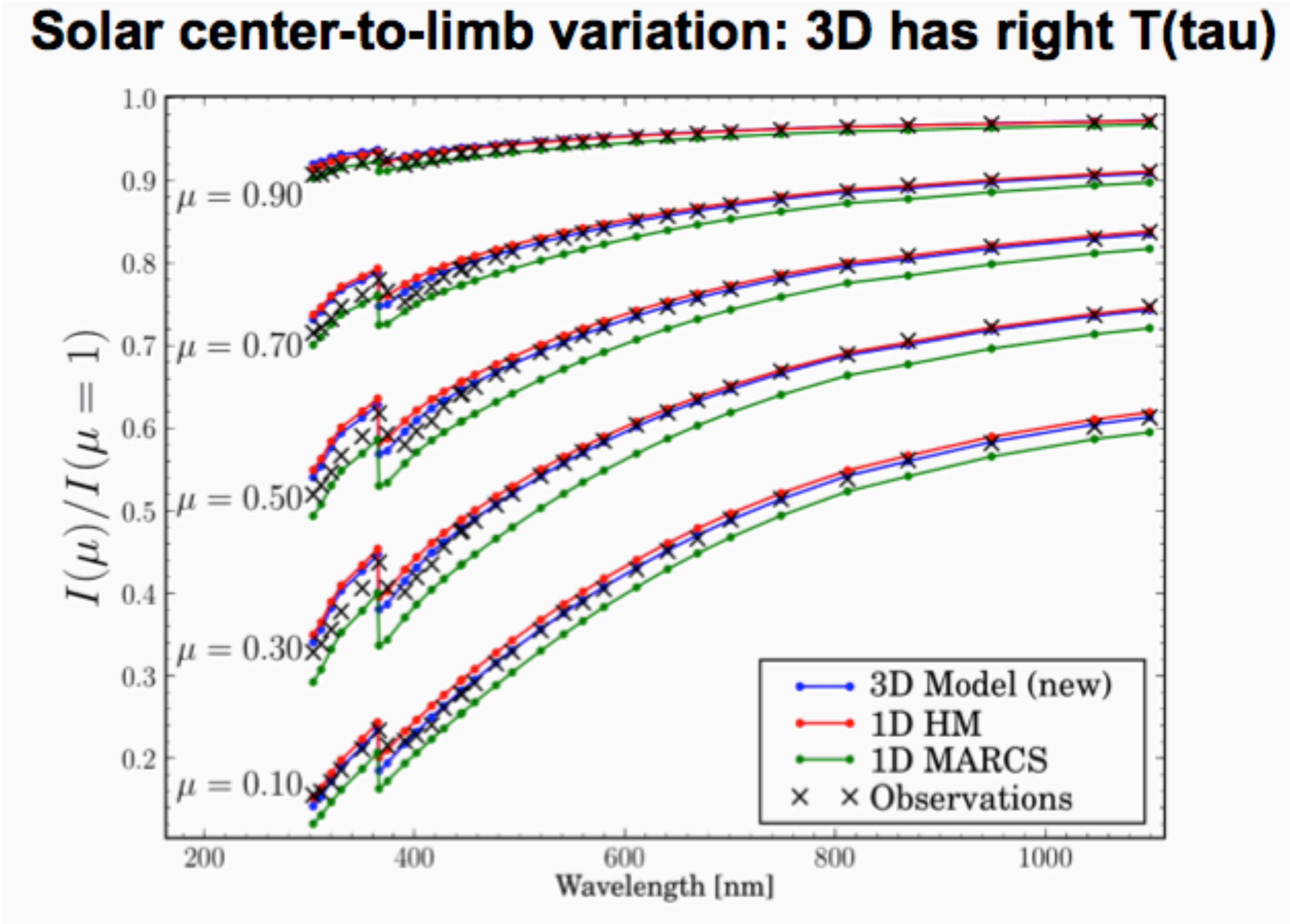
From Asplund

3D atmosphere simulation



From Asplund

Temperature structure



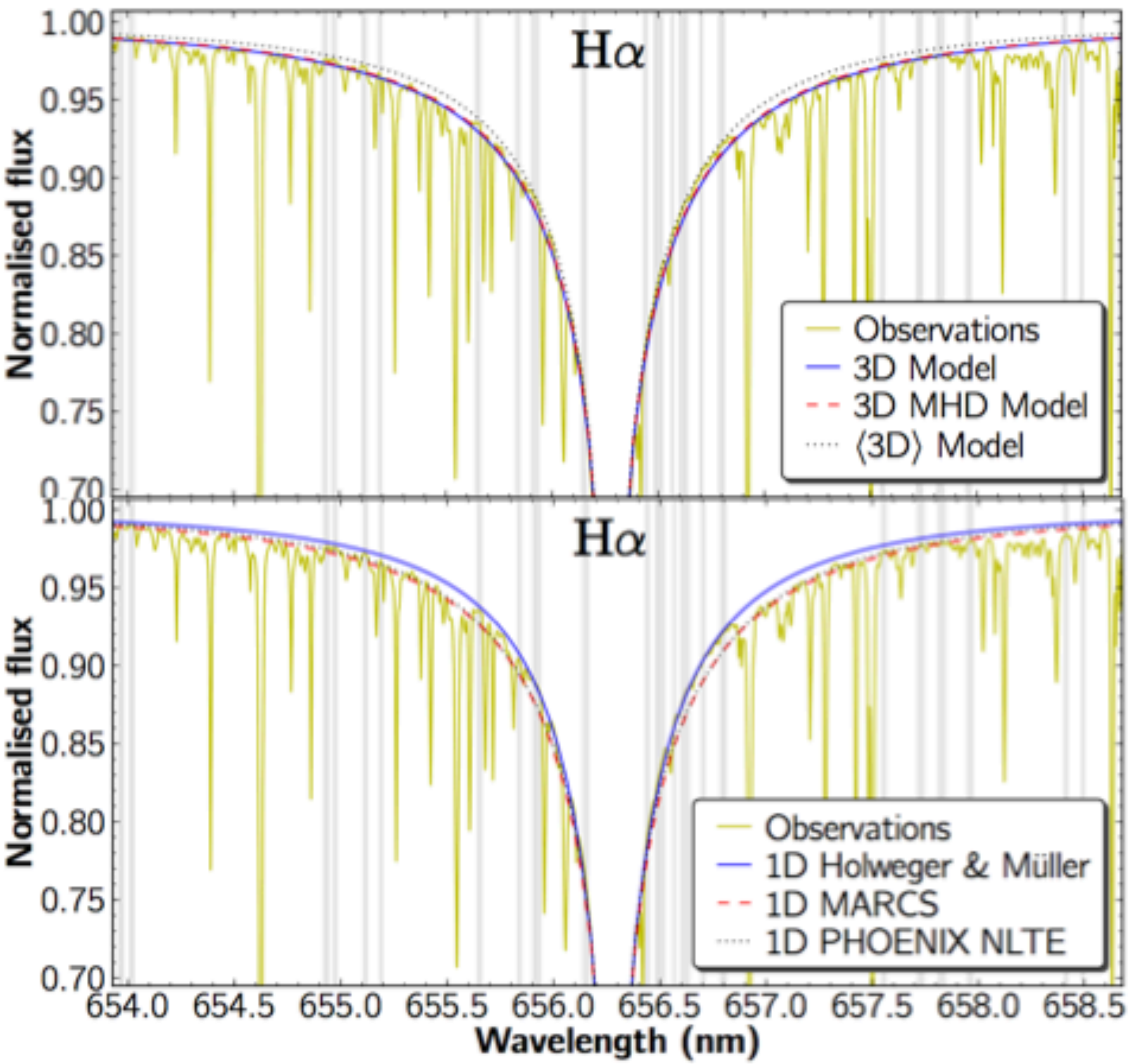
From Asplund

T_{eff} from H lines

