Cool stars model atmospheres for Gaia : MARCS, PHOENIX and ATLAS

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LABORATOIRE UNIVERS & PARTICULES MONTPELLIER

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

work well for most cool stars.

Many successes (Teff-scales, abundances, ...)

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 request

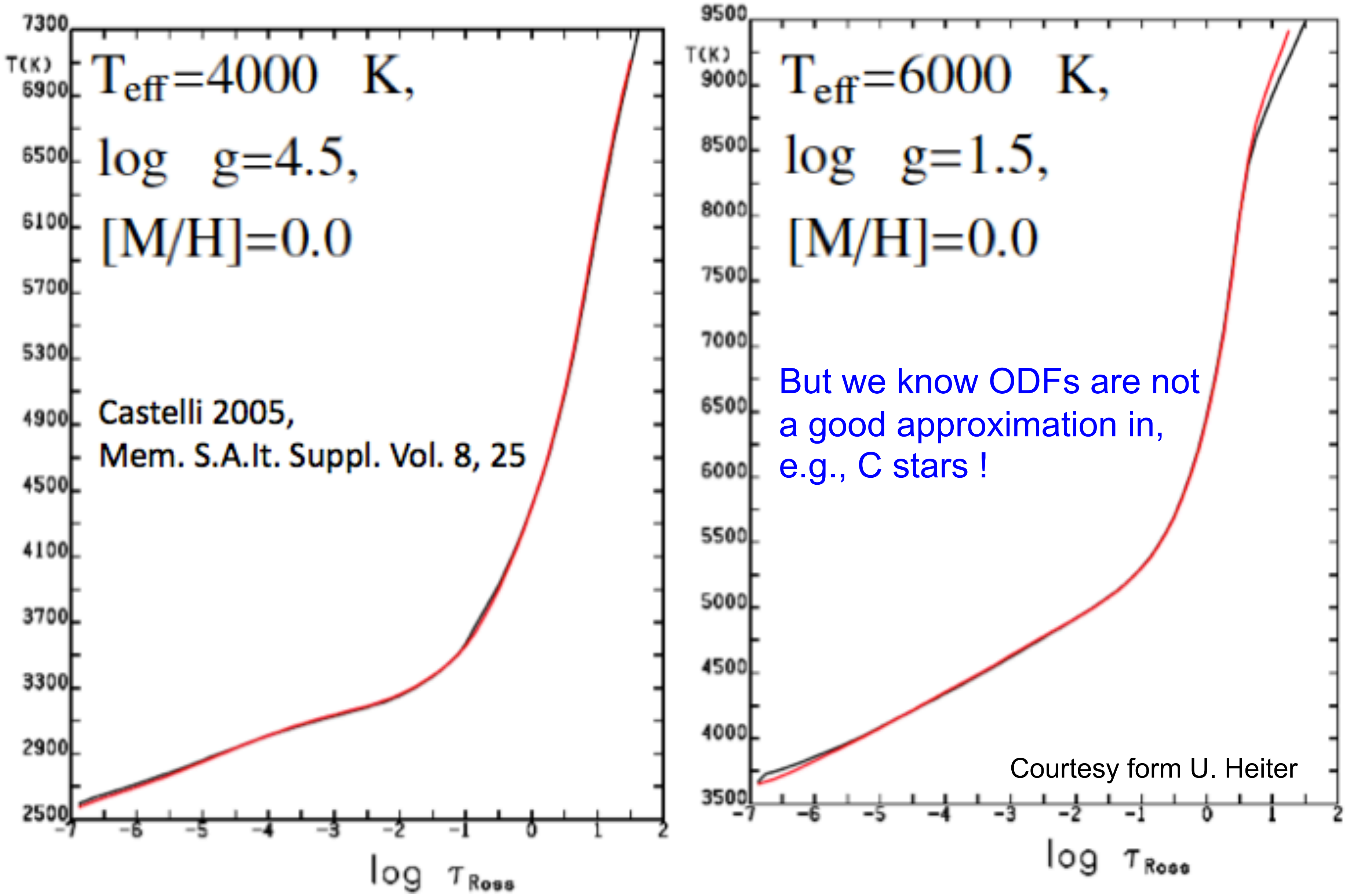
ATLAS

- 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

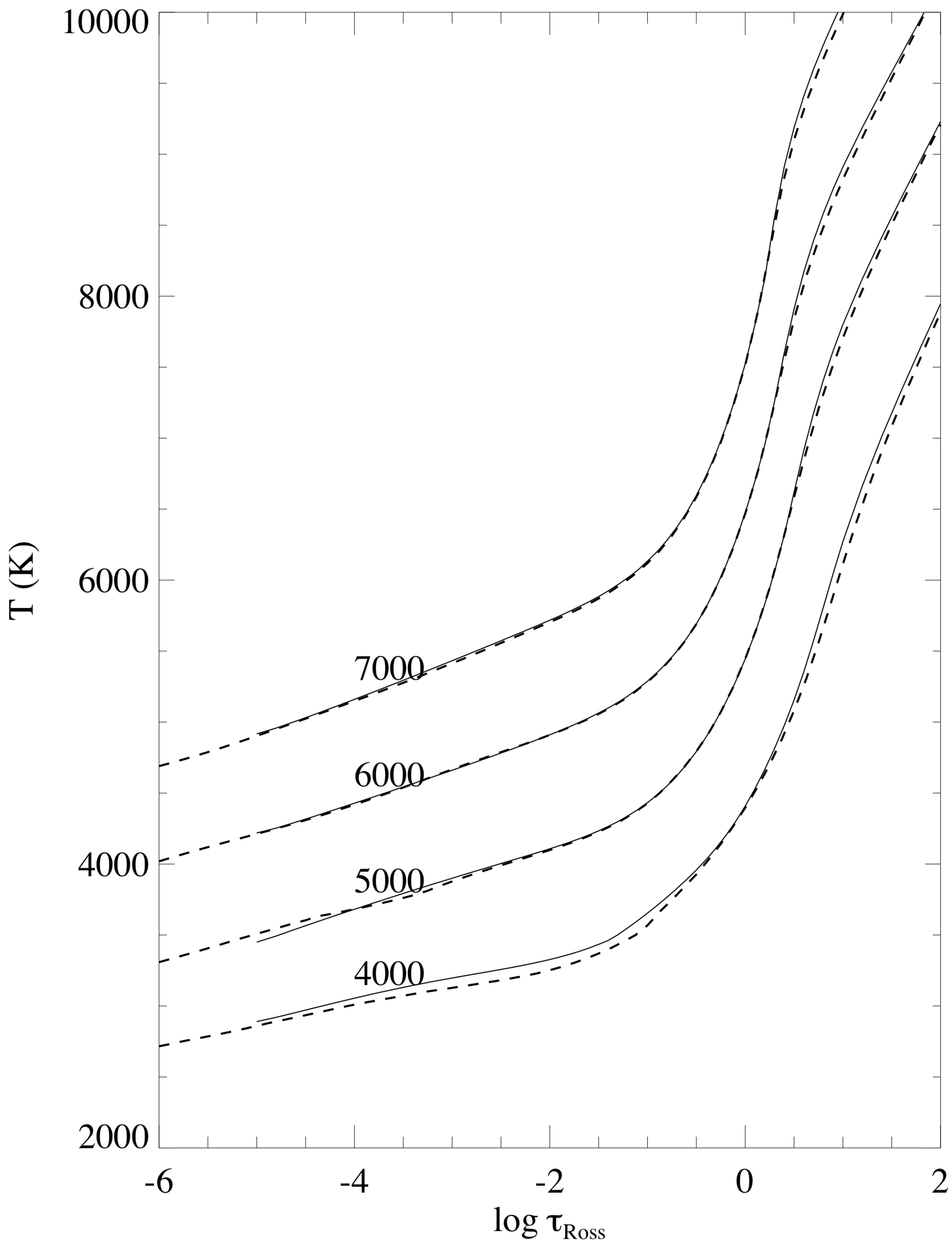
PHOENIX

- P. Hauschildt, F. Allard, et al.
- More versatile code, here only its 1D LTE version
- Extensive line data, also for very cool stars, but number of sources different from MARCS
- See Peter's talk this morning!

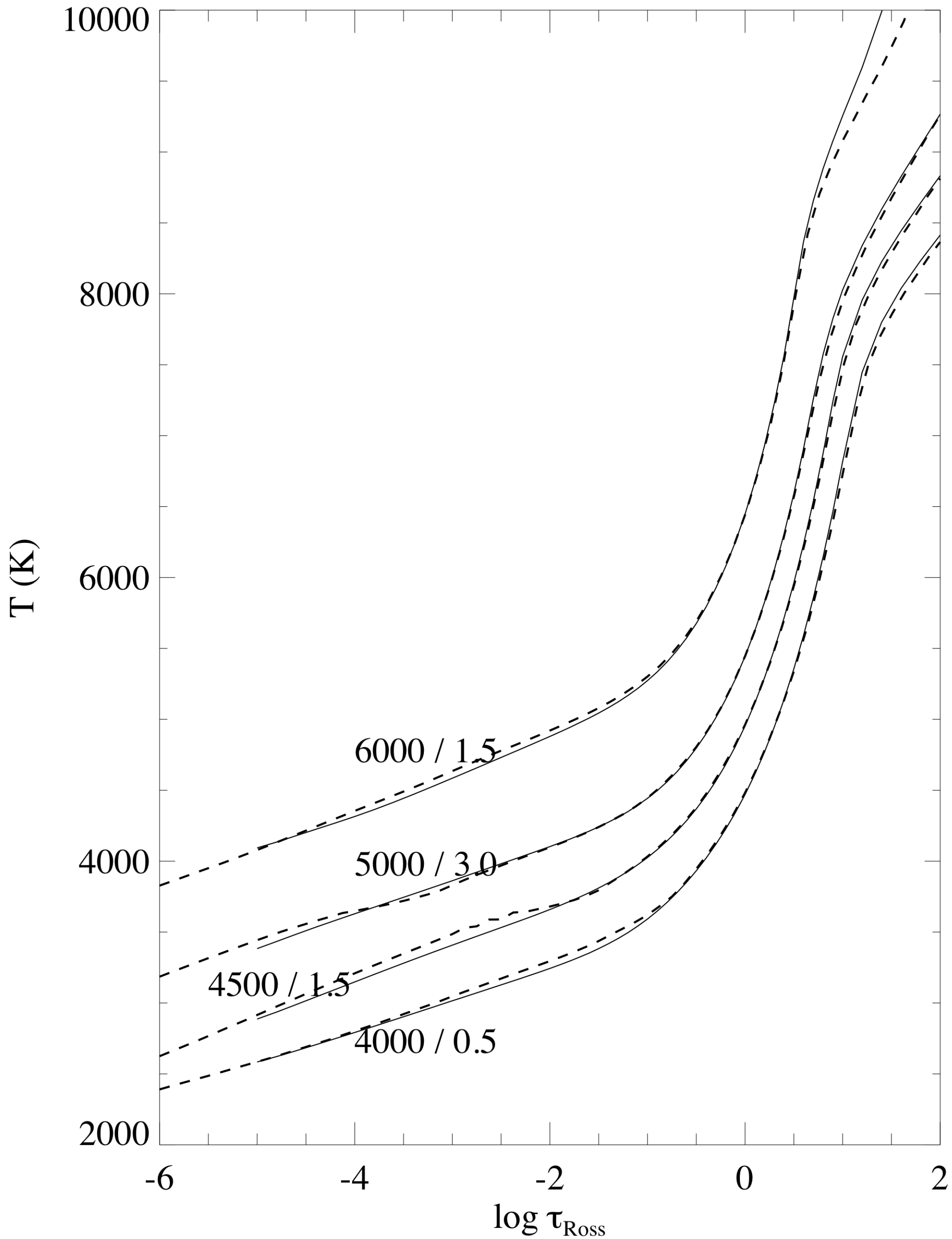
ATLAS9 vs ATLAS12



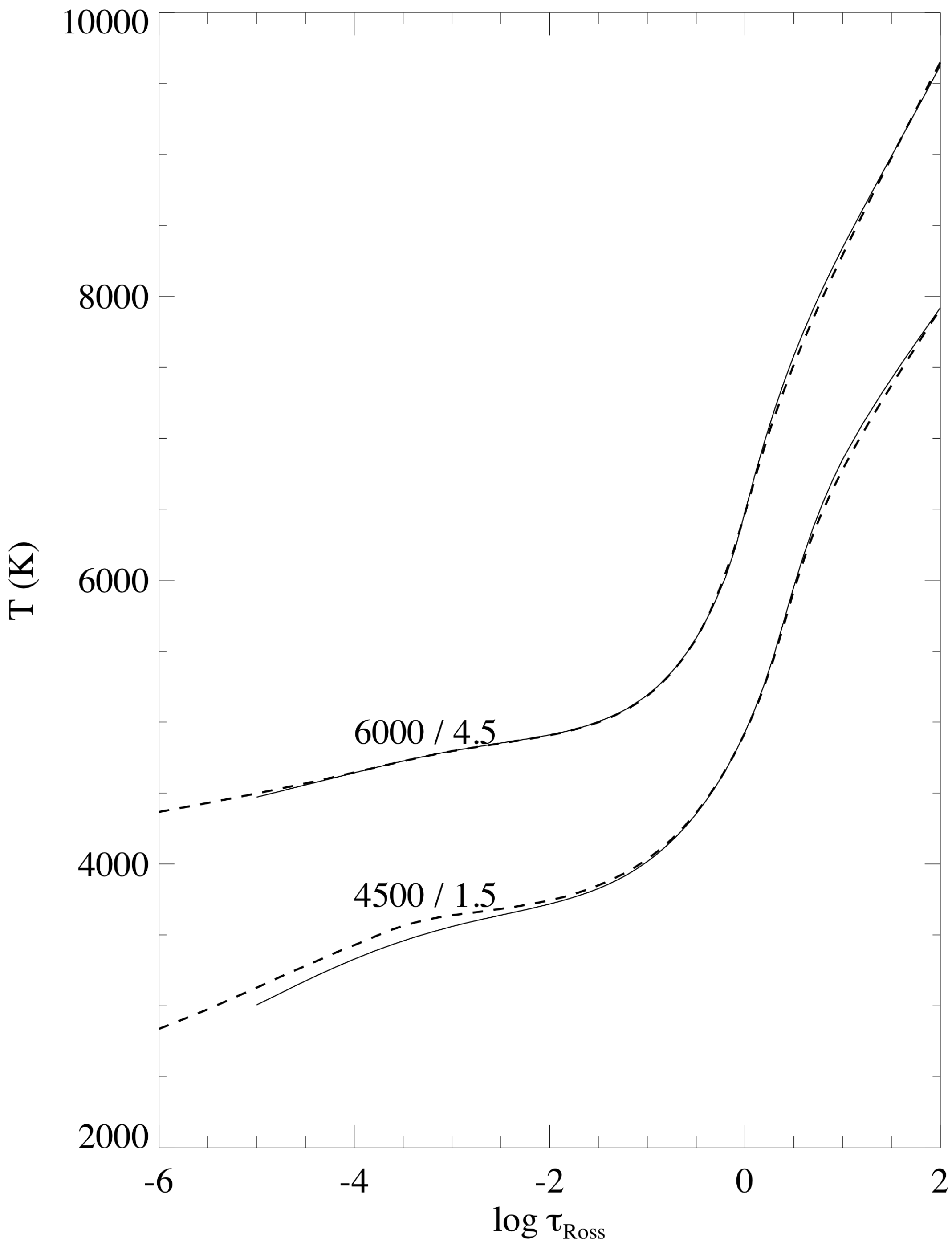
MARCS vs. ATLAS ODFnew, logg=4.5, solar comp



