Oxygen in cool stars according to CO^{5}BOLD

H.-G. Ludwig

ZAH – Landessternwarte, Heidelberg

Overview

- Quote from the book "Oxygen in the Universe" (Stasinska et al. 2011) from the section on the solar photospheric abundance of oxygen:

  In this section the team of authors ran into the awkward situation that there was no unanimous opinion among the team members about the best procedure of its determination and ultimately best estimate of the oxygen abundance in the solar atmosphere.

  - Nicolas Grevesse 8.69 ± 0.05 vs. CO^{5}BOLD 8.76 ± 0.07

- Related discussions helped to proceed towards a concordance abundance

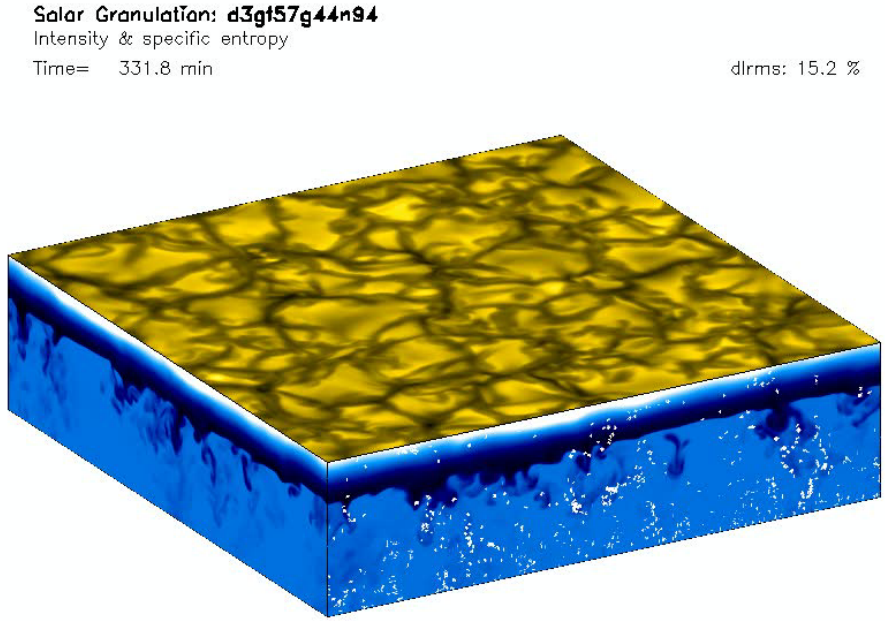