Pereira et al. 2013:
Very good agreement for the Sun in 3D

~60K higher T_{eff} in 3D than in 1D

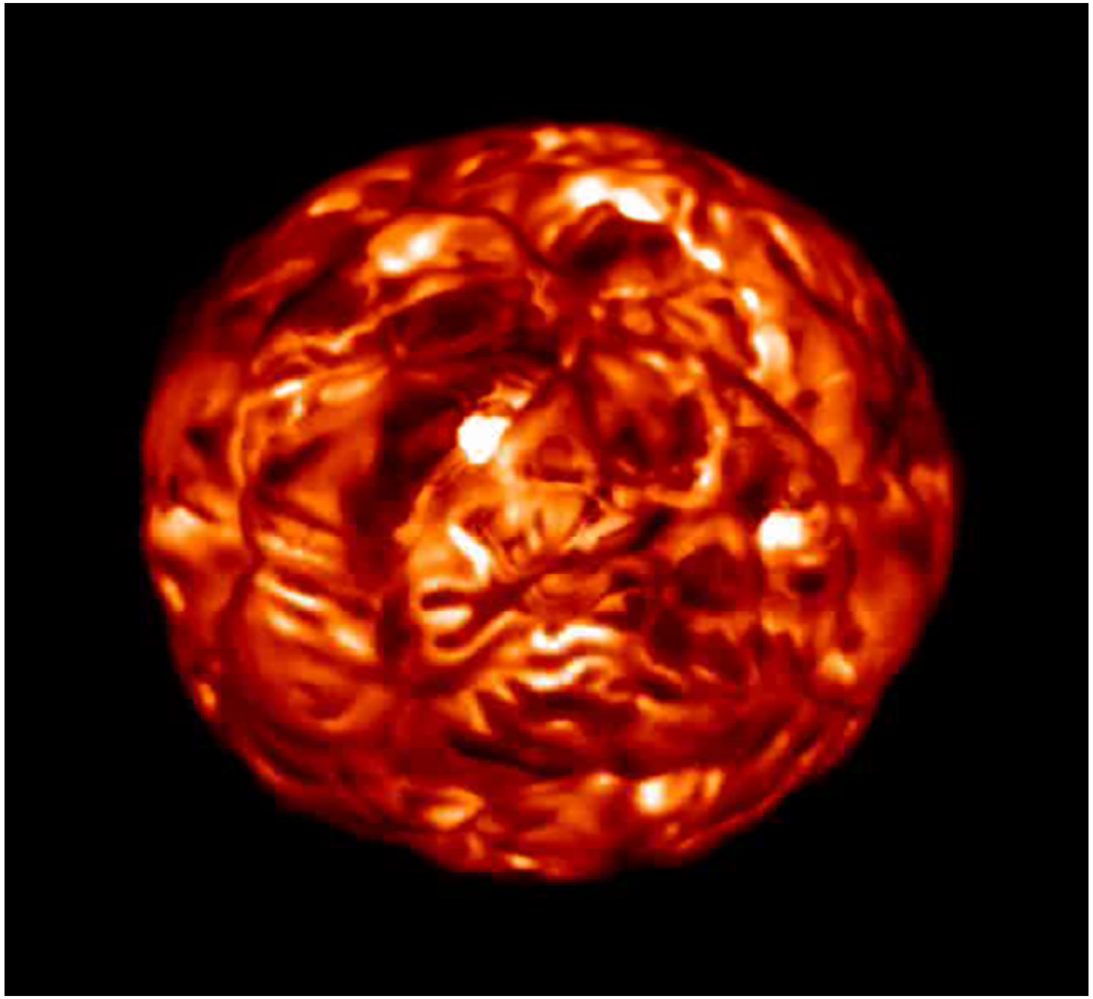
What about for other stars? Low [Fe/H]?