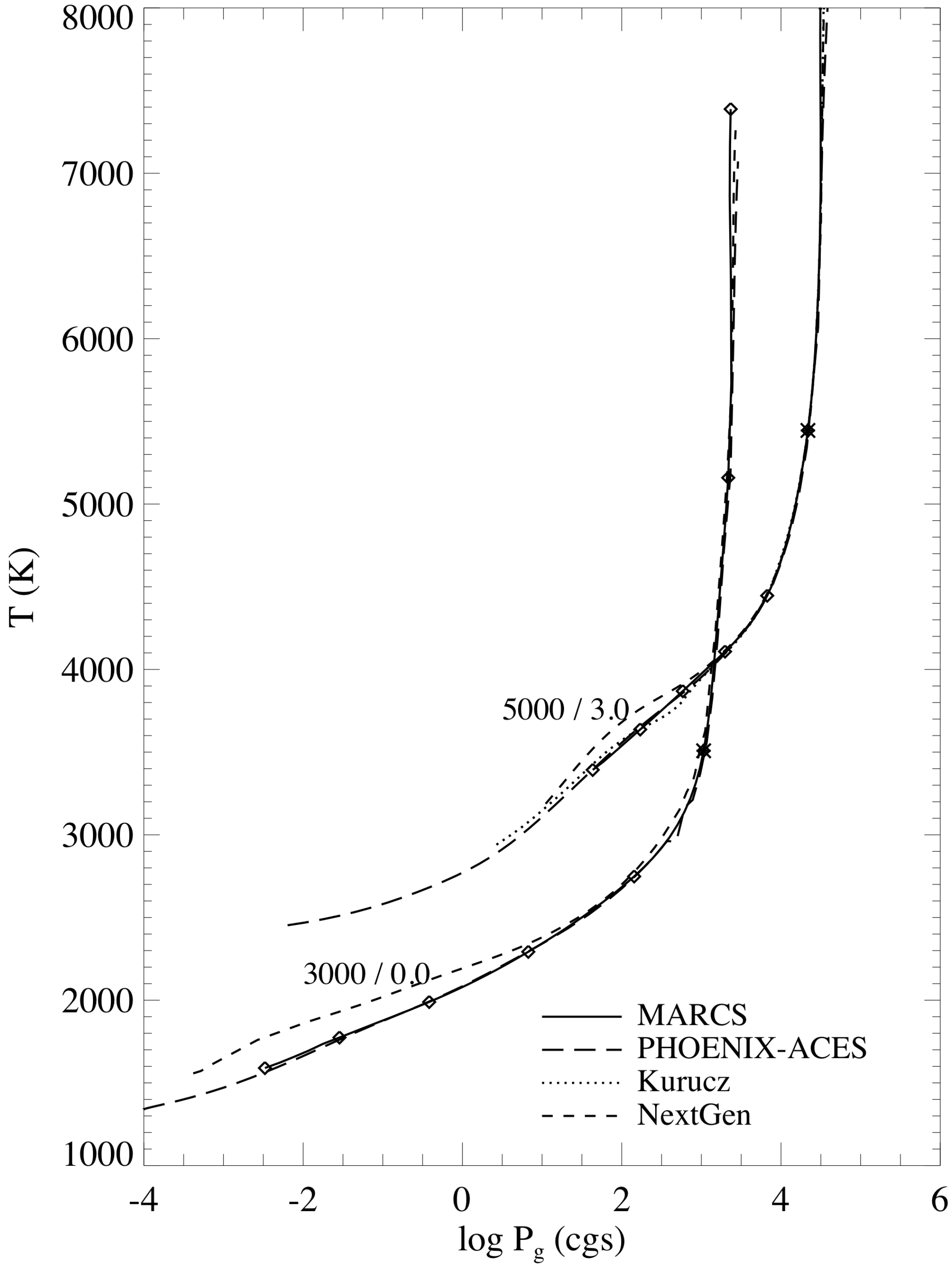
MARCS vs. ATLAS ODFnew giants and SG



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



MARCS + PHOENIX (Sph) ATLAS (PP)



Some limitations are intrisic to the methods

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

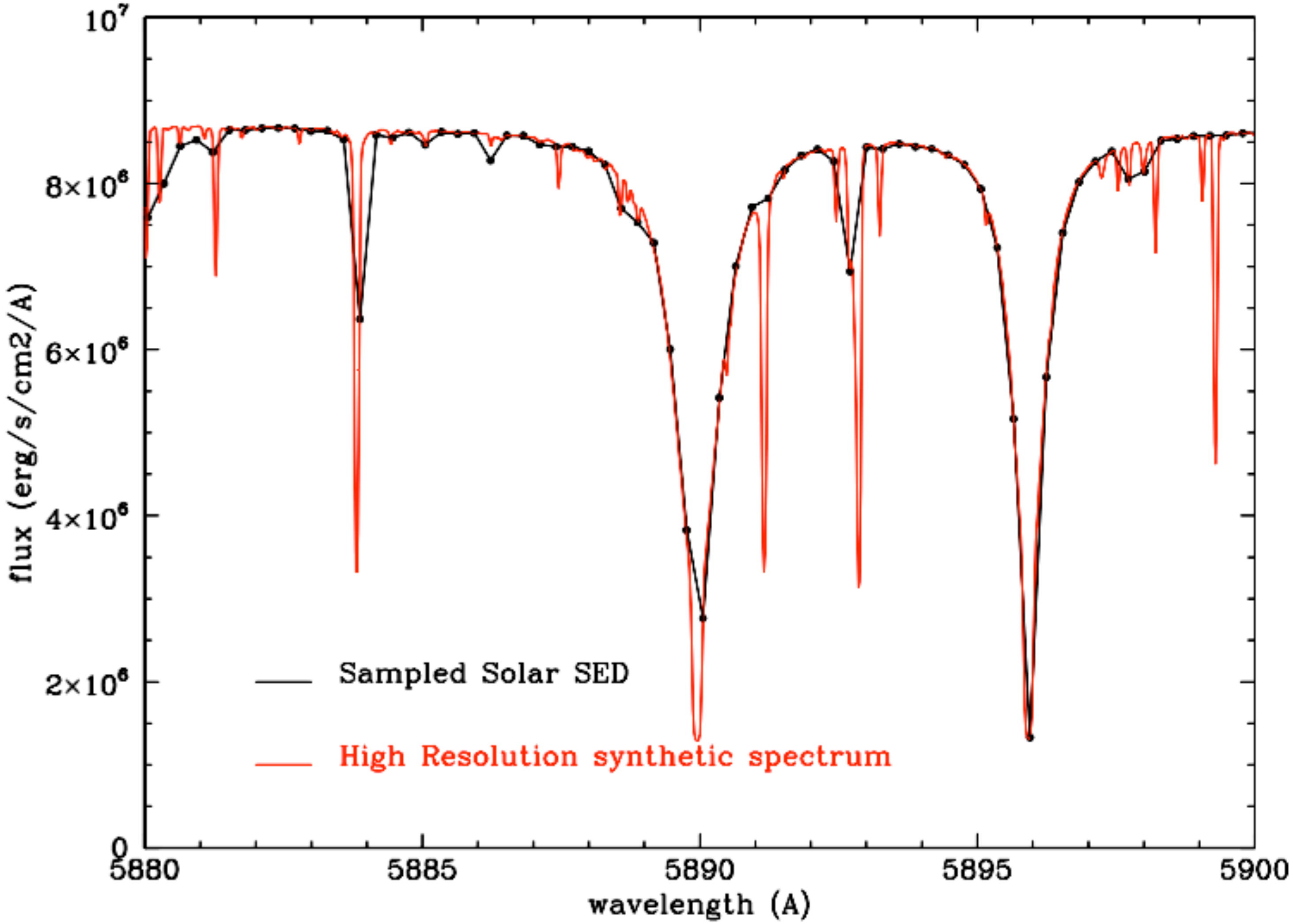
BUT

- Sampling : number of points
- LTE-NLTE (see Bergemann & Collet this morning)
- 1D-3D (idem)

Sampling of opacities and fluxes

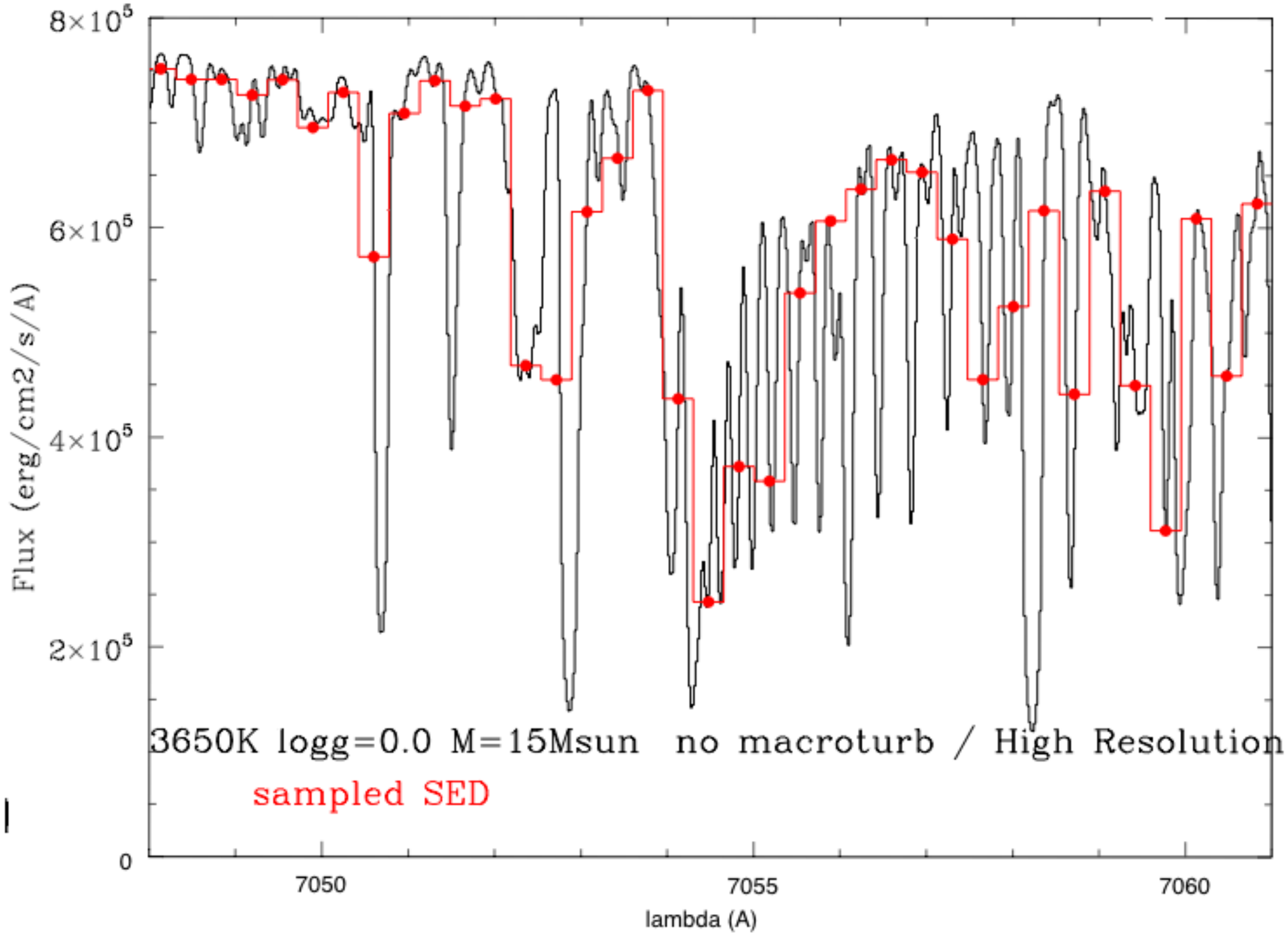
- OS: Monte Carlo evaluation of the radiation field using a set of wavelengths
  - **how many** are needed for a given **convergence** criterium (e.g. ΔT=1K) ?
  - Other concern: **how well** is the **spectrum** represented (e.g. to compute photometry) ?

Sampling of opacities and fluxes (2)



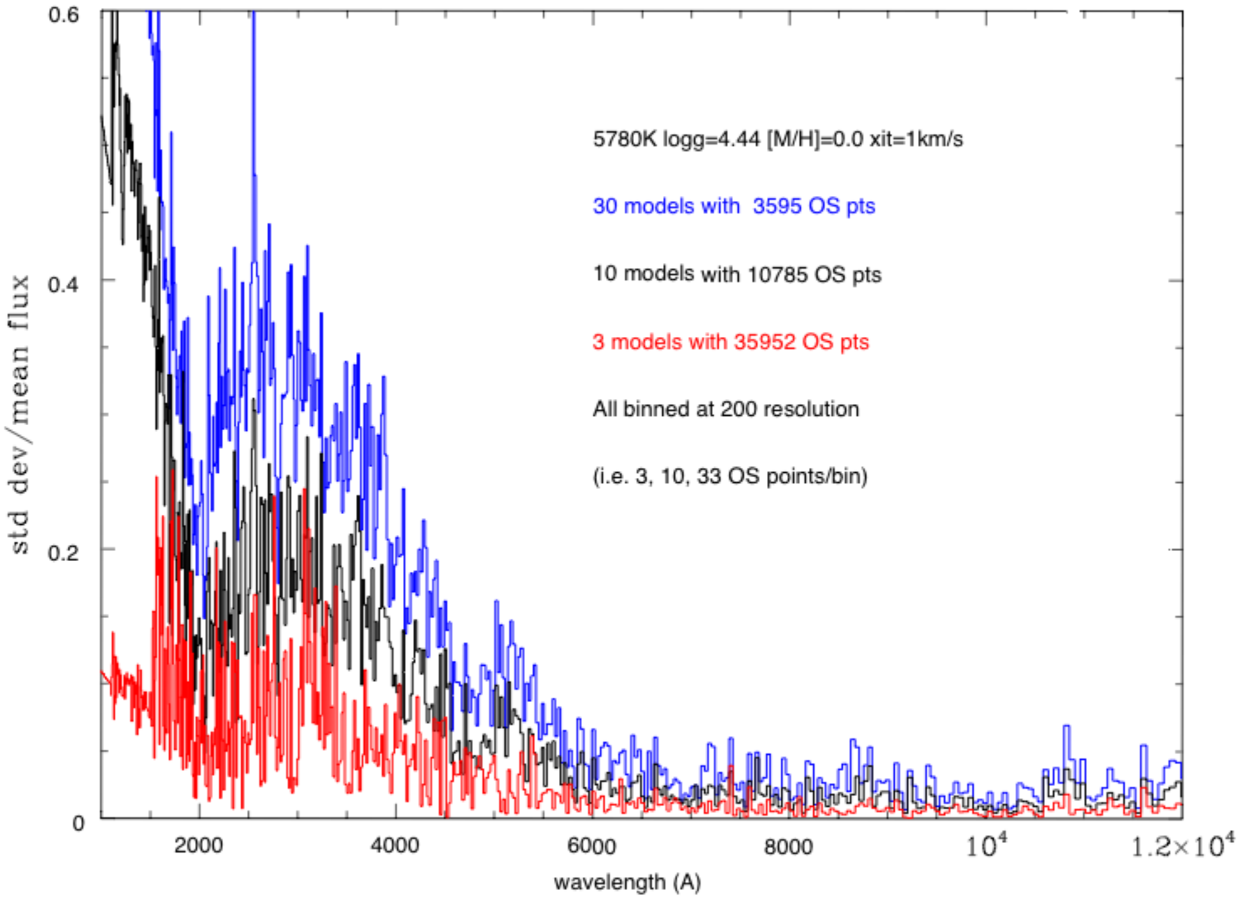
A sampled SED **is not** a high resolution spectrum smoothed to lower resolution !

Sampling of opacities and (S)SED (1)



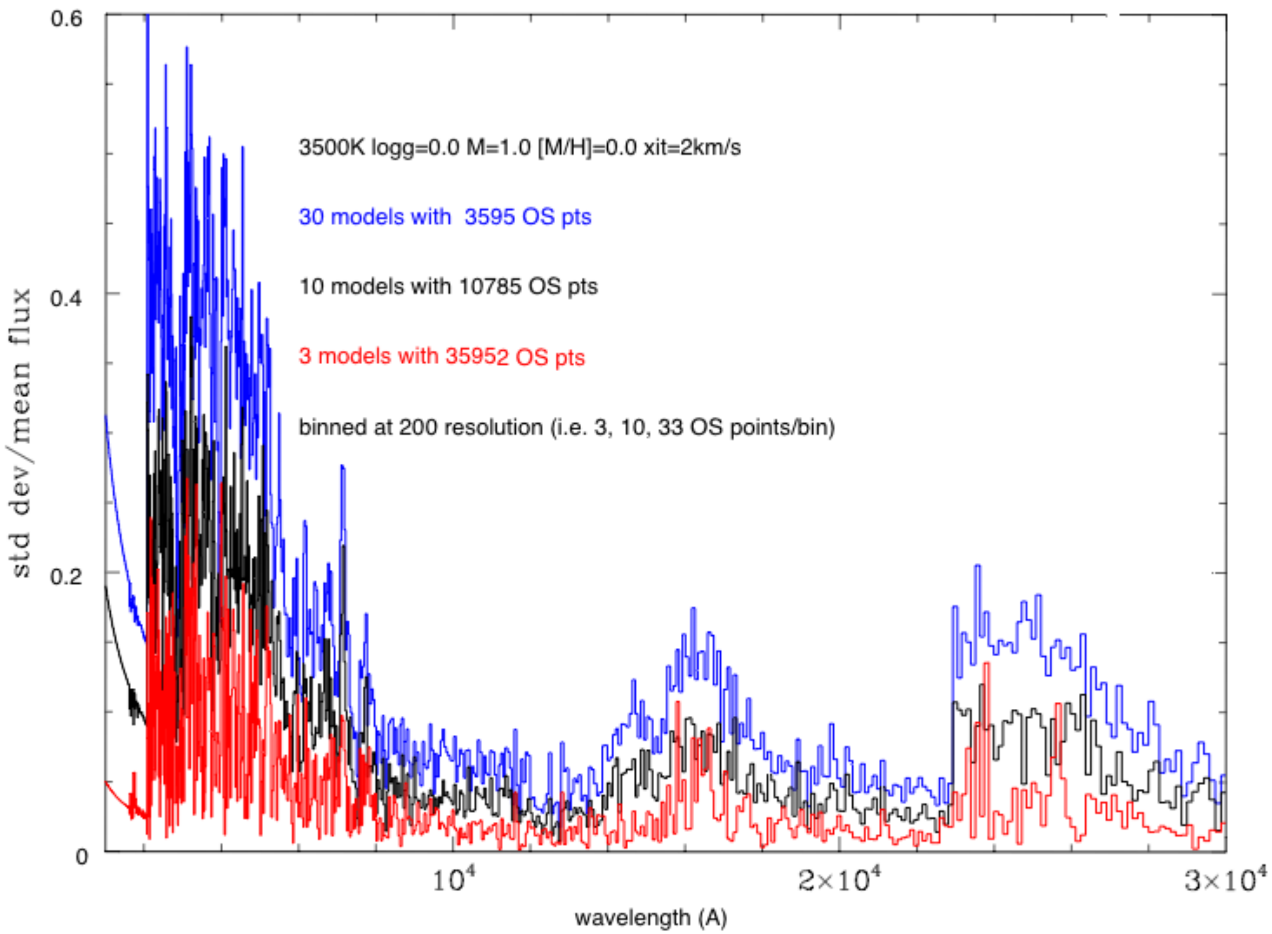
A sampled SED compared to a high resolution spectrum