- Comments on worrying points

- Touching on stellar abundances $\rightarrow$ more by J. Gonzalez Hernandez

- News presented here mostly work by Elisabetta Caffau

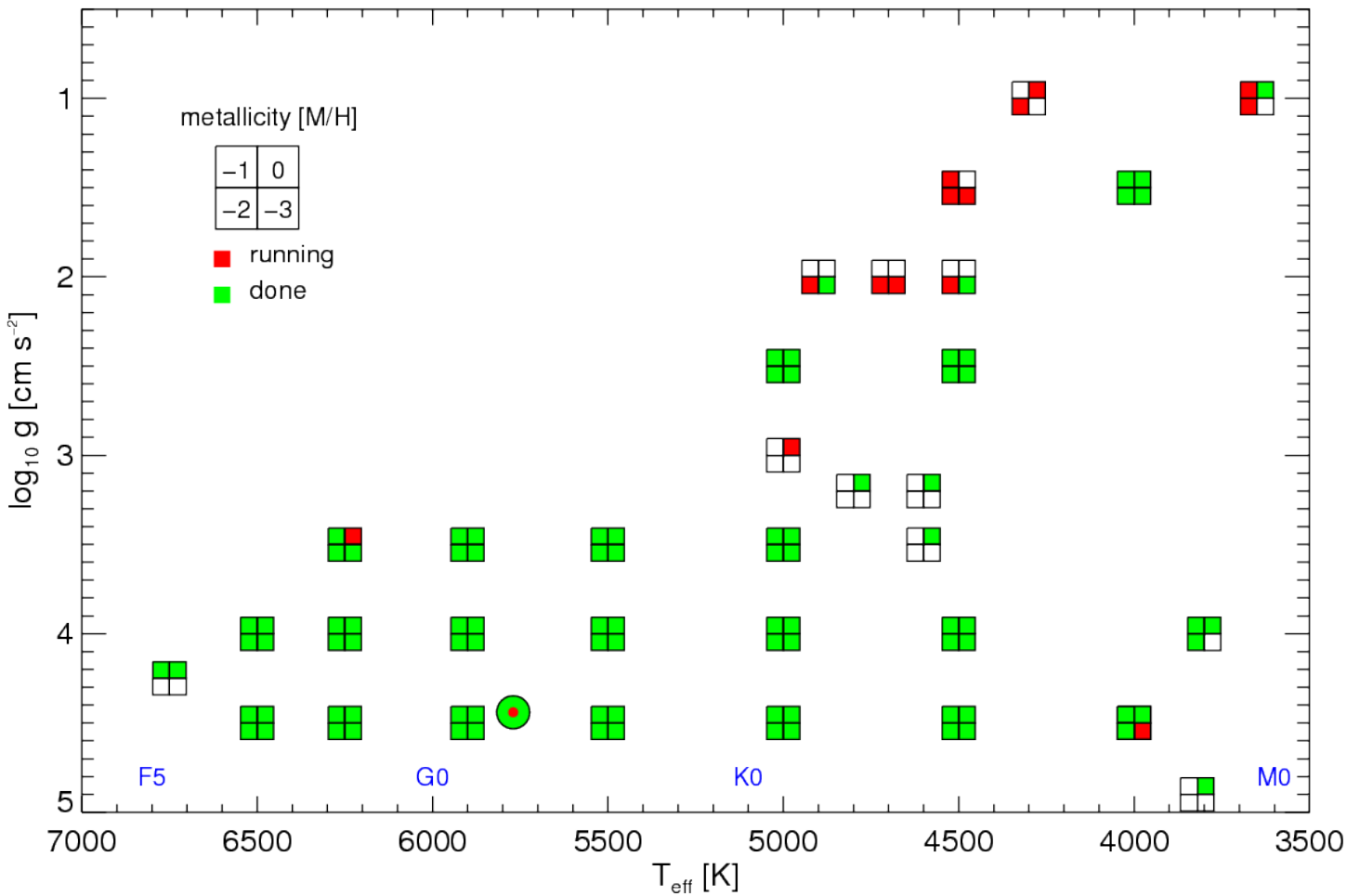
- CO^{5}BOLD? What's that?

The radiation-magnetohydrodynamics code CO^{5}BOLD



- COnservative COde for the COmputation of COmpressible COnvection in a BOx of L Dimensions, $\mathrm{L} = 2, 3$
- B. Freytag & M. Steffen, with contributions from S. Wedemeyer-Böhm, J. Leenaarts, W. Schaffenberger, HGL
- Solution of the HD or MHD equations coupled to equation of radiative transfer
- Result: statistical realization of flow from sub-photosphere to chromosphere