From Asplund

3D simulations of RSG

A. Chiavassa, B. Freytag, H.G. Ludwig, M. Steffen, B. Plez



Radiative hydrodynamics code (Co5bold, Freytag et al. 2002) :

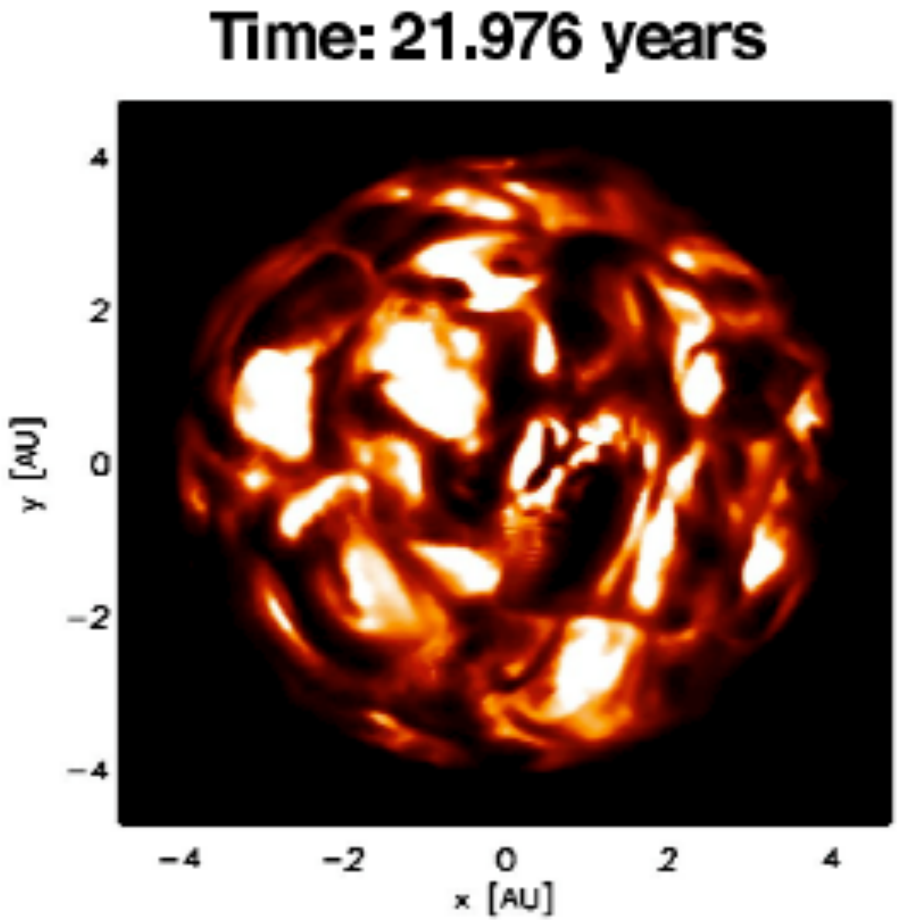
- “star-in-a-box” (cartesian)
- LTE radiative field (grey, or opacity binning)

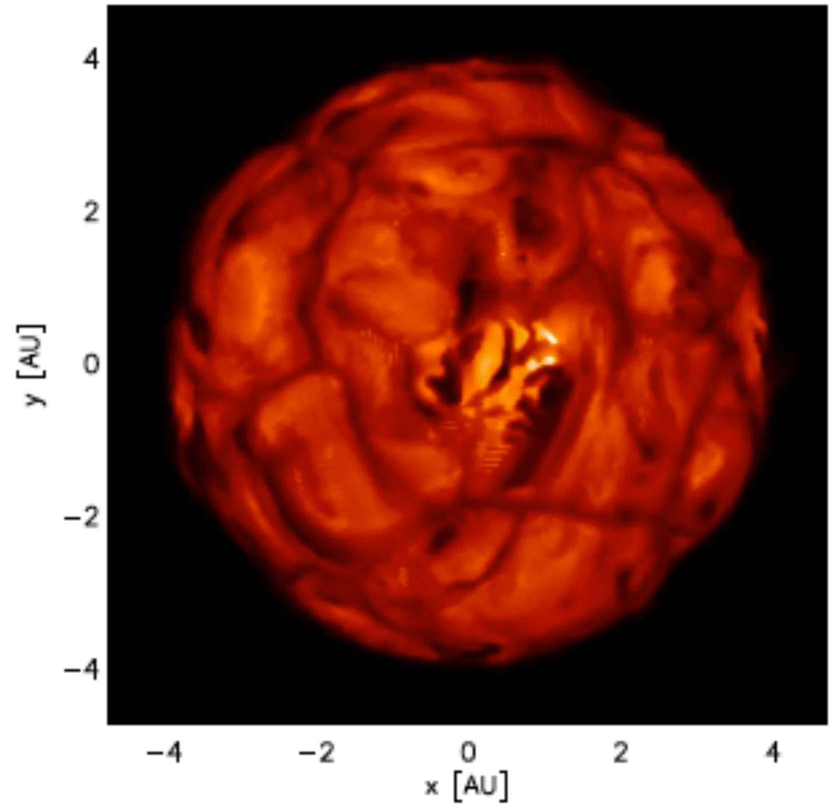
⇒ Large convective cells
⇒ Characteristic times = 1 month, 1year
⇒ Supersonic velocities