Sampling of opacities and fluxes (3)



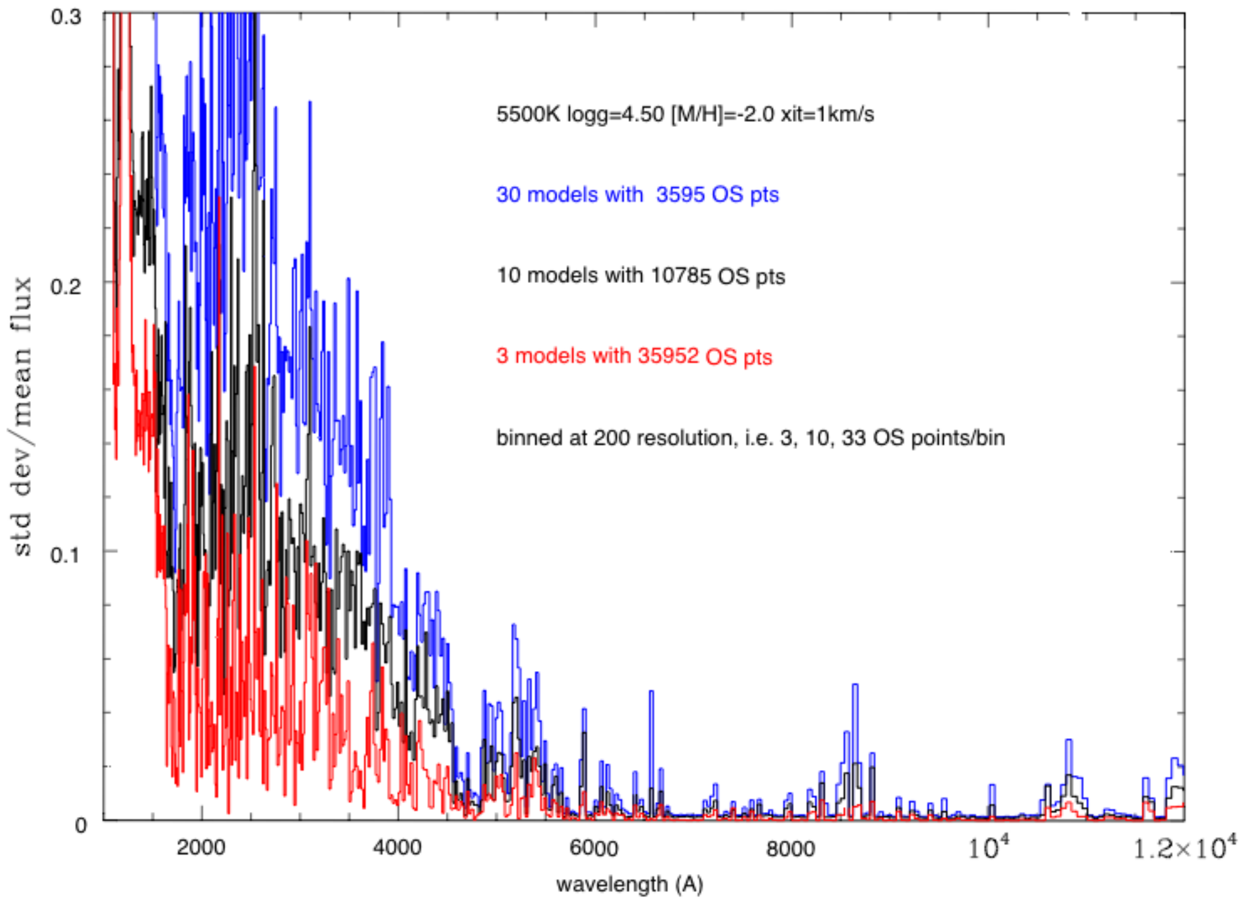
Sampled SED fluctuations with the number of OS points : solar model

Sampling of opacities and fluxes (4)



SED fluctuations with the number of OS points : 3500K giant

Sampling of opacities and fluxes (5)



SED fluctuations with the number of OS points : 5500K Fe-poor dwarf

Sampling of opacities and fluxes (6)

- Fluctuations arise where there are **lines**
- with 36000 OS points, fluctuations are **below a few % everywhere the flux matters**.

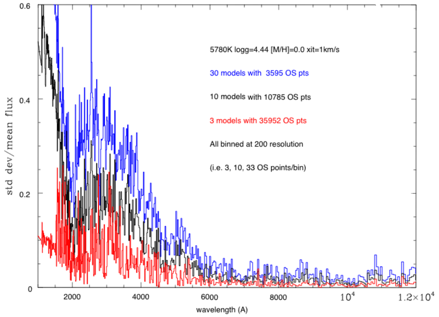
Exceptions are:

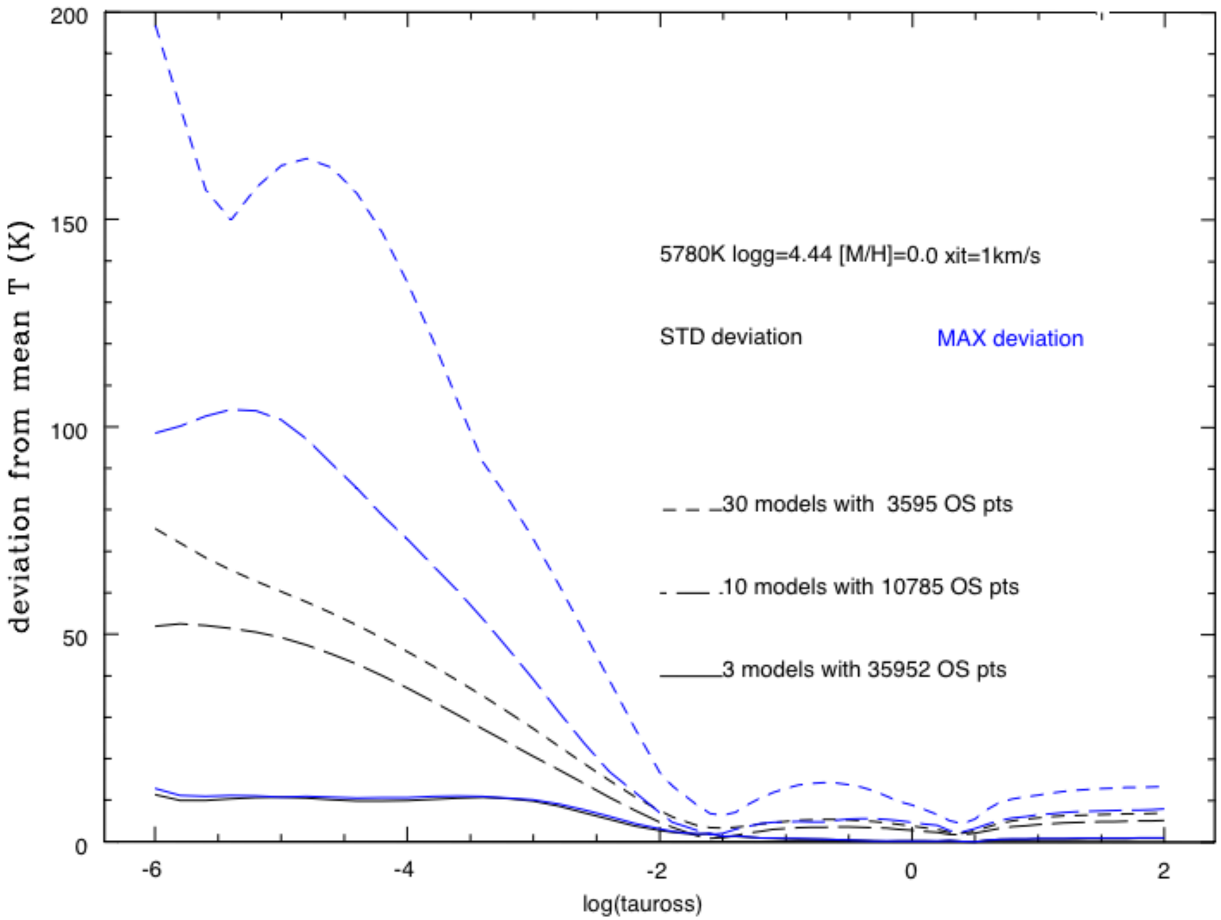
  - IR CO bands of cool stars (5%)
  - UV of solar-type stars (10%)

- From the trend, we expect fluctuations to be a factor $\sqrt{3}$ smaller with our 108000 points.

What about the **atmospheric structure** ?

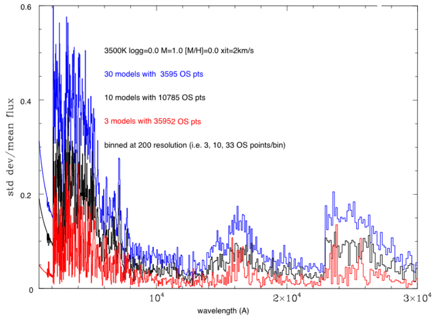
Sampling of opacities and T-tau (1)

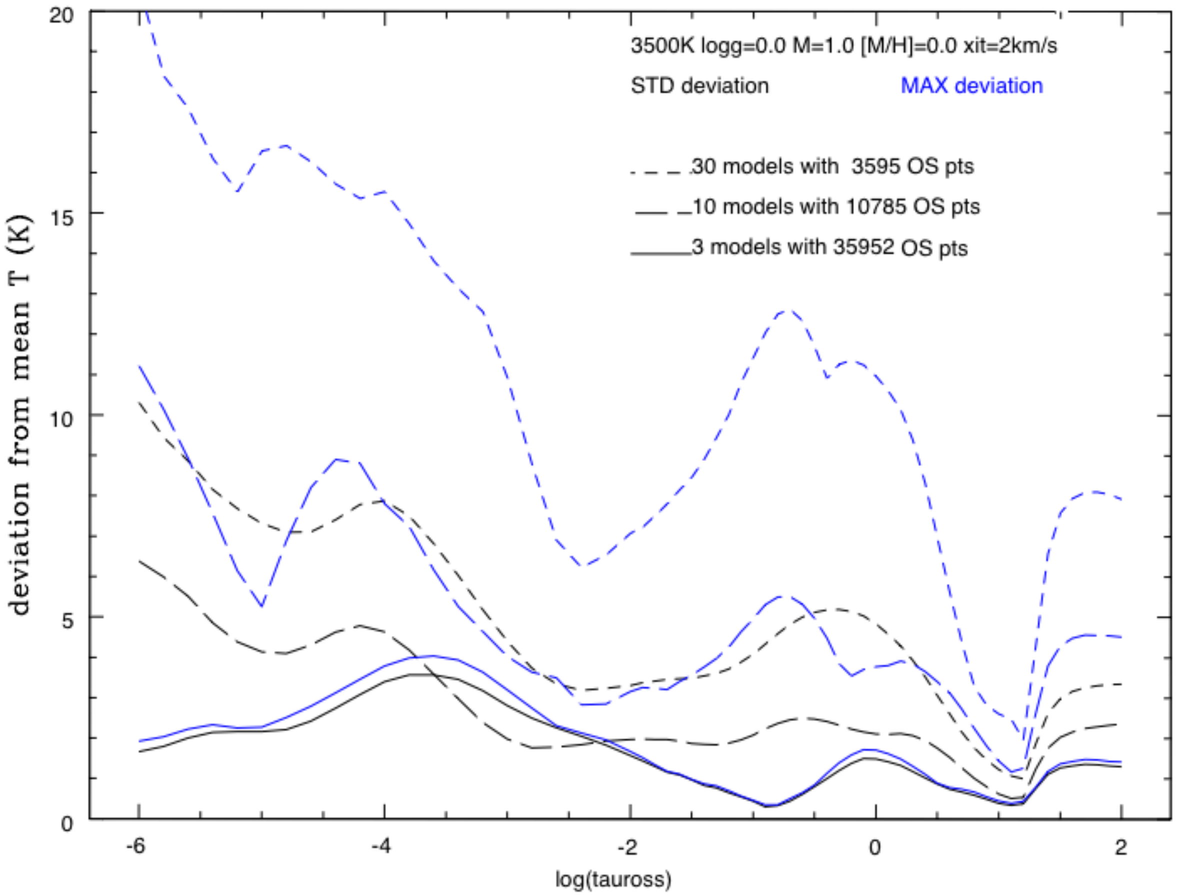




T fluctuations with the number of OS points : solar model

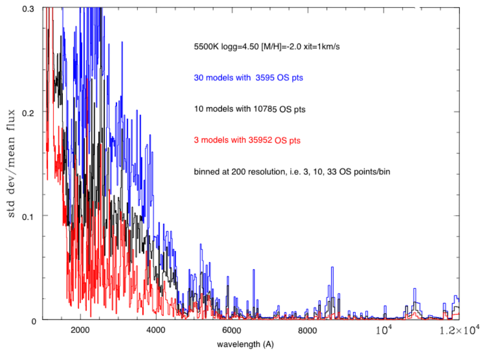
Sampling of opacities and T-tau (2)

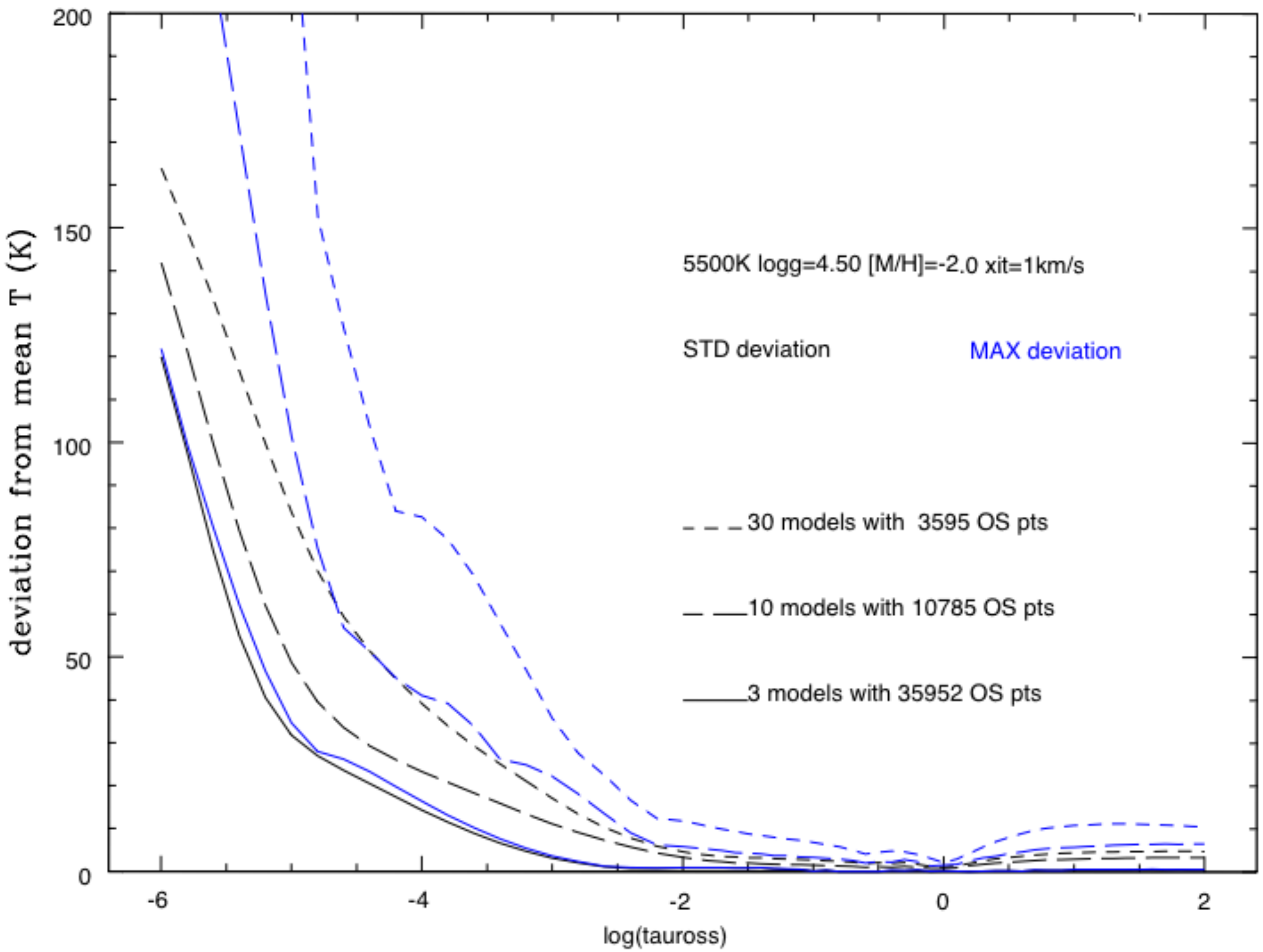




T fluctuations with the number of OS points : 3500K giant

Sampling of opacities and T-tau (3)