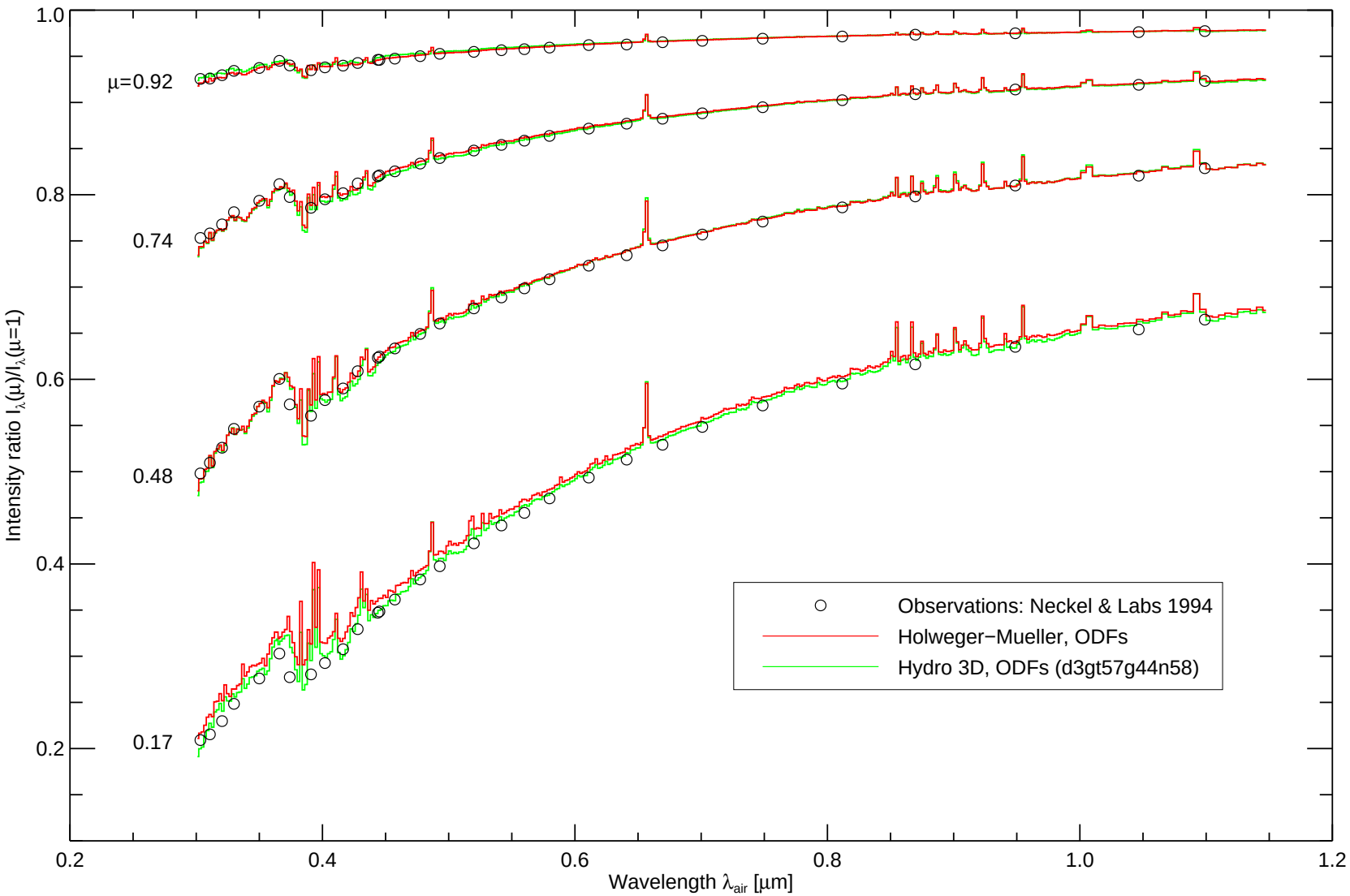
CIFIST+ 3D model atmosphere grid



(Ludwig, Caffau, Steffen, Freytag, Bonifacio, Kučinskas)

- $T_{\rm eff}$ - $\log g$ - $[{\rm M/H}]$ space, filling of parameter space mainly project driven
- In addition models at $[{\rm M/H}] = -4$, brown dwarfs, and hydrogen-rich WDs

3D model versus semi-empirical Holweger-Müller model



▷ Theory challenges precision of semi-empirical models and observations!

The CIFIST oxygen project (2008)

E. Caffau, H.-G. Ludwig, M. Steffen, T.R. Ayres, R. Cayrel,
P. Bonifacio, B. Plez, B. Freytag, W. Livingston

- Total of 9 spectral lines of O I (6158 . . . 11302 Å)
- 2 different disk-center spectra ("intensity")
  spectra of center-to-limb variation for selected lines
- 2 different full-disk spectra ("flux")
- Different 1D reference atmospheres (LHD, HM, AT9)
- 3D CO^{5}BOLD simulation
  - 19 snapshots representing the flow statistics
  - 12-bin multi-group opacities (MARCS)
- Include careful error estimates

Comparison Asplund et al. (2004) and CIFIST oxygen project

Line (nm)	Asplund et al. (2004) EW (pm)	A(O)	oxygen project EW (pm)	A(O)
615.8	0.41	8.62	0.36	8.64
630.0	0.43	8.69	0.35	8.70
636.3	0.14	8.67	0.15	8.78
777.1	7.12	8.64	8.14	8.75
777.4	6.18	8.65	6.86	8.74
777.5	4.88	8.66	5.42	8.76
884.6	3.52	8.60	3.51	8.68

- 5 allowed and 2 forbidden (630.0, 636.3 nm) transitions in common (all for $S_{\mathrm{H}} = 0$)
- Allowed transitions affected by NLTE effects, particularly O-triplet
- Can be constraint by studying center-to-limb variation
  - uncertain collisions with neutral H parameterized by S_{H}

$$S_{\mathrm{H}}^{\mathrm{Asplund}} = 1 \quad \text{corresponds to} \quad S_{\mathrm{H}}^{\mathrm{CIFIST}} = 0$$