Numerical resolution max = 401^3

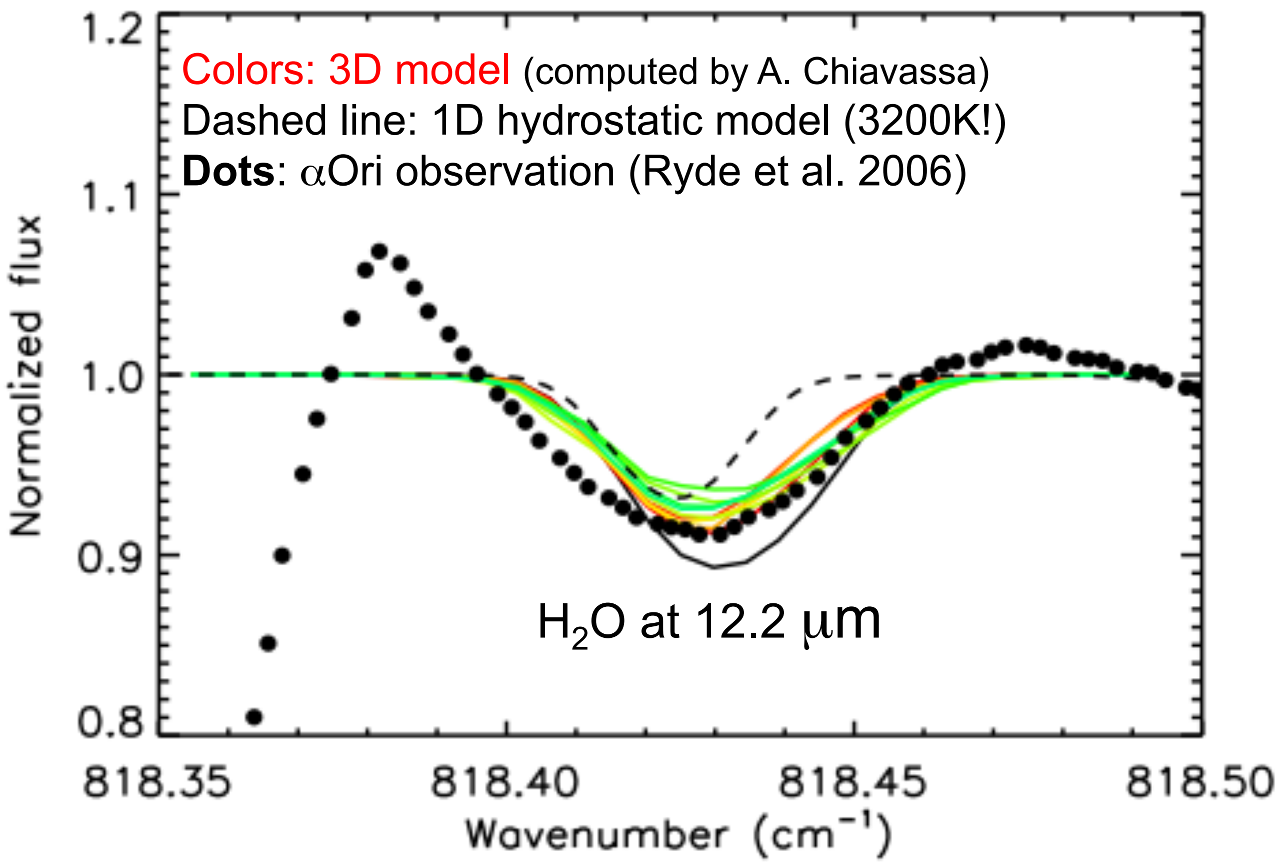
Optical vs. IR

Chiavassa et al. 2011 (Gaia G band vs. H band) : Grey model for Betelgeuse

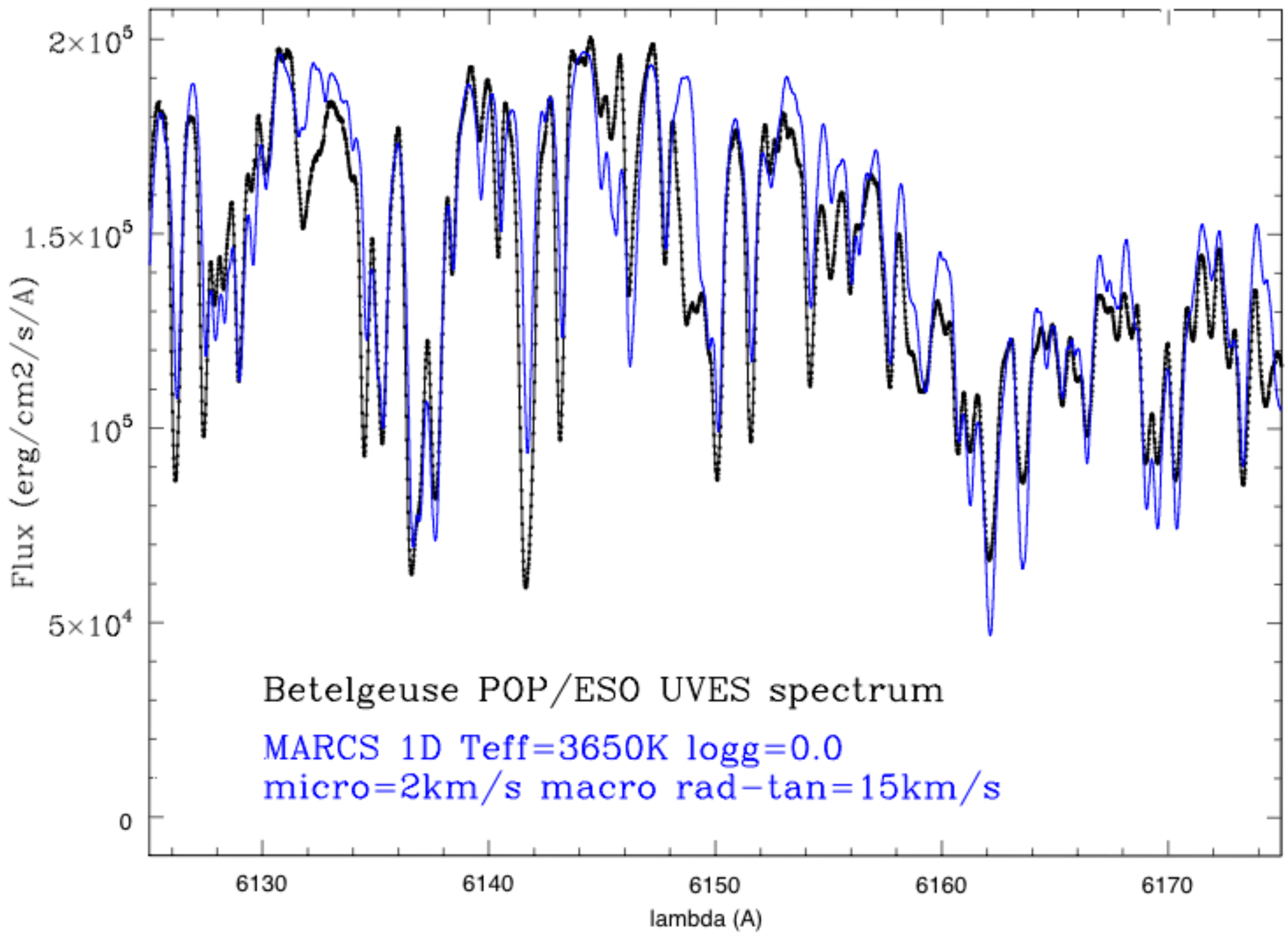




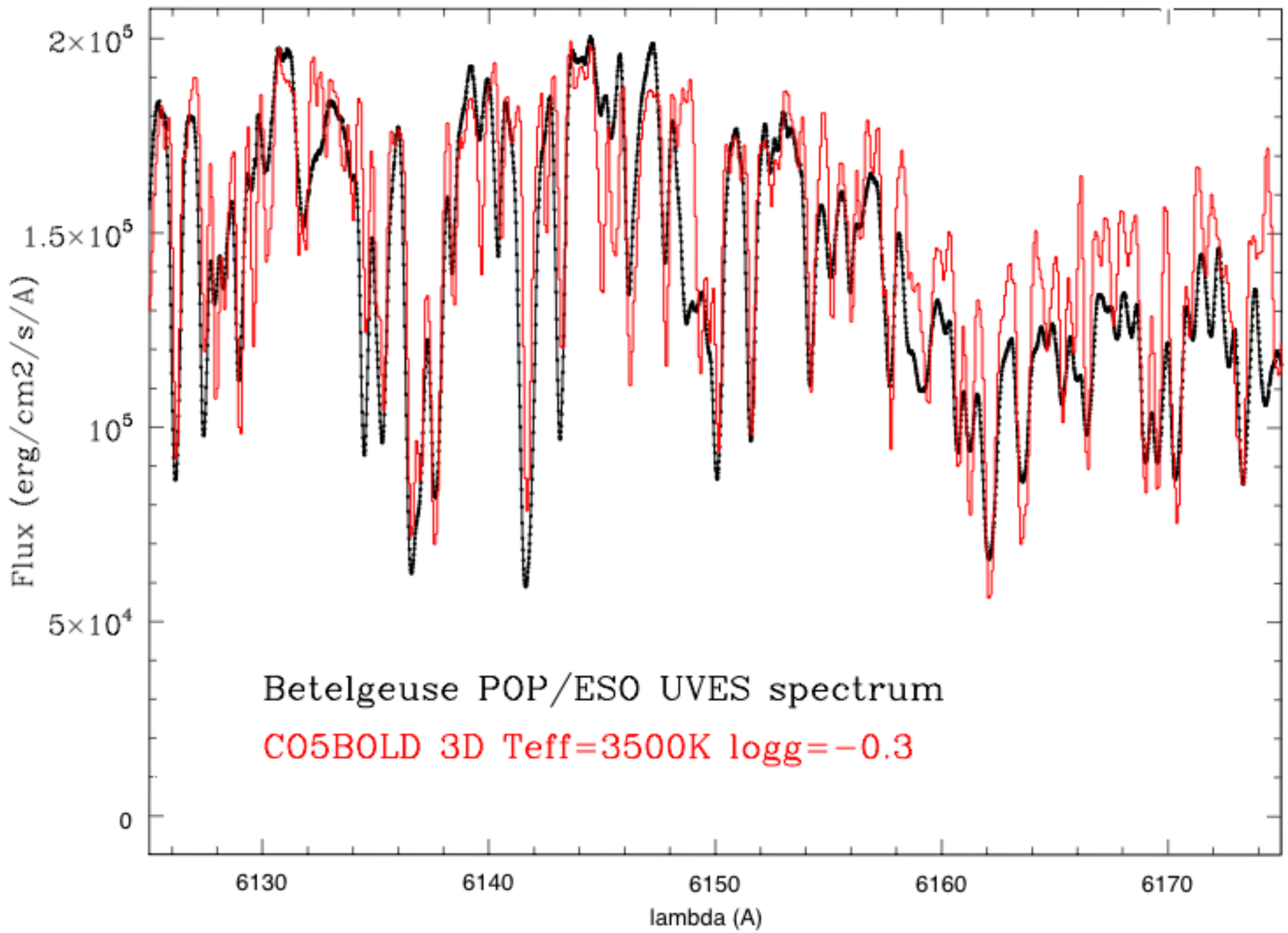