T fluctuations with the number of OS points : 5500K Fe-poor dwarf

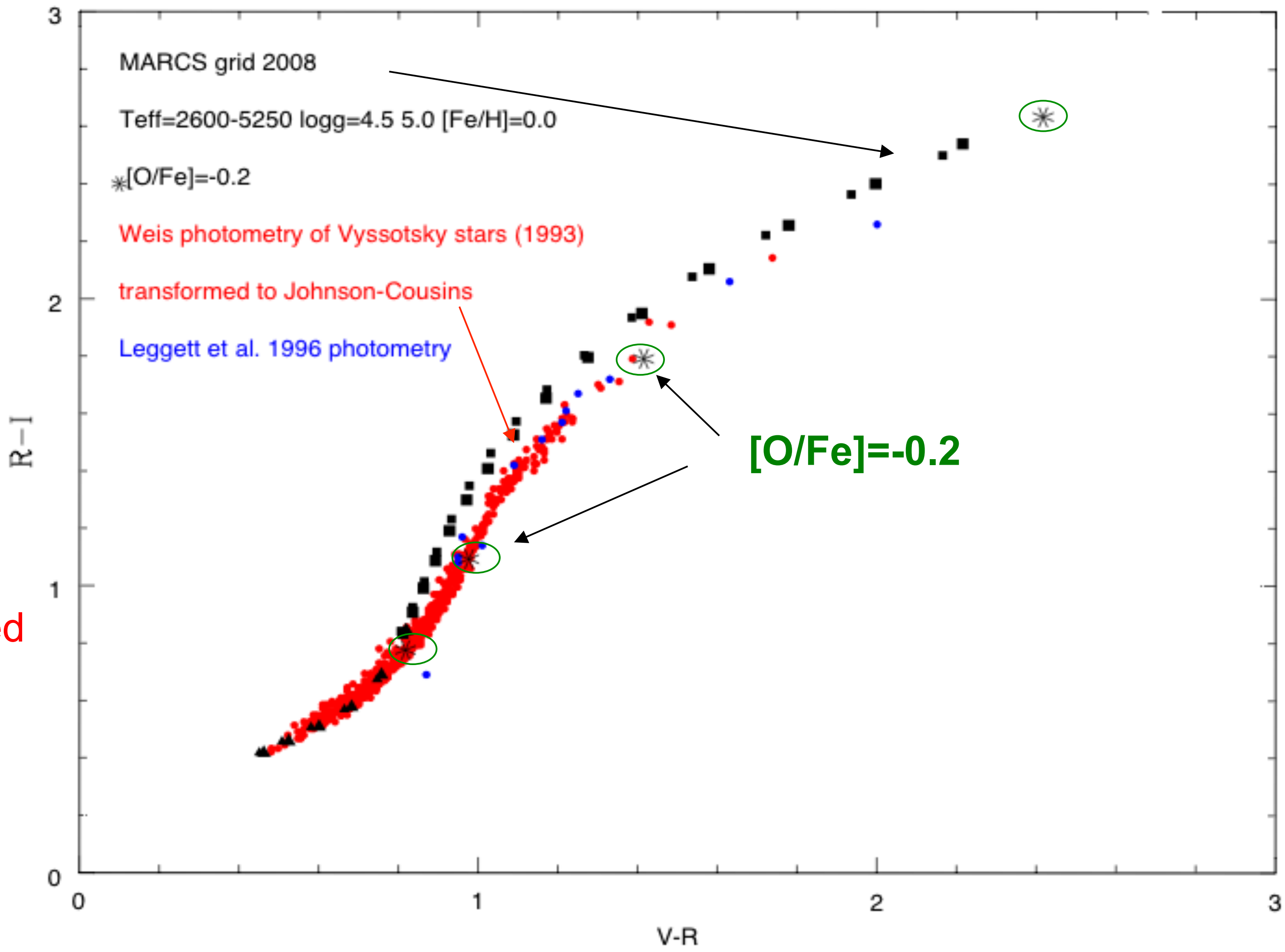
Sampling of opacities and T-tau (4)

• Fluctuations of T-structure are **only a few K** in all cases with 36000 OS-points, for **$-2 < \log\tau < 2$**
• At lower optical depths, fluctuations are large for metal-poor model, small for cool giant, <10K for Sun
• error on T-tau **always <20K for cool giant** !

=> errors on T-structure occur if line opacity not well sampled, i.e. **line and OS-point density too low**

=> That the fluxes are not so good, does not mean the atmospheric structure is wrong (and vice-versa)!

Also: beware of subtle effects: O/Fe in dM models



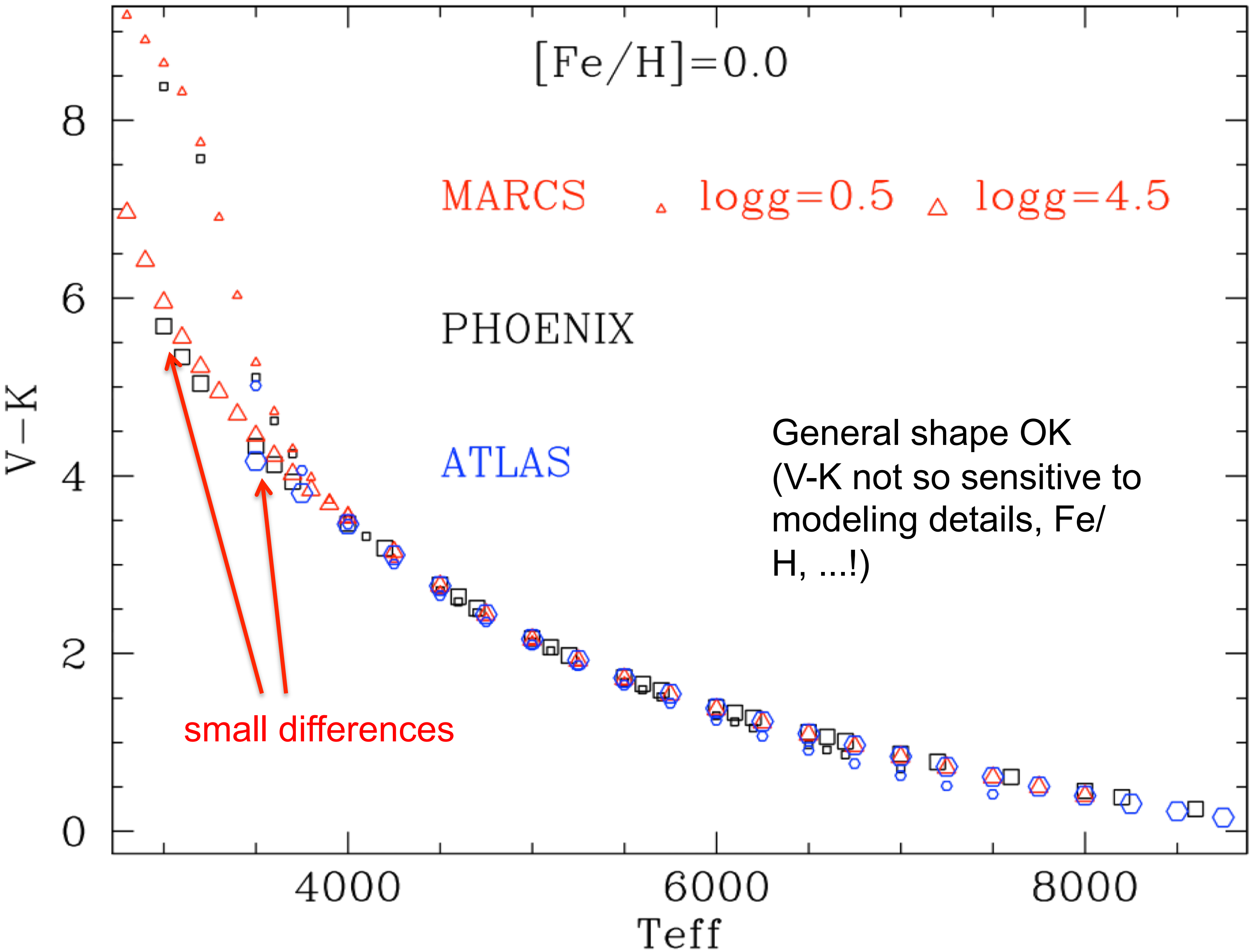
Abundances must be checked before we can discuss missing ingredients in models

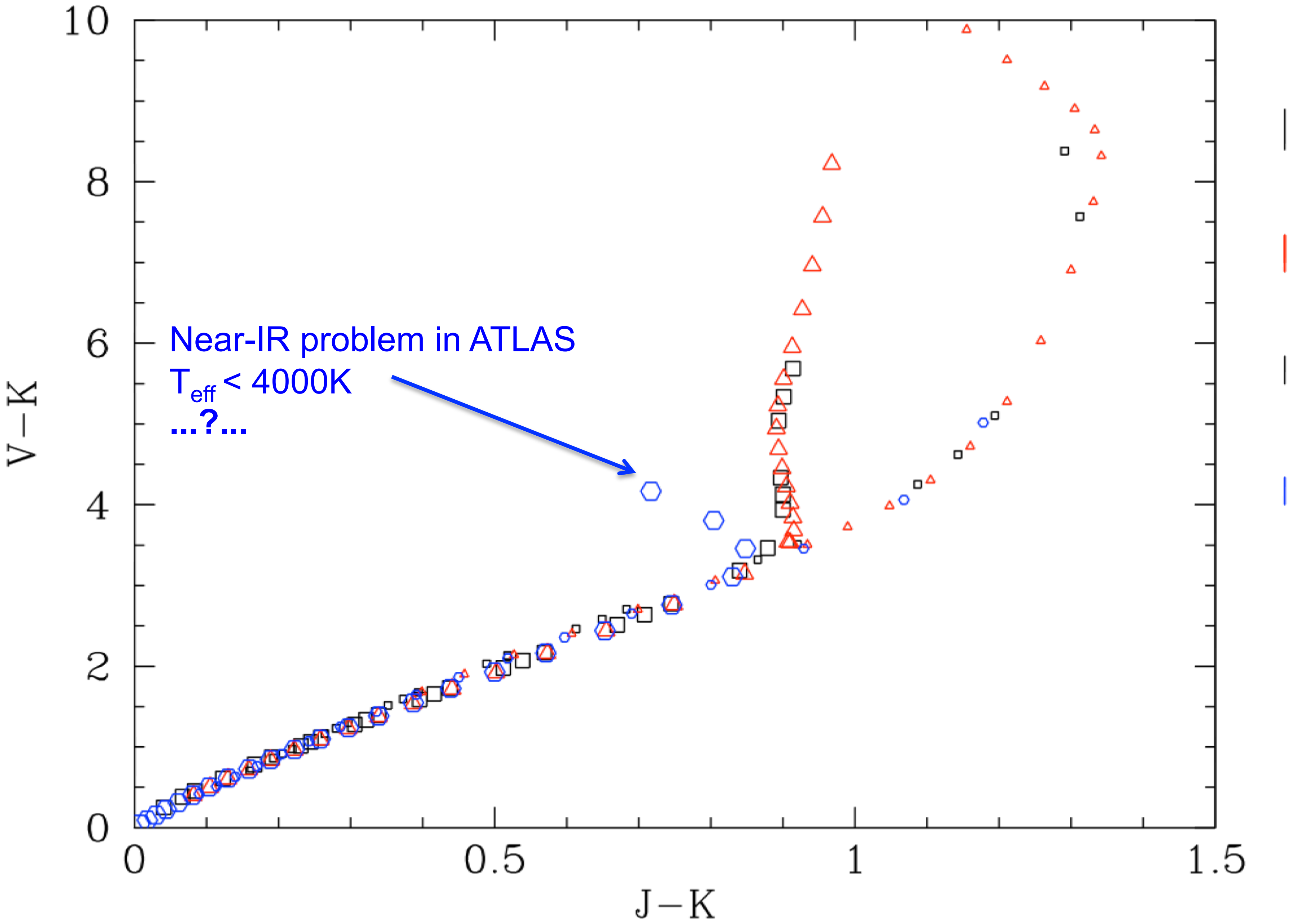
Comparisons of spectra: SED

- Here, only photometry :
- For MARCS and PHOENIX computed using filters defined in Bessell et al 1998
- For ATLAS (ATLAS9/ODFnew), colors (same filters) on :