- Agreement on absolute NLTE *corrections* for triplet lines

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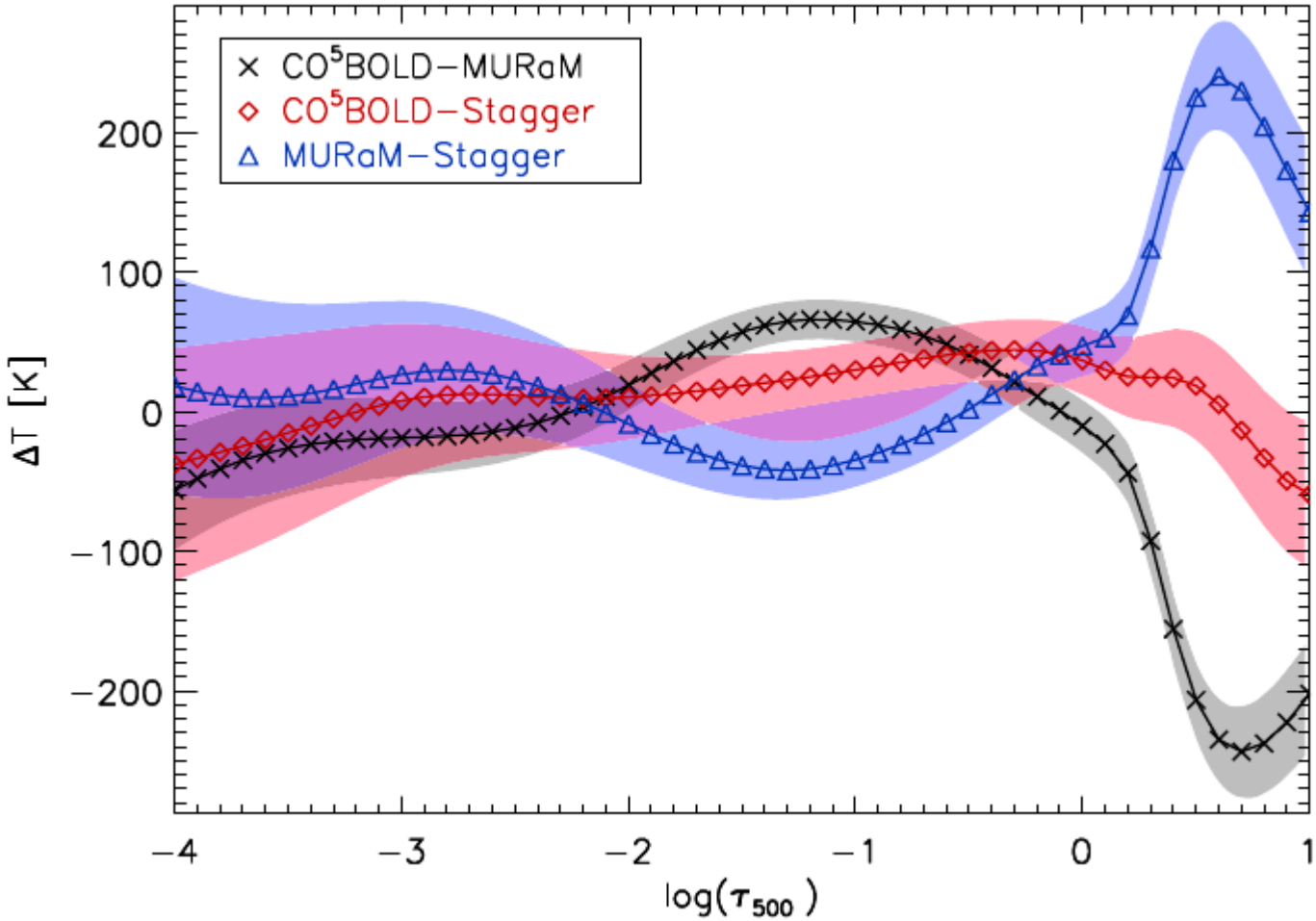
- Differences in measured equivalent width → O-triplet lines
  - choice of observational material → quality of solar atlases?
  - continuum placement critical; CIFIST "high", Asplund et al. "low"
- Contribution of Ni to O I+Ni I 630 nm blend? → prime O-abundance indicator
- Same EWs give significantly higher abundances in oxygen project
  - systematics in 3D models and associated spectral synthesis codes?