3D simulations **velocity field** and line broadening



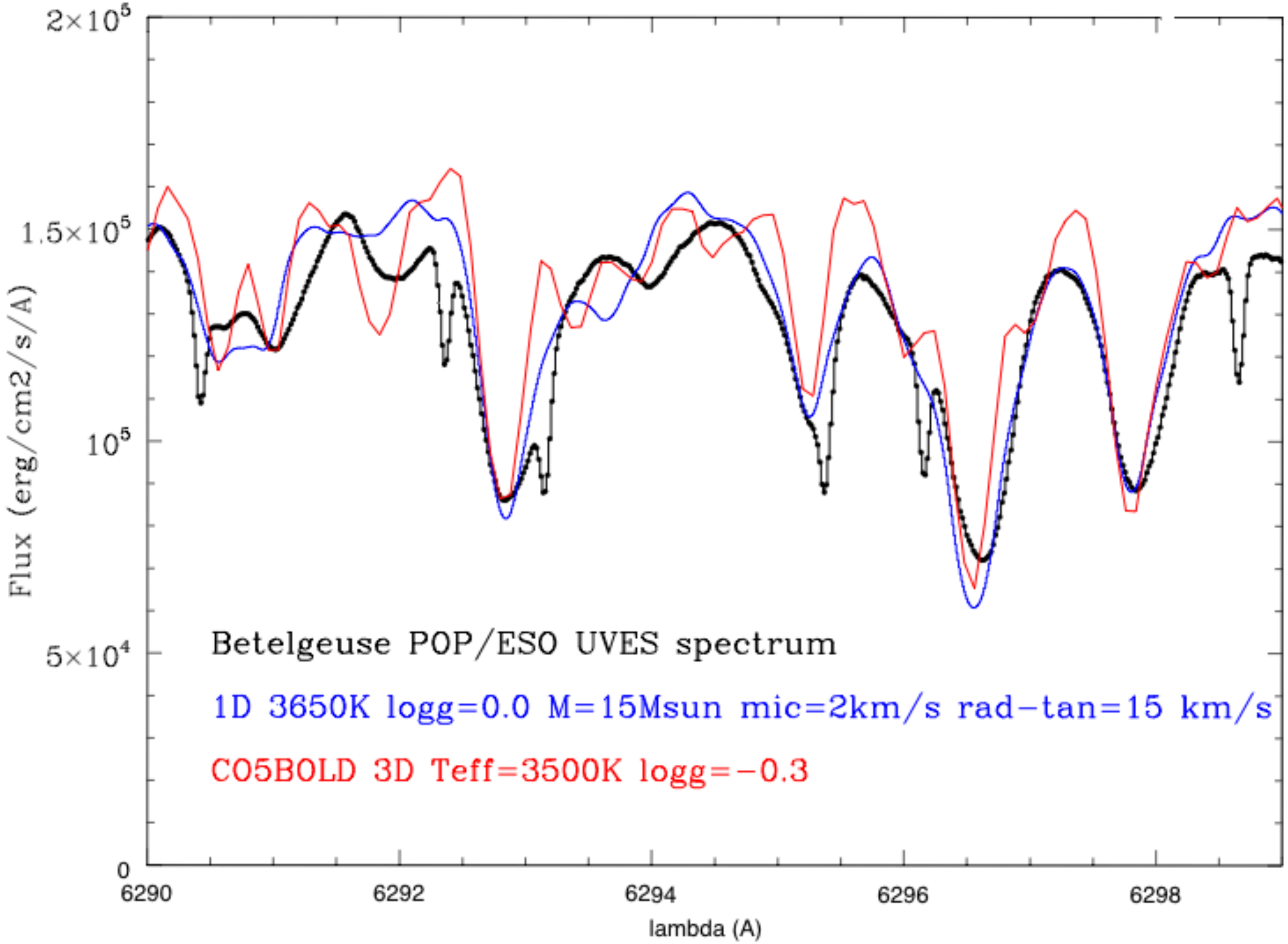
- Line **broadening and shift** are **predicted** by simulations
- Profiles are **asymmetric** and **vary** with time
- More observations are needed to (in?)validate models