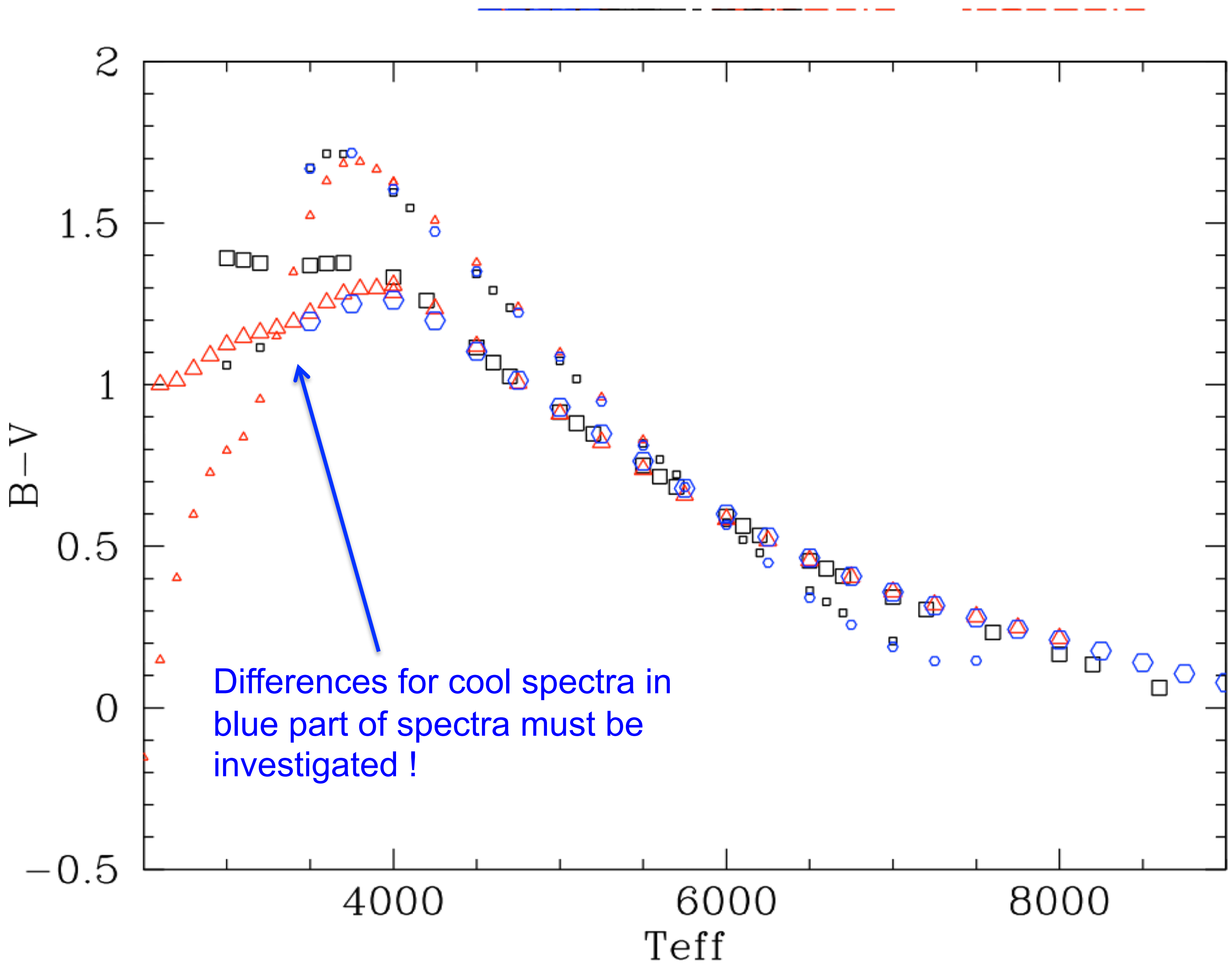
  wwwuser.oat.ts.astro.it/castelli/

- Only [Fe/H]=0.0

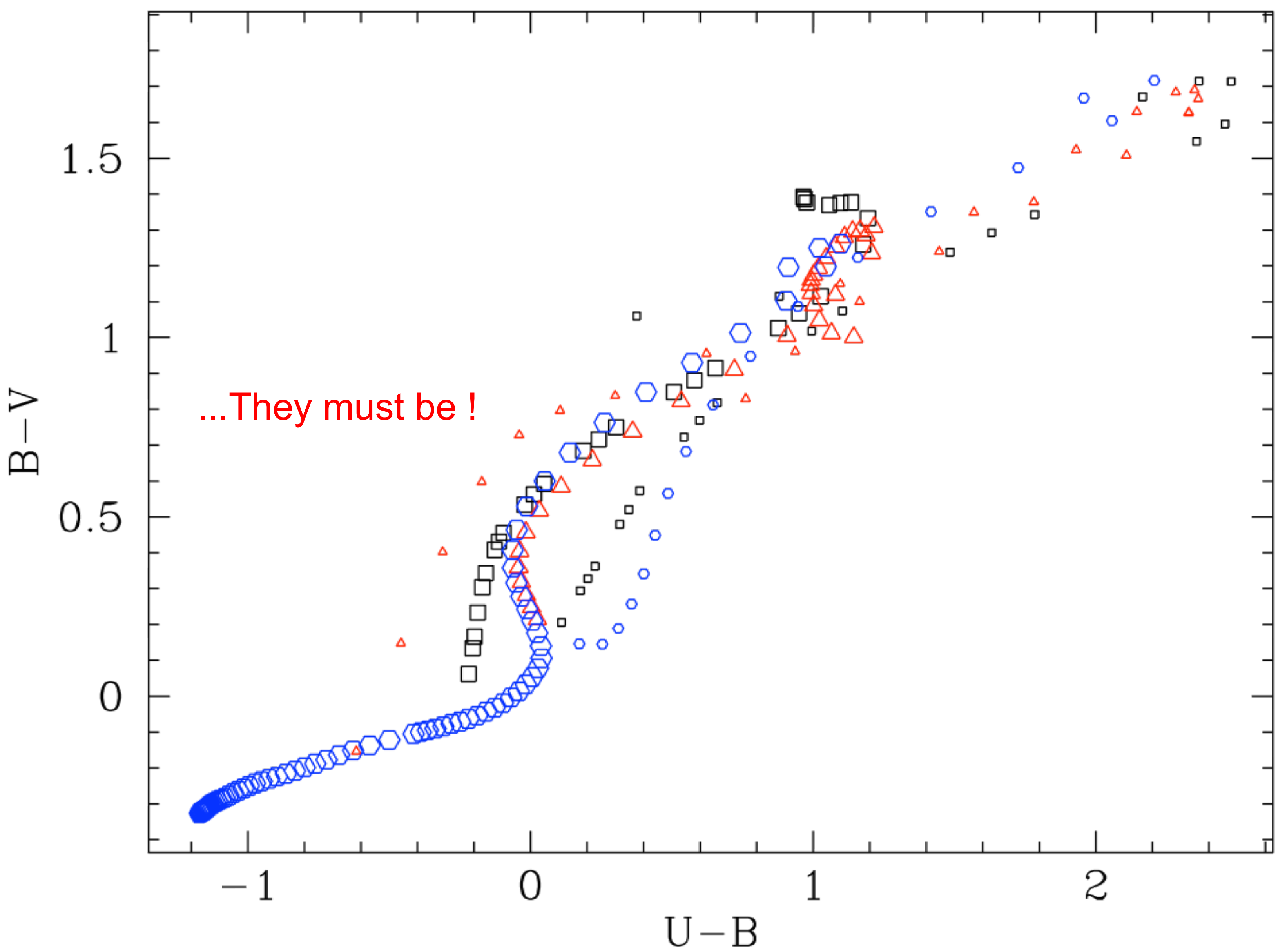

[Fe/H]=0.0
MARCS logg=0.5 logg=4.5
PHOENIX
ATLAS
General shape OK
(V-K not so sensitive to
modeling details, Fe/
H, ...!)
small differences
8
6
4
2
0
V−K
4000
6000
8000
Teff



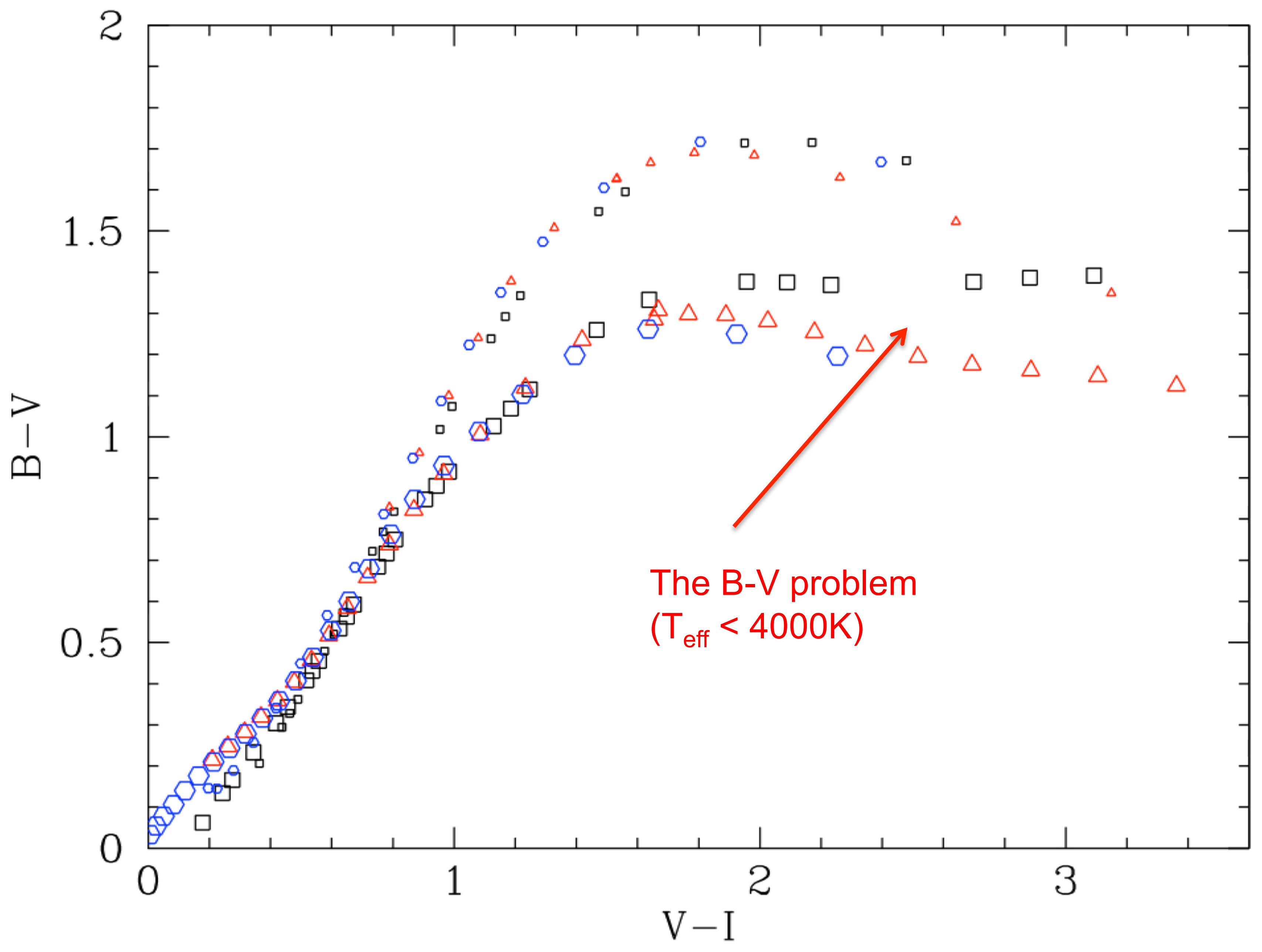
Near-IR problem in ATLAS
Teff < 4000K
...?...
V−K
J−K
0
0.5
1
1.5
2
4
6
8
10



2
1.5
1
0.5
0
−0.5
B−V
4000
6000
8000
Teff
Differences for cool spectra in blue part of spectra must be investigated !



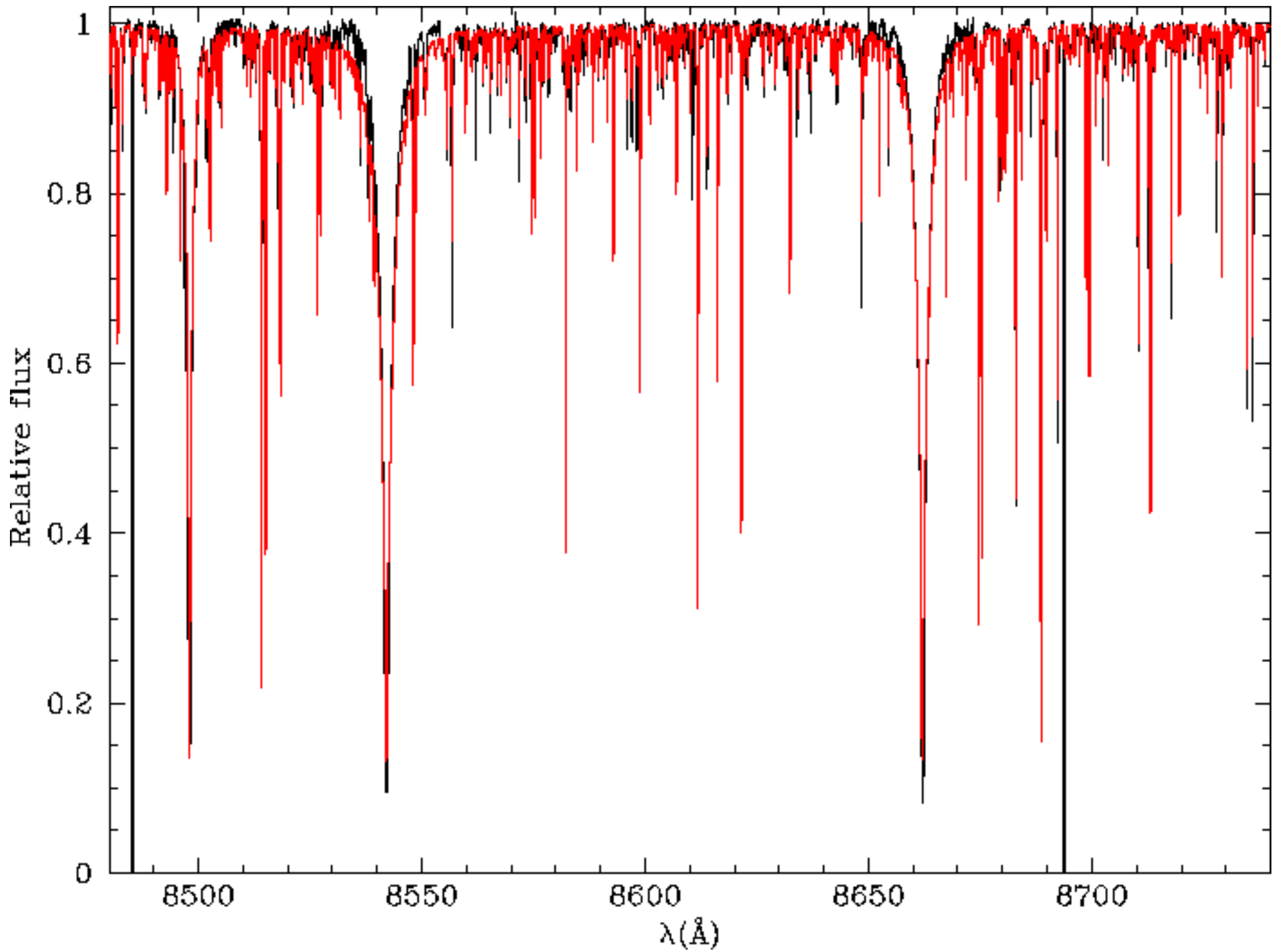
1.5
1
0.5
0
−1
0
1
2
B−V
U−B
...They must be !



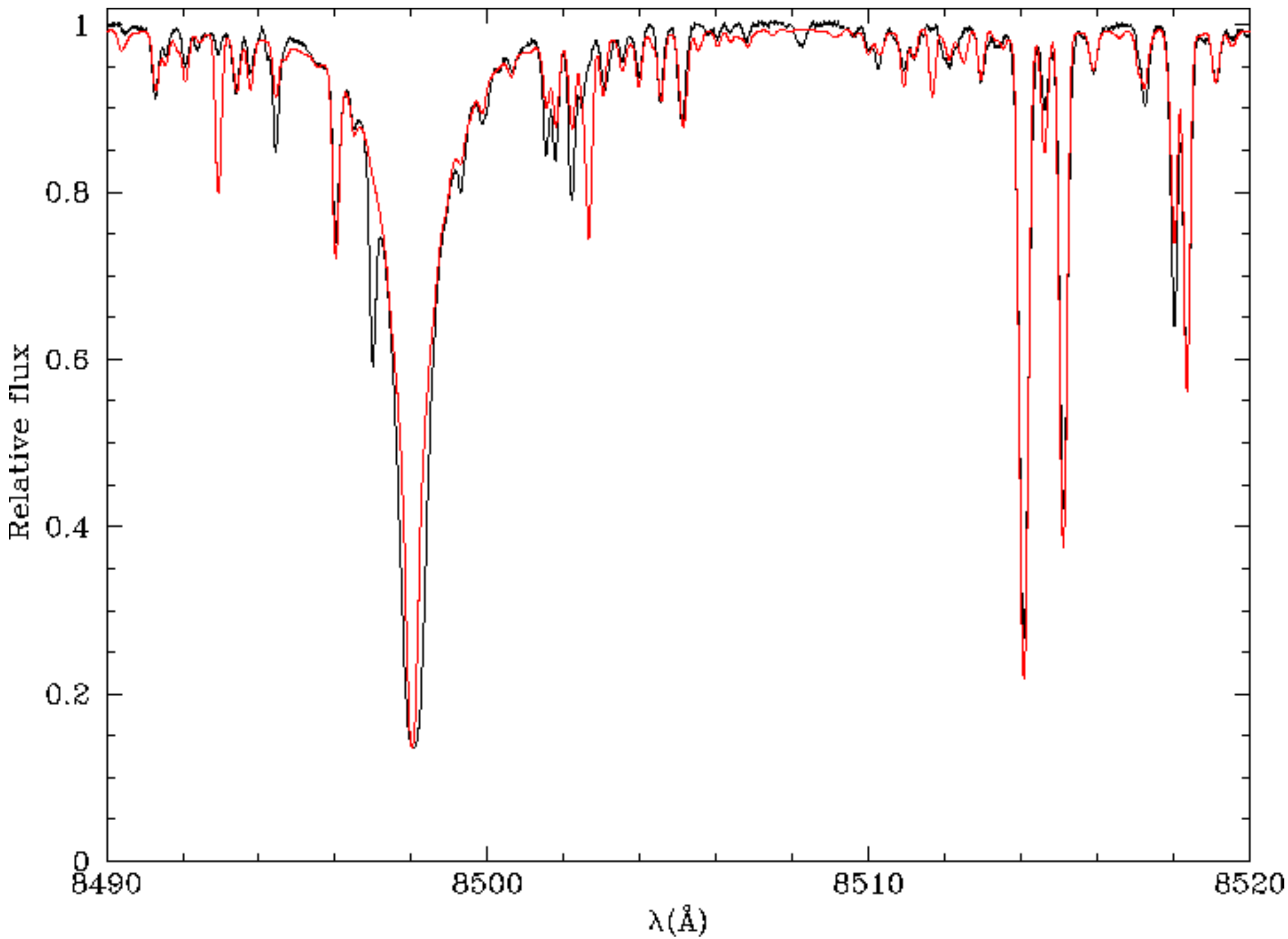
2
1.5
1
0.5
0
B−V
0
1
2
3
V−I
The B-V problem
(T_eff < 4000K)

RVS domain

- Example of Arcturus + MARCS
- Contributions to the spectrum
- High resolution spectra (MARCS and PHOENIX) computed with their respective data sets and codes, degraded to the resolution of the RVS
  - Giants and dwarfs 3000K ≤ T_{eff} ≤ 6000K



Arcturus: full resolution **FTS spectrum** (Hinkle et al. 2000, ASP), and **MARCS model** T_{eff}=4300K, logg=1.50, [Fe/H]=-0.5, v_{turb}=1.7km/s, C: 7.96, N: 7.61, O: 8.68, $^{12}C/^{13}C$=7