MARCS 1D spectrum vs. observation of α Ori. Note Teff=3650K, and contrast of TiO band OK



Example of 3D grey model spectrum. Note **Teff=3500K**, and contrast of TiO band still too weak. (computed by A. Chiavassa)



Line widths: **3D** are slightly too narrow, but **1D** has **2 free parameters** : micro- and macro-turbulence.

(computed by A. Chiavassa)

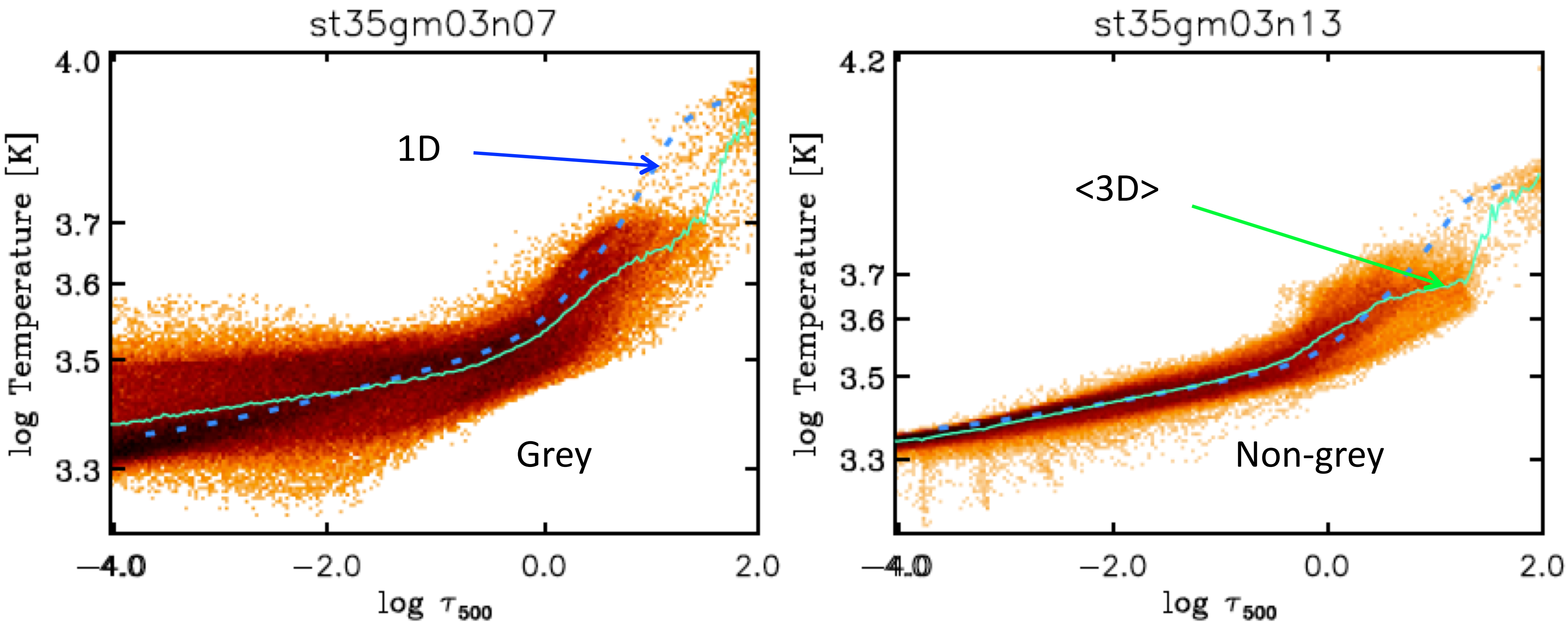
Problems in 3D simulations

- **T gradient** may be too shallow -> does not reproduce depth of all spectral features.
- **velocity dispersion** appears too small.

This **could be cured** by currently running generation of **non-grey models** (+ inclusion of radiative pressure?)

Also : prospects for mass-loss mechanism

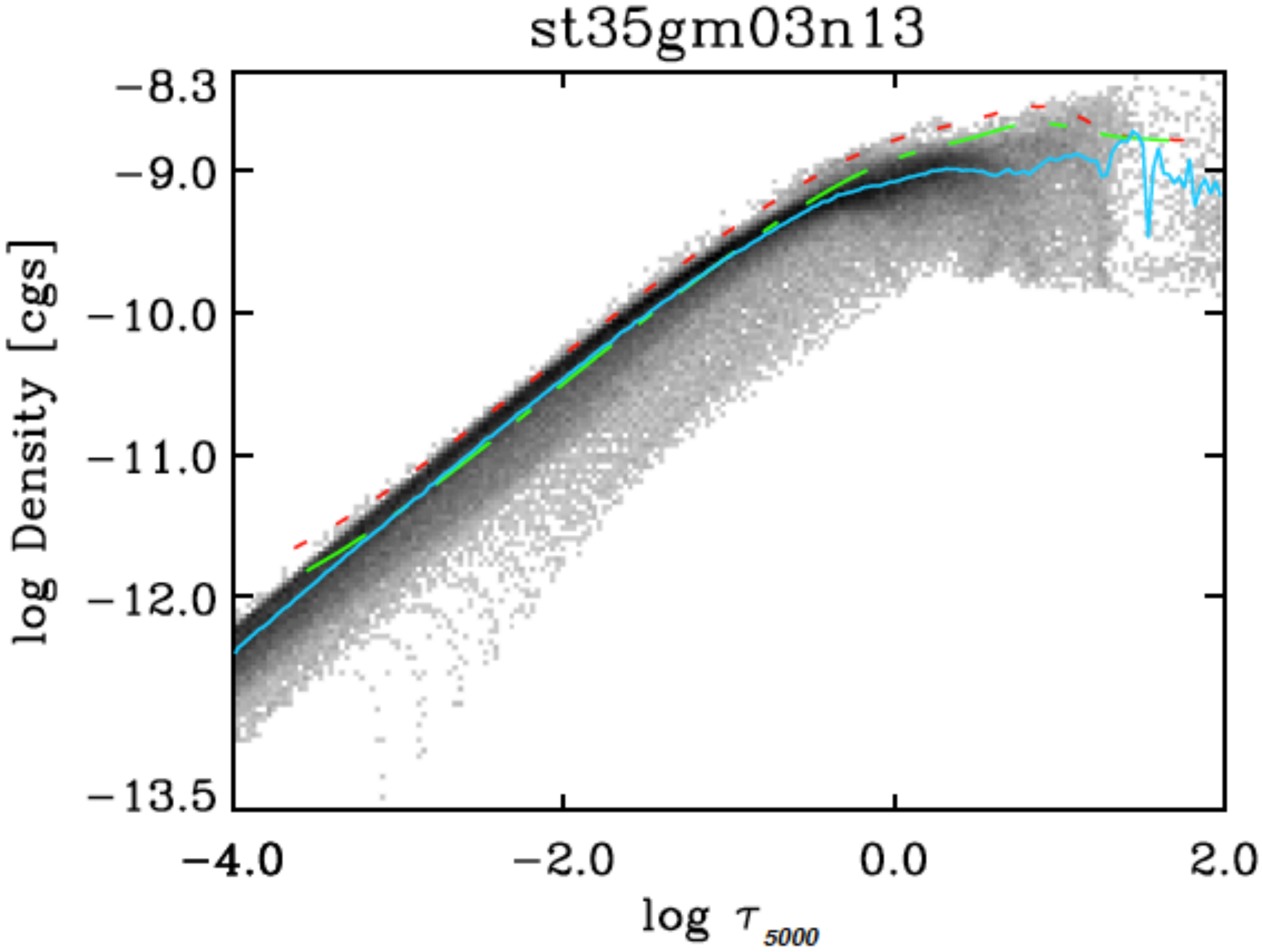
3D simulations; treatment of radiation field



Non-grey treatment (opacity bins) increases heat exchange between hot and cool regions -> closer to radiative equilibrium
Chiavassa et al. 2011

Non-grey 3D vs 1D: turbulent pressure

<3D> : 1D with g : 1D with g_{eff}=g-gradP_{turb}/ρ



1D vs 3D : some conclusions

classical 1D models account in **great detail for chromaticity of opacity and radiation** + radiation pressure, they include adequate data (opacities ...),
but too simple recipes for convection and turbulent pressure ($P_t=\beta.\rho.v_t^2$),
and 1D only! Real stars are not!

radiative-hydrodynamics 3D models
predict
- **v-field** -> line profiles (no micro and macro turbulence parameter)
- **T-inhomogeneities** -> spectrum and images (i.e. interferometry)

But they include a more approximate treatment of radiation.

=> 3D models must be further developed and recipes devised from them that can be used in simpler, cheaper 1D (or 2D?) models.

Models and stellar parameters

A 1D model atmosphere is defined by T_{eff}, g, M (or R, or L), and chemical composition

- $L = 4\pi R^2 \sigma T_{eff}^4$
- $g = GM/R^2$
- σT_{eff}^4 measures the flux per unit surface at a prescribed radius (e.g. $R(\tau_{Ross})=1$)
- The same radius is used for g

These are clear definitions.

What about observations?

Observations and stellar parameters

• **Spectroscopy** : T_{eff} and g from lines. But NLTE ! 3D effects ! Line-broadening theory ! Errors in models !

NB: line measurements to 1% -> **errors in analysis/models dominate**

• **Photometry / spectrophotometry** : in principle same problems; uses global information (spectral shape)

• **Interferometry** : what is the angular diameter ?! Real problem for red giants: wavelength dependency, limb-darkening, ... Must use models to derive diameter!! 3D, in principle better!

Use all and **check inconsistencies**!