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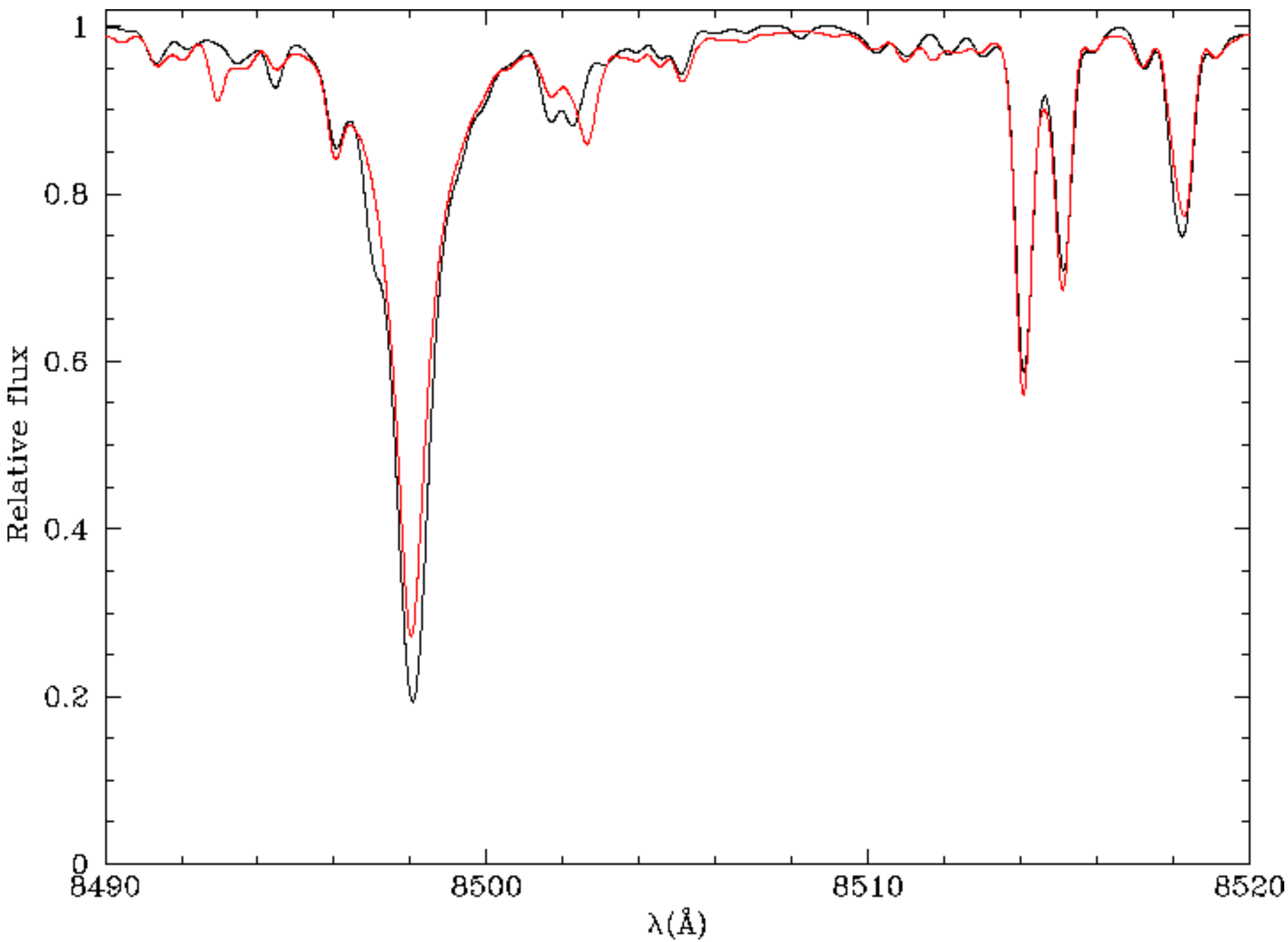
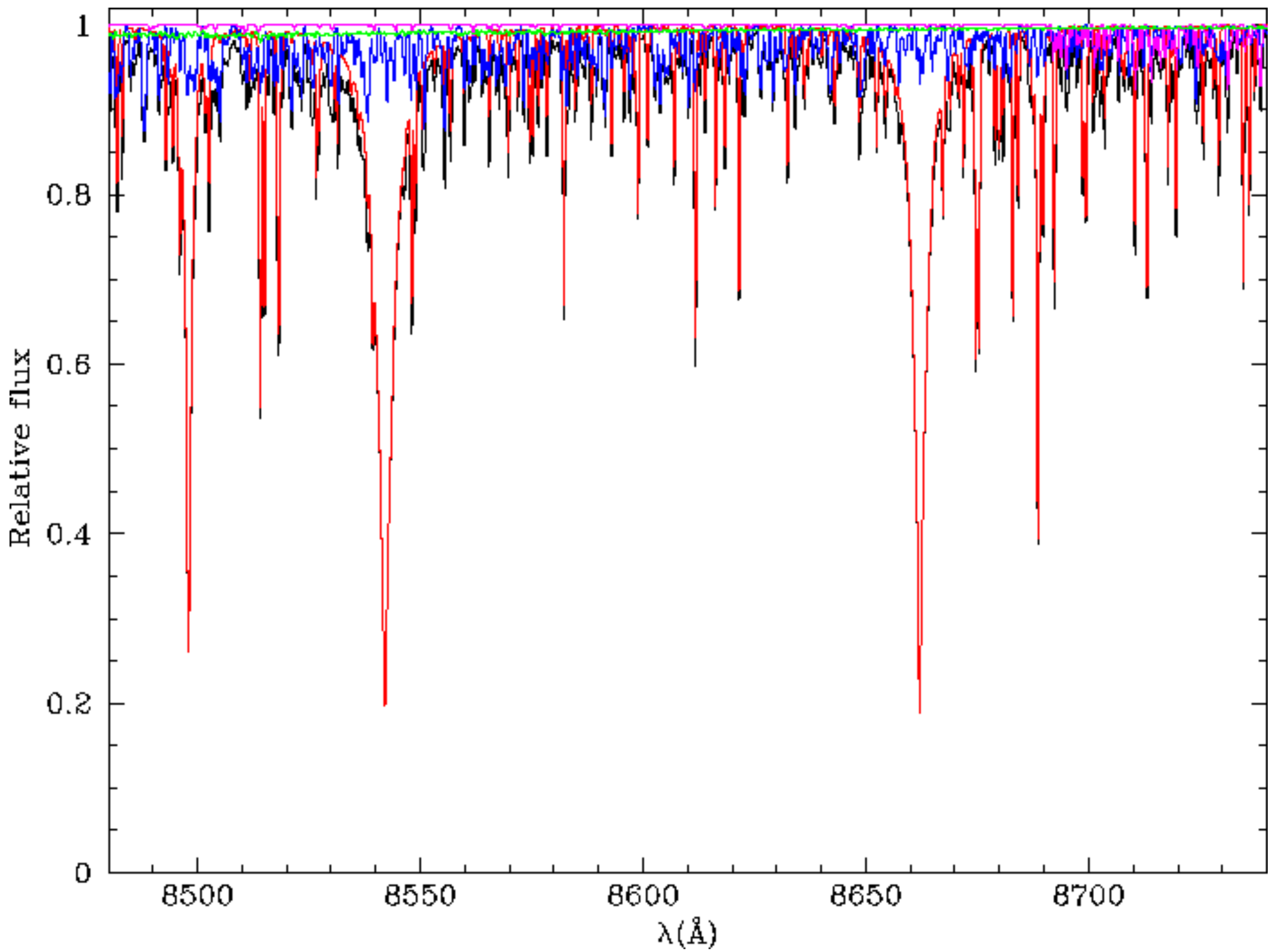


Arcturus: **R=20000 spectrum** (Hinkle et al. 2000, ASP, degraded), and **MARCS model** T_{eff}=4300K, logg=1.50, [Fe/H]=-0.5, v_{turb}=1.7km/s, C: 7.96, N: 7.61, O: 8.68, $^{12}C/^{13}C$=7

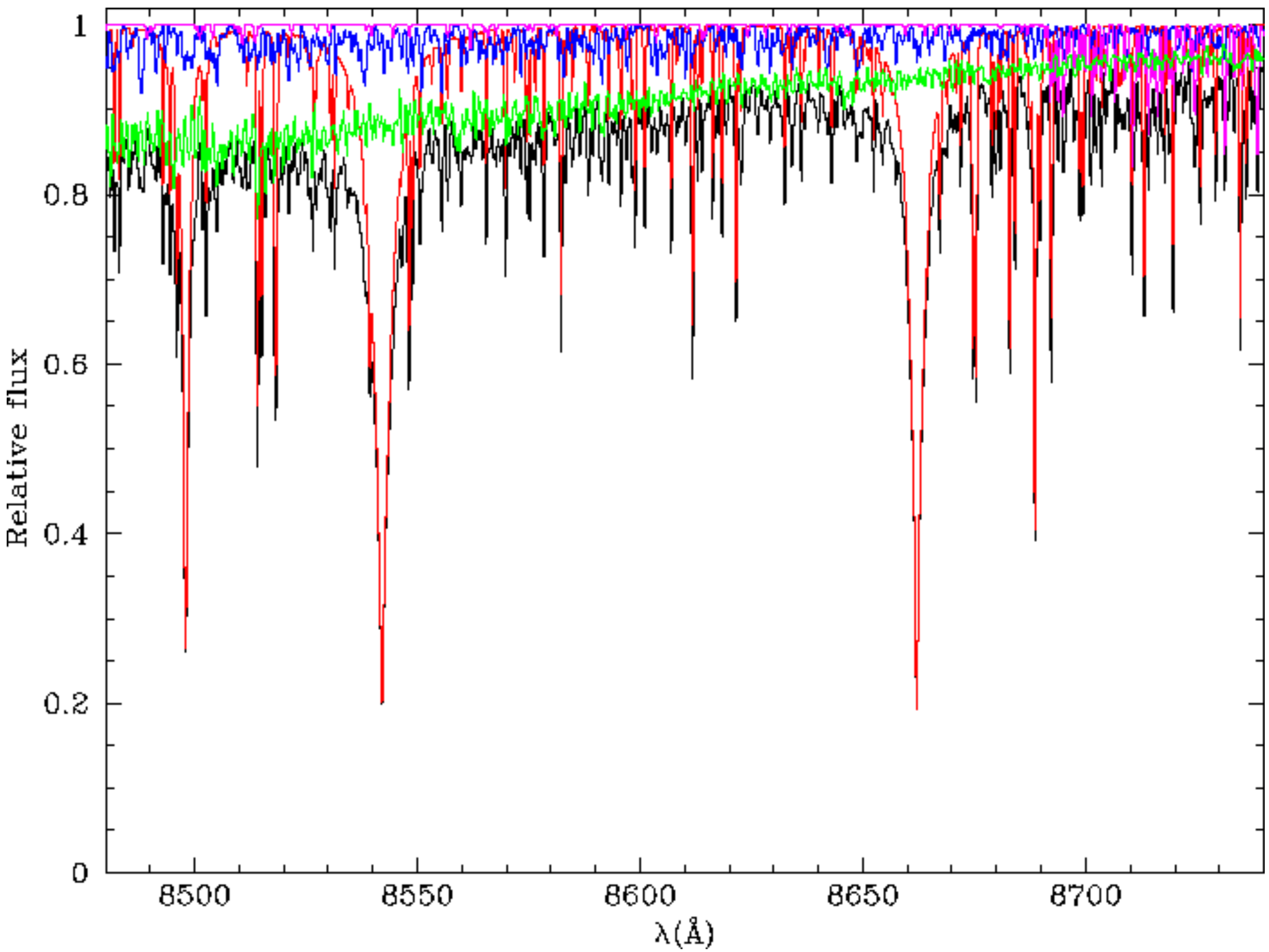
Contributions to the Gaia-RVS window

4000K logg=1.60 C/O=0.5



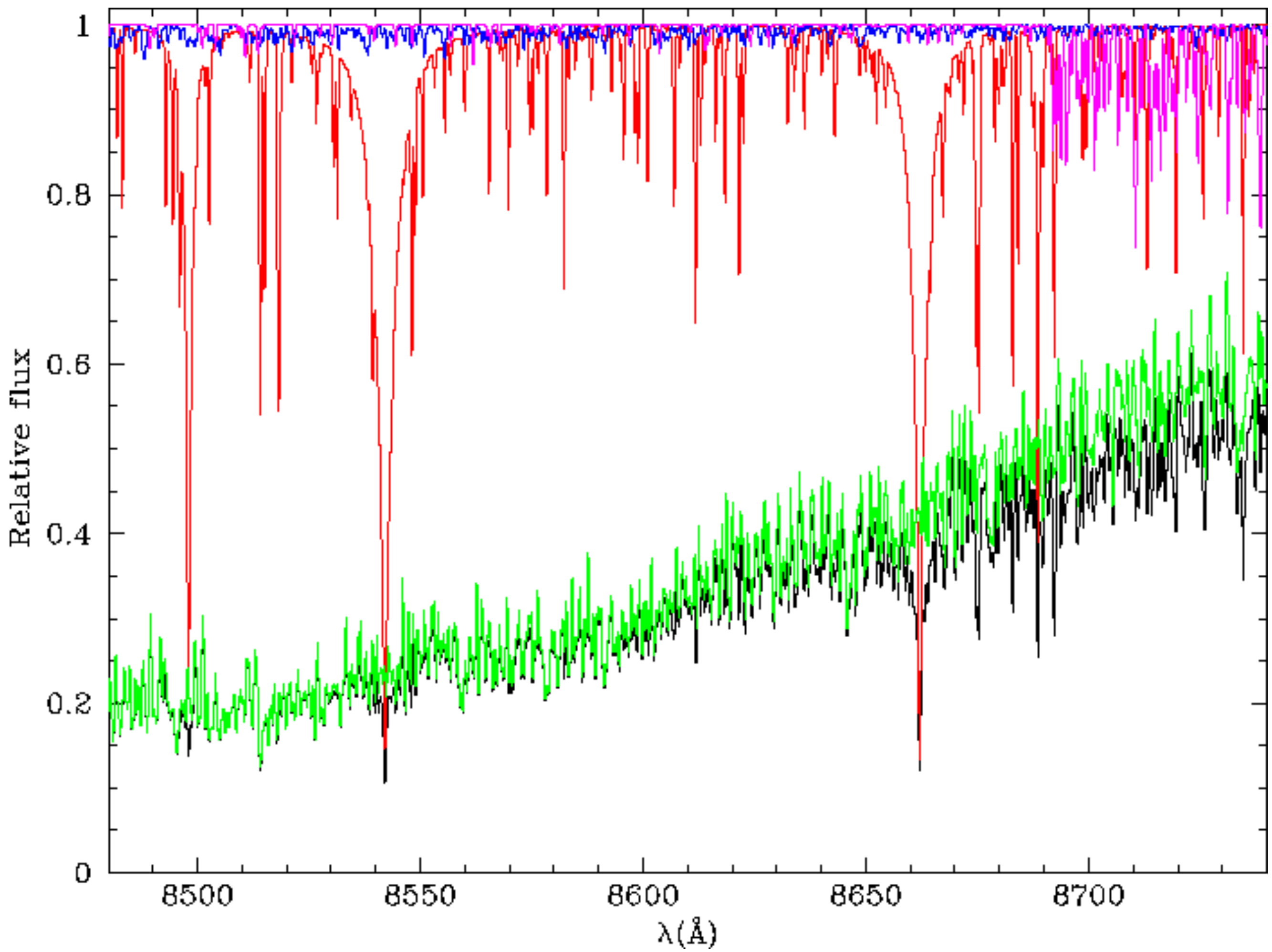
Contributions: all lines; atoms; TiO, CN, FeH

3600K logg=1.00 C/O=0.5



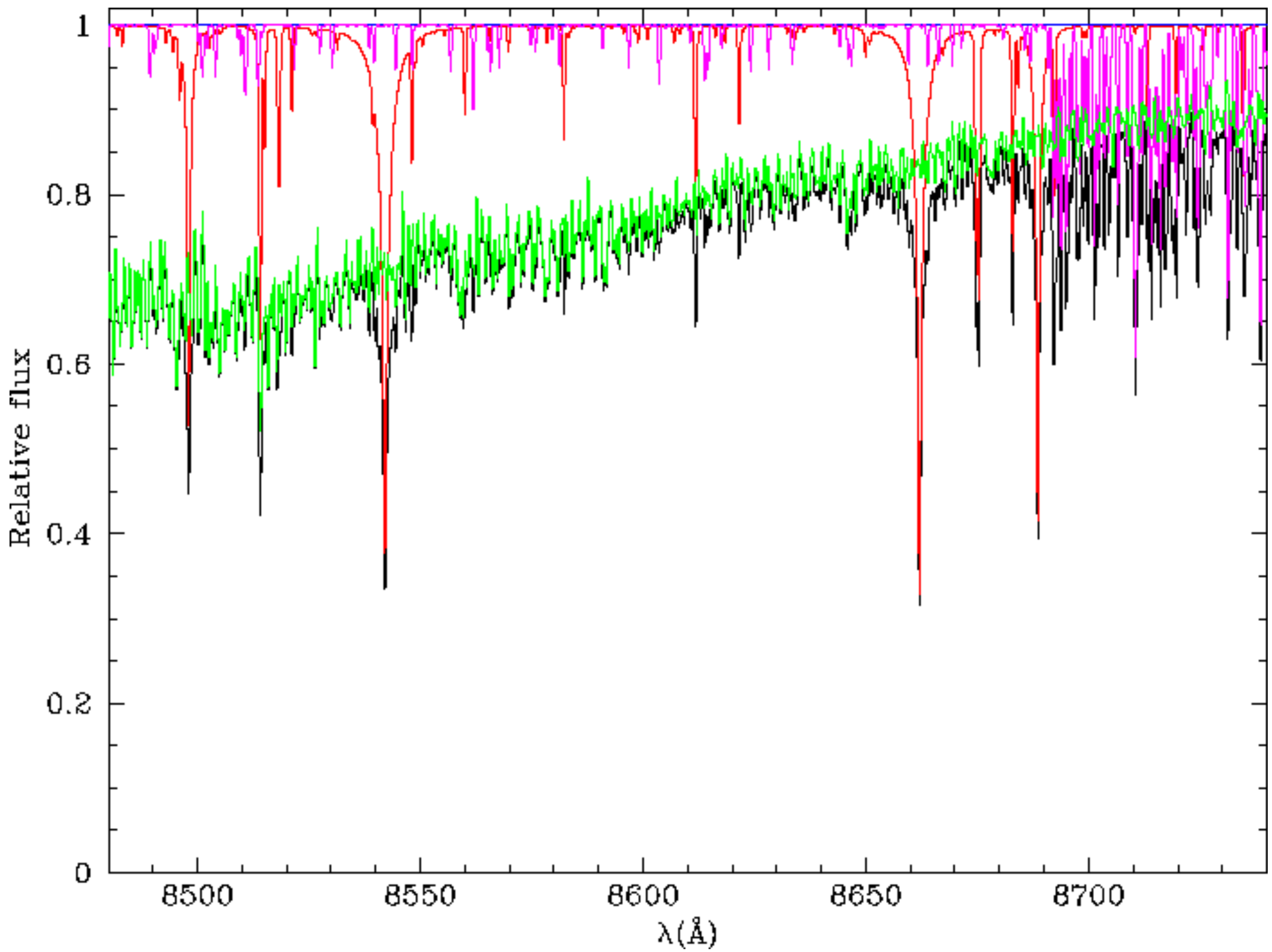
Contributions: all lines; atoms; TiO, CN, FeH