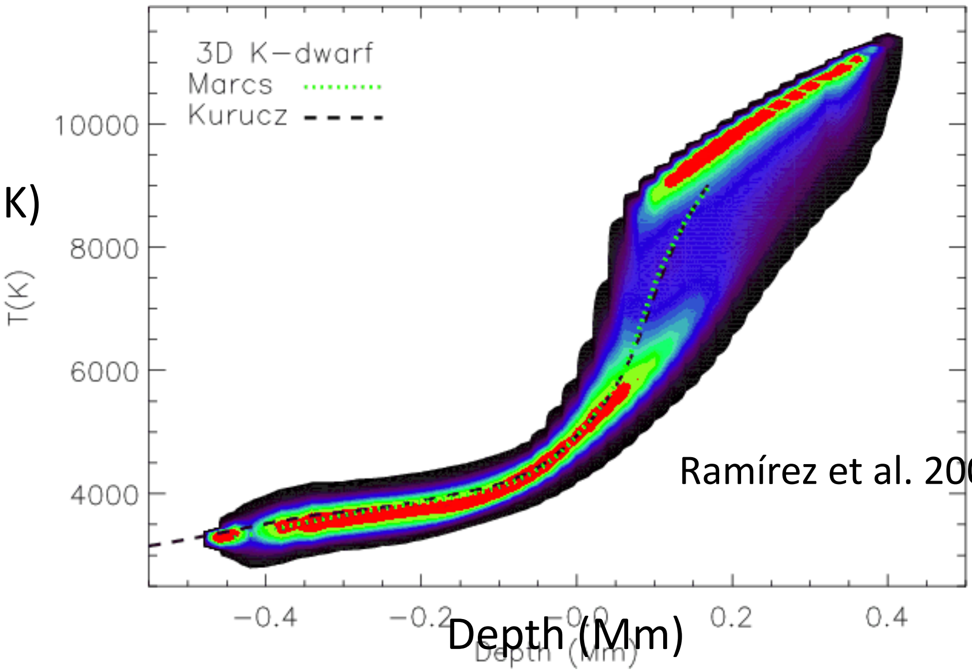
Absolutely calibrated fluxes very useful ! => $(R/d)^2 F_{mod}(\lambda) = f_{obs}(\lambda)$

To be remembered on T_{eff}

- T_{eff} is only a *measure of the average bolometric flux*.
- It does not have to represent some typical temperature in the photosphere.

There are fluctuations!

T(K)



Depth (Mm)

Ramírez et al. 2009, A&A, 501, 1087

- Flux comes from various depths, at different wavelengths.
- It may also come from different places on the stellar surface
- All this gets worse in **low gravity** stars, and in **low metallicity** stars

T_{eff}-scale of RSG : still debated

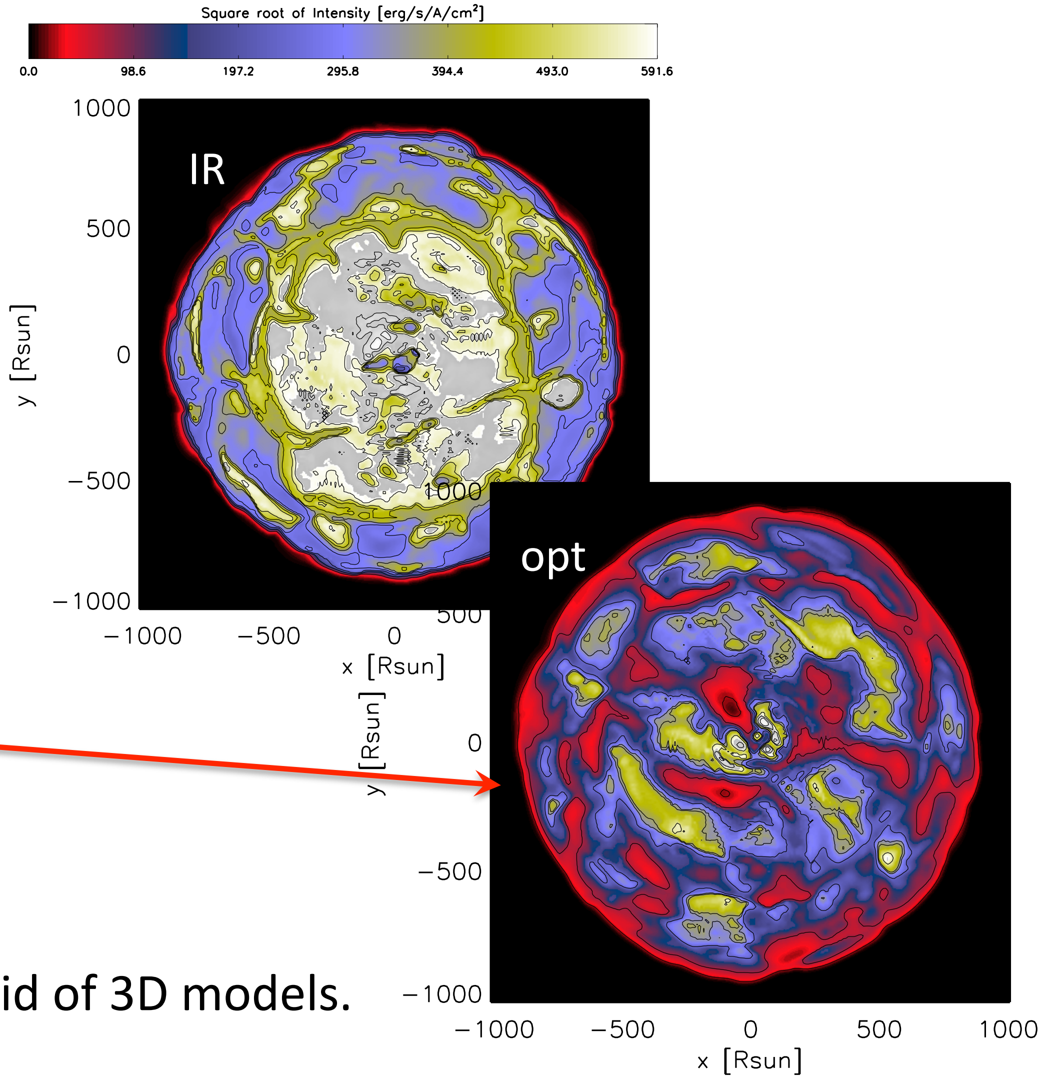
3D simulation (Chiavassa) :

L = 89000 Lsun, R = 850 Rsun
=> Teff=3450K

Fit of SED with 1D MARCS model
=> T_{eff} = 3700K

$\mathbf{4\pi R^2 \sigma T_{eff}^4 = 121000 \neq 89000}$

Inhomogeneities !



98% of the flux emitted by 75% of the surface

Will be further investigated on a grid of 3D models.

Thanks for your attention !

I hope this was useful

Questions or comments?