3200K logg=0.35 C/O=0.5



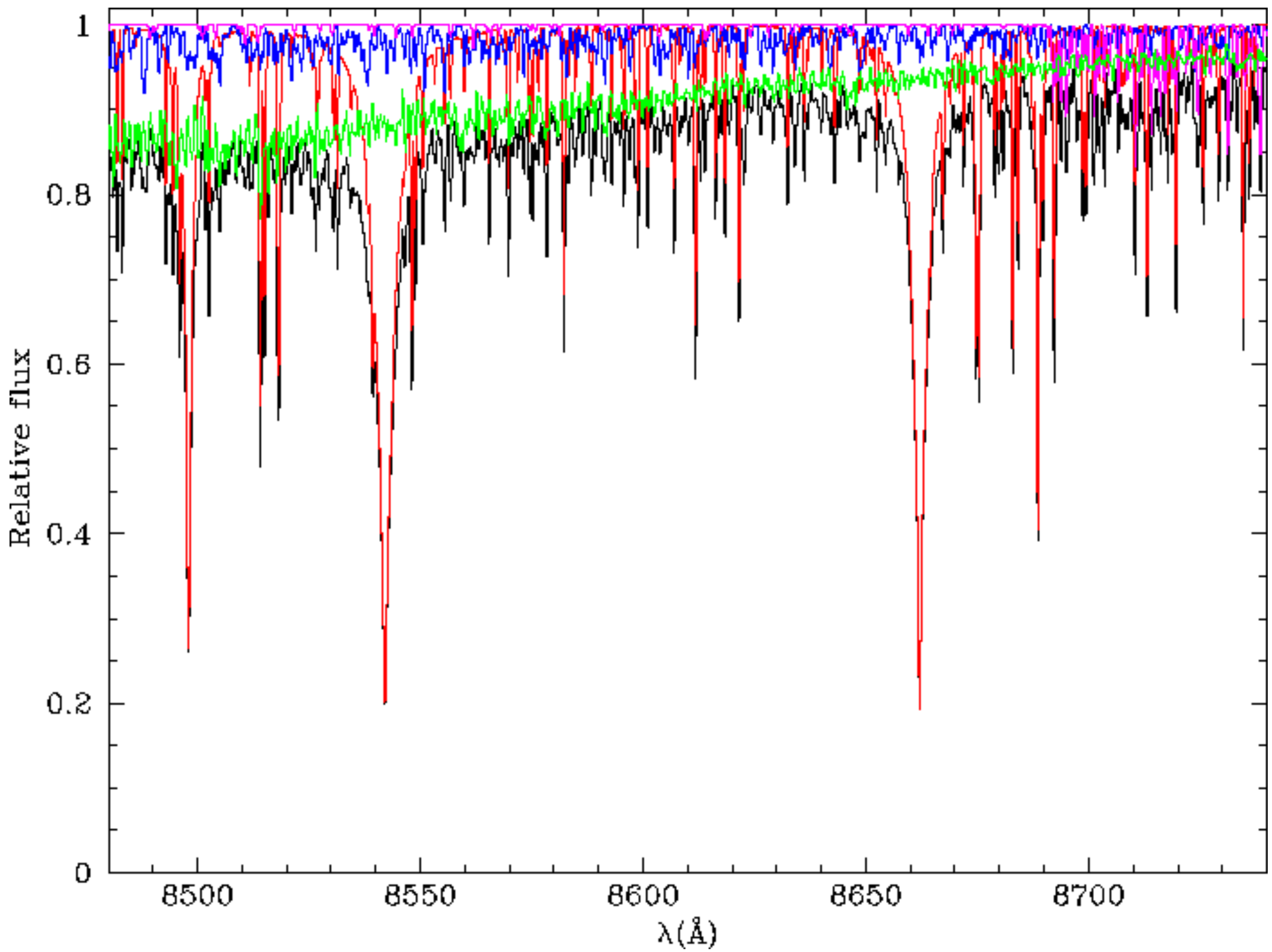
Contributions: all lines; atoms; TiO, CN, FeH

3200K logg=5.00 C/O=0.5



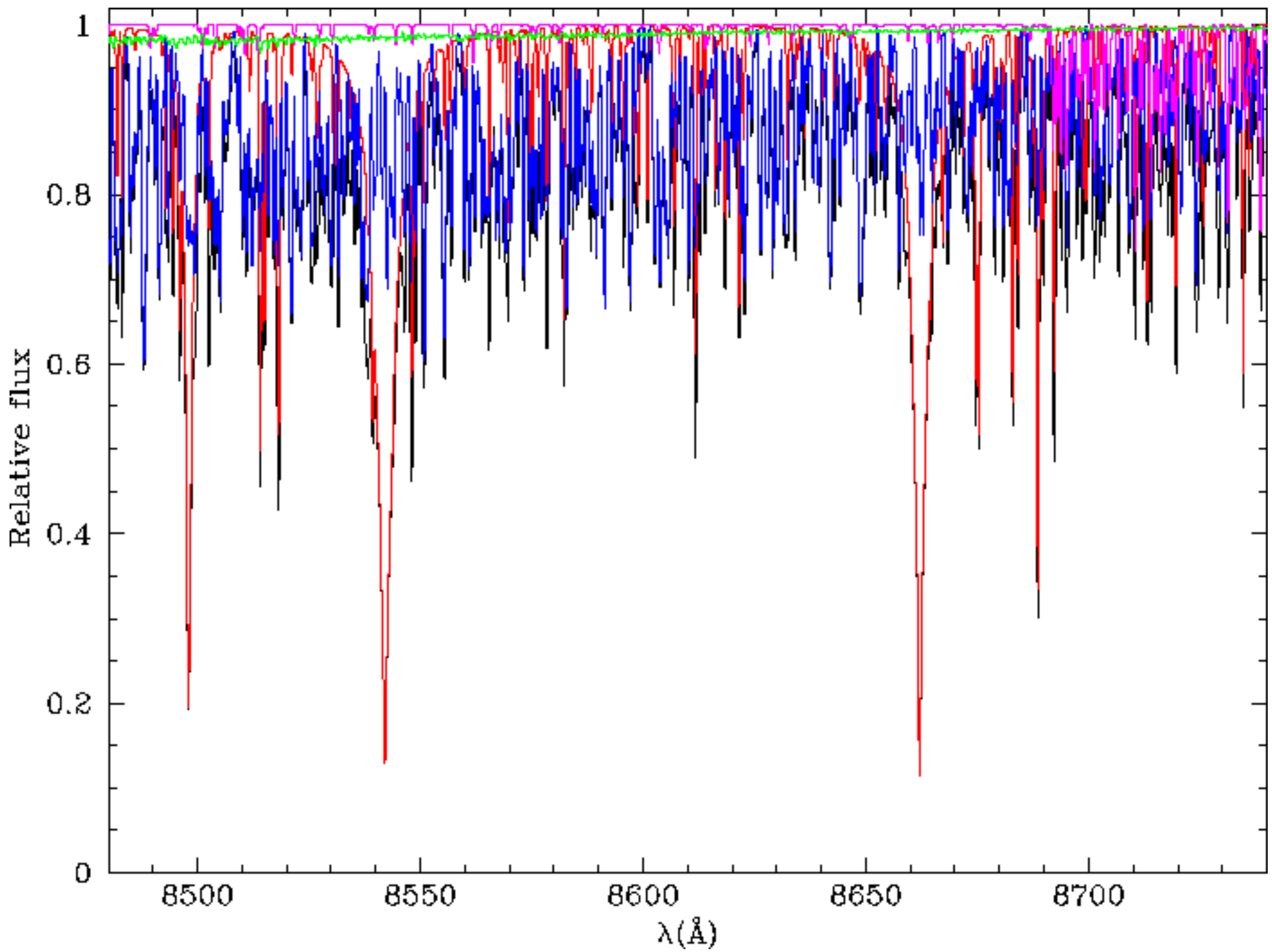
Contributions: all lines; atoms; TiO, CN, FeH

3600K logg=1.00 C/O=0.5



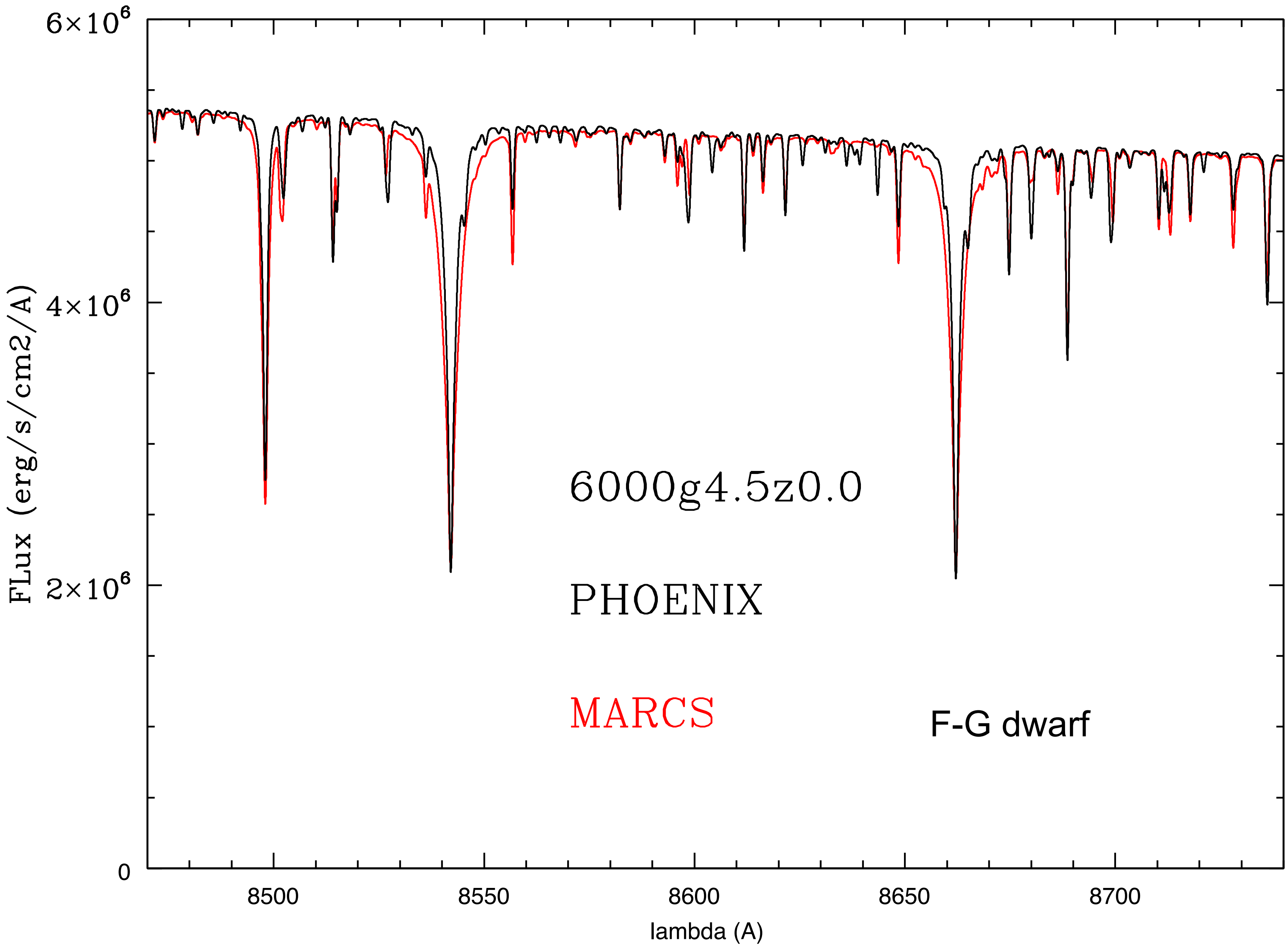
Contributions: all lines; atoms; TiO, CN, FeH

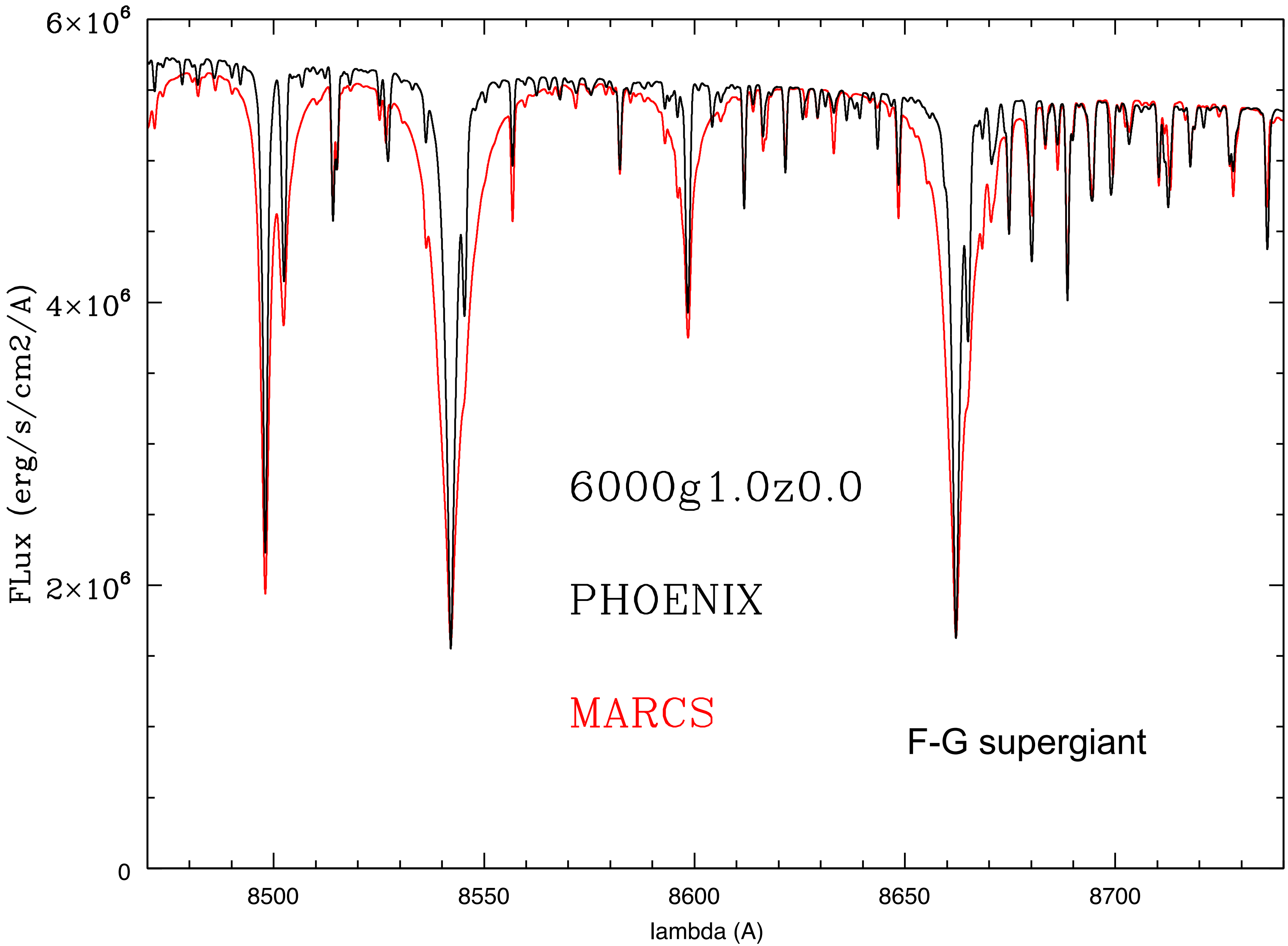
3600K logg=1.00 C/O=0.99



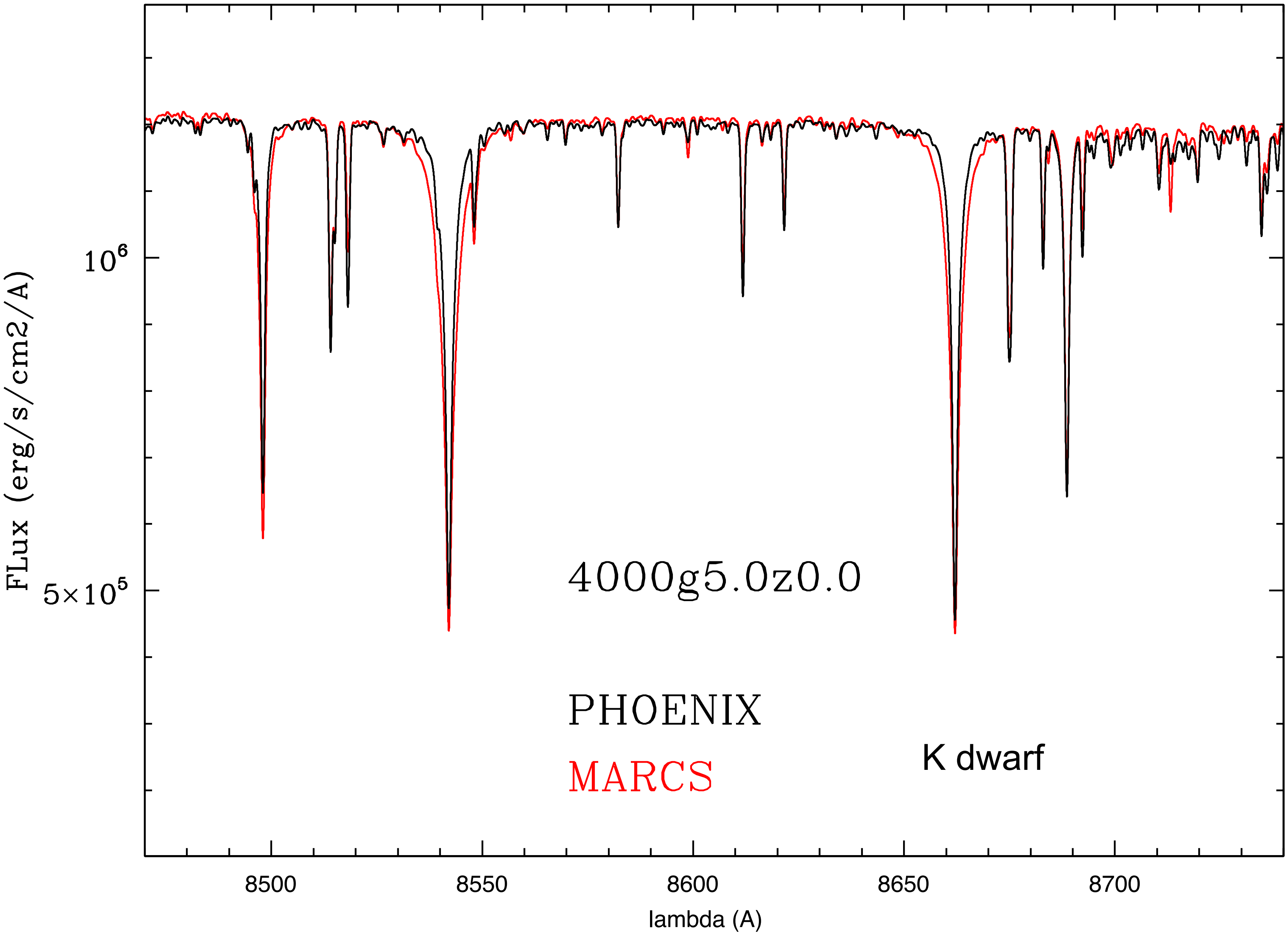
Contributions: all lines; atoms; TiO, CN, FeH

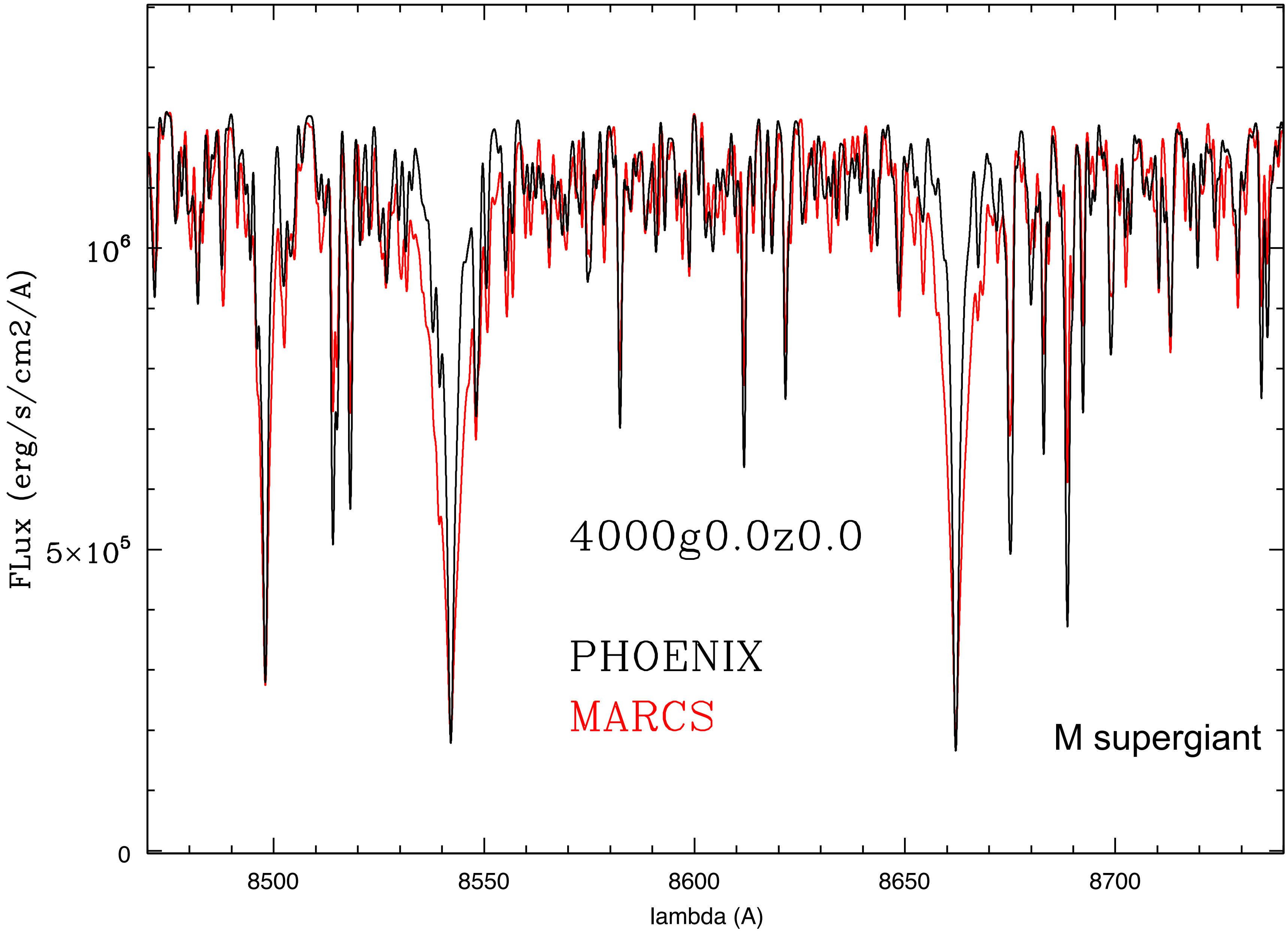
Comparisons PHOENIX - MARCS


6×10^6
4×10^6
2×10^6
0
FLux (erg/s/cm2/A)
8500
8550
8600
8650
8700
lambda (A)
6000g4.5z0.0
PHOENIX
MARCS
F-G dwarf

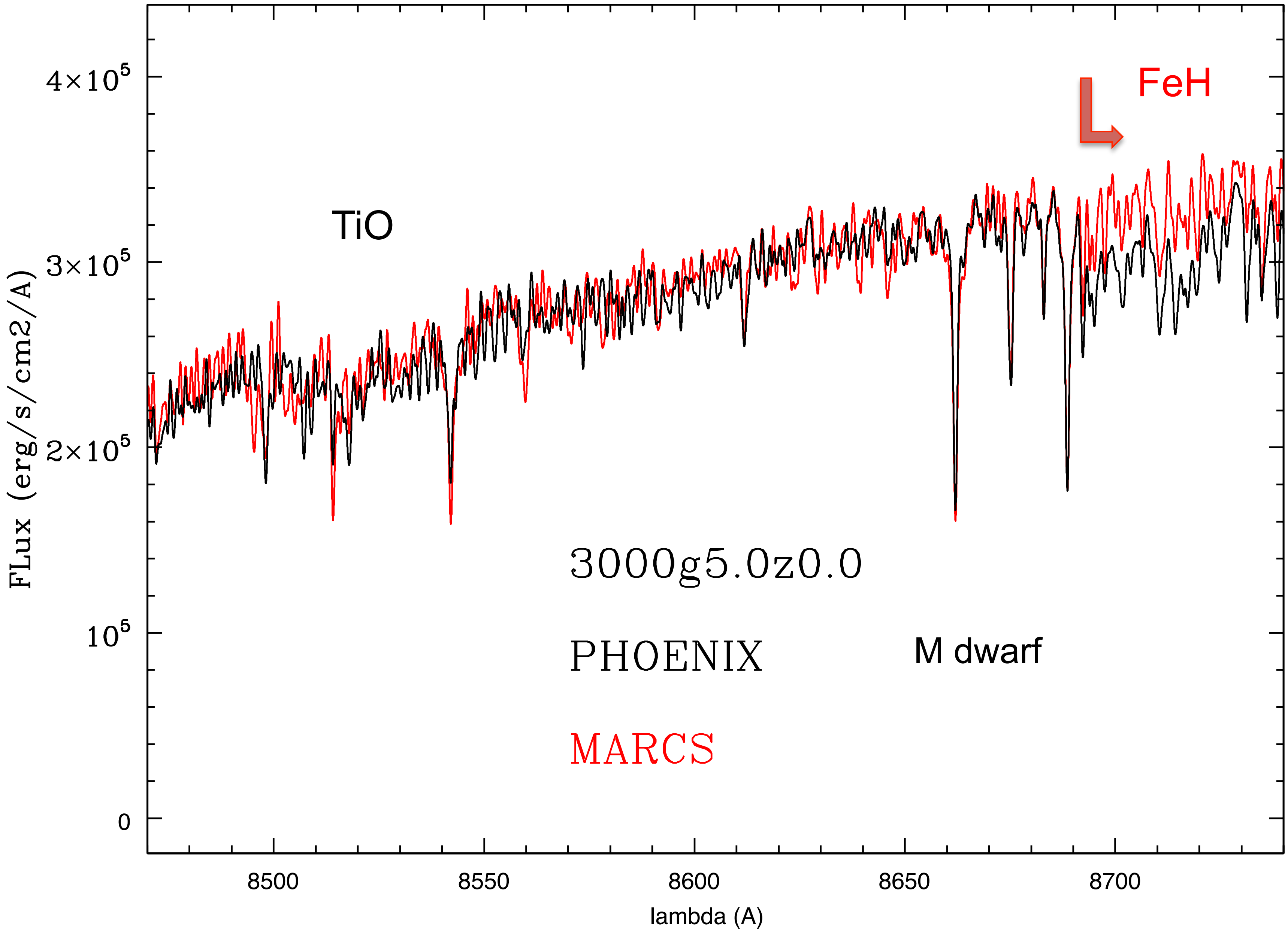


6×10⁶
4×10⁶
2×10⁶
0
FLux (erg/s/cm2/A)
8500
8550
8600
8650
8700
lambda (A)
6000g1.0z0.0
PHOENIX
MARCS
F-G supergiant

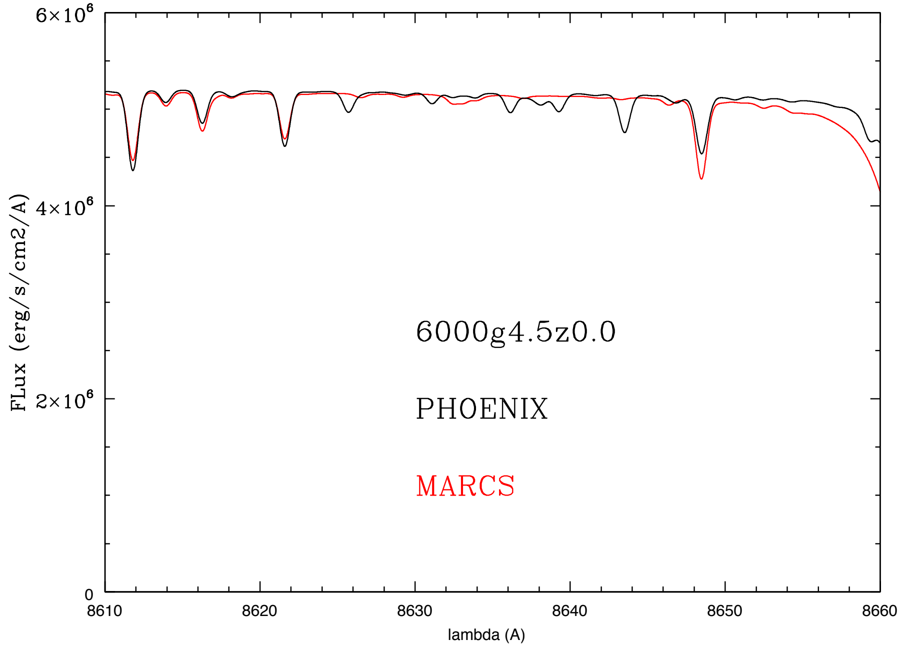

4000g5.0z0.0
PHOENIX
MARCS
K dwarf
FLux (erg/s/cm2/A)
10^6
5×10^5
8500
8550
8600
8650
8700
lambda (A)



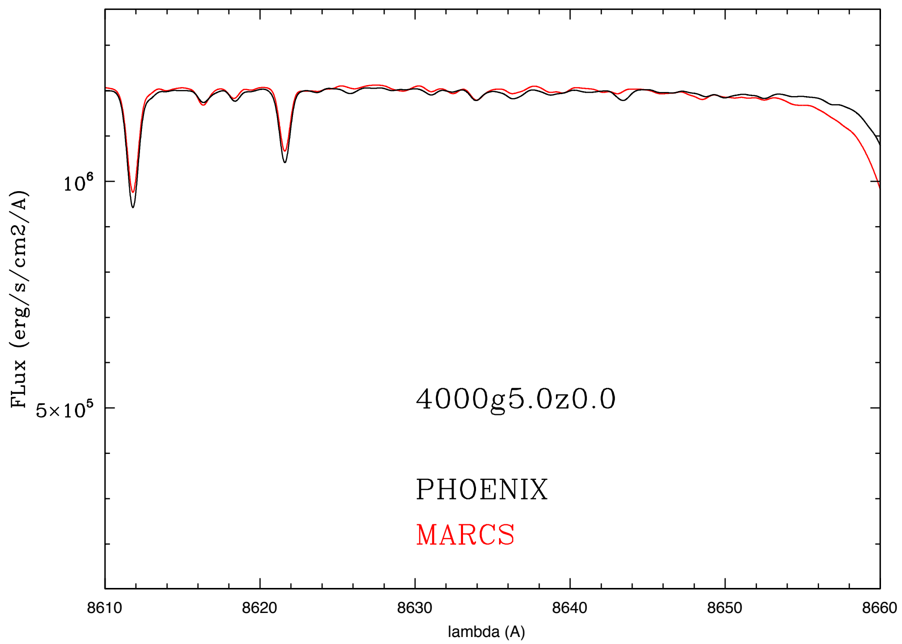
FLux (erg/s/cm2/A)
10^6
5×10^5
0
8500
8550
8600
8650
8700
lambda (A)
4000g0.0z0.0
PHOENIX
MARCS
M supergiant

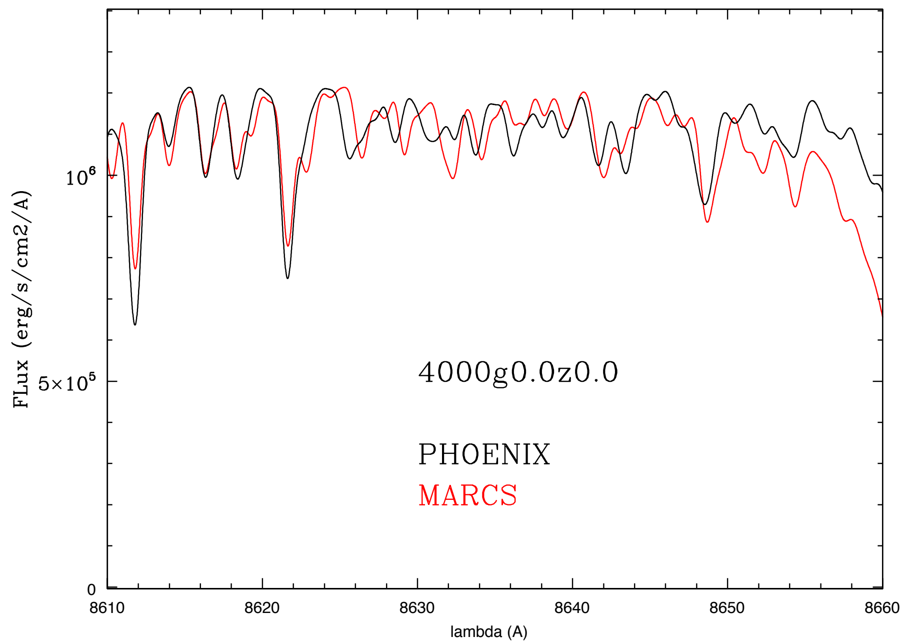


FeH
TiO
3000g5.0z0.0
PHOENIX
MARCS
M dwarf
4×10^5
3×10^5
2×10^5
10^5
0
FLux (erg/s/cm2/A)
8500
8550
8600
8650
8700
lambda (A)



Zoom on 8610 – 8660 Å





In conclusion

- Still **significant differences between model spectra**, although model structures are quite close (but comparisons not exhaustive!)
- At low resolution :
  - most differences in **UV** (all)
  - ATLAS deviates in near-IR below 4000K
  - PHOENIX deviates in B-V below 4000K, and above 7500K
- At high resolution (RVS) :
  - **A number of faint features** don't match each other
  - Collisional broadening should be improved in PHOENIX (following Barklem et al.)
  - **M dwarfs** : important differences in detail of TiO, and strength of FeH !

Recommendations

- This must be continued, and **more comparisons** made!
- **Detailed comparisons** must be made with **carefully calibrated spectrophotometric** data, and high resolution spectra, for stars with well known parameters (WP "provide calibration of training data" CU8)
- Better line positions, esp. for **molecules**!

THANKS!