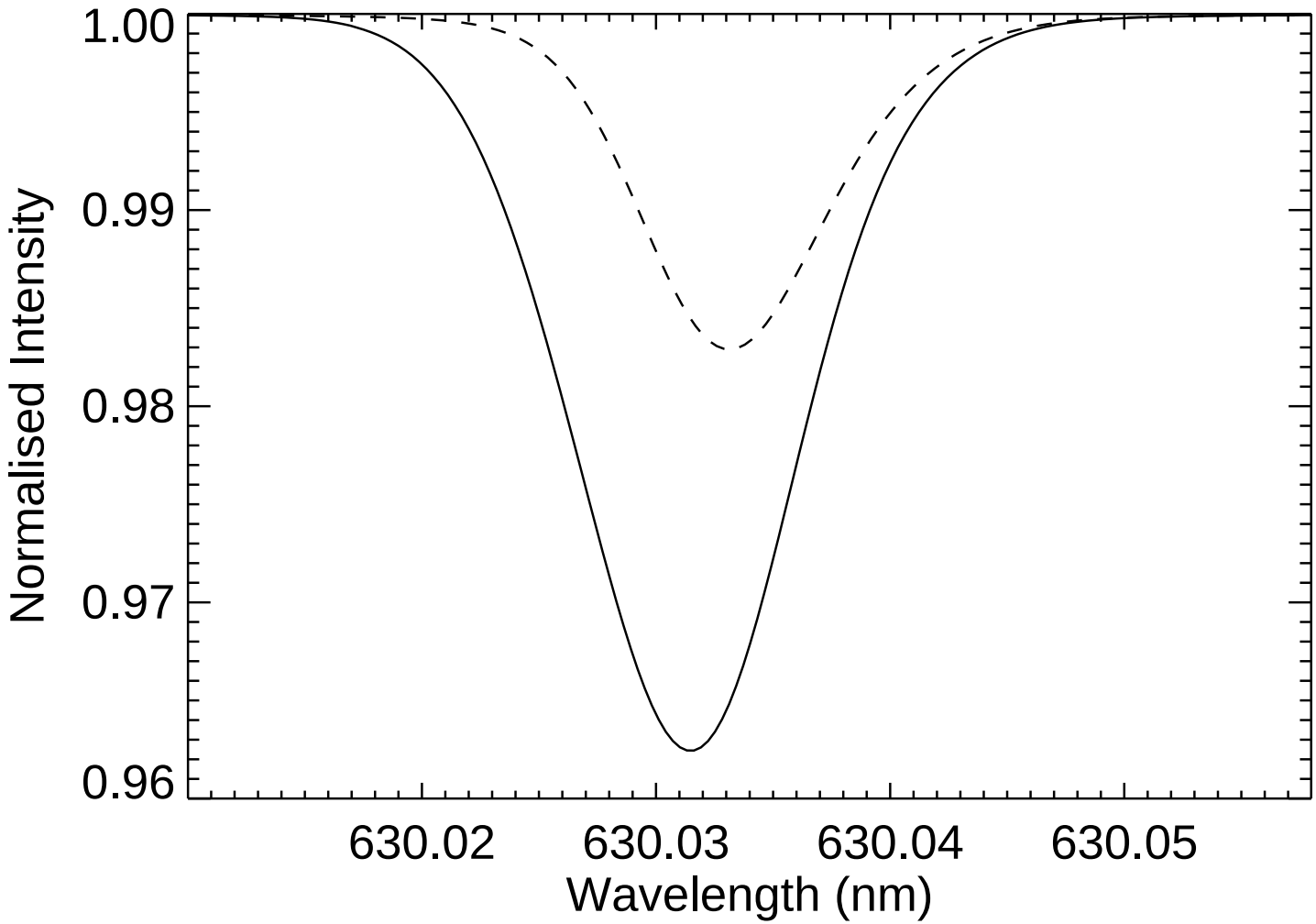
3D model systematics: 3D models move closer



(Figure from Beeck et al. 2012)

- CO^{5}BOLD and STAGGER (Collet et al. 2011) agree within 50 K for $\tau_{500} < 1$
- Discrepancies reduced by about factor 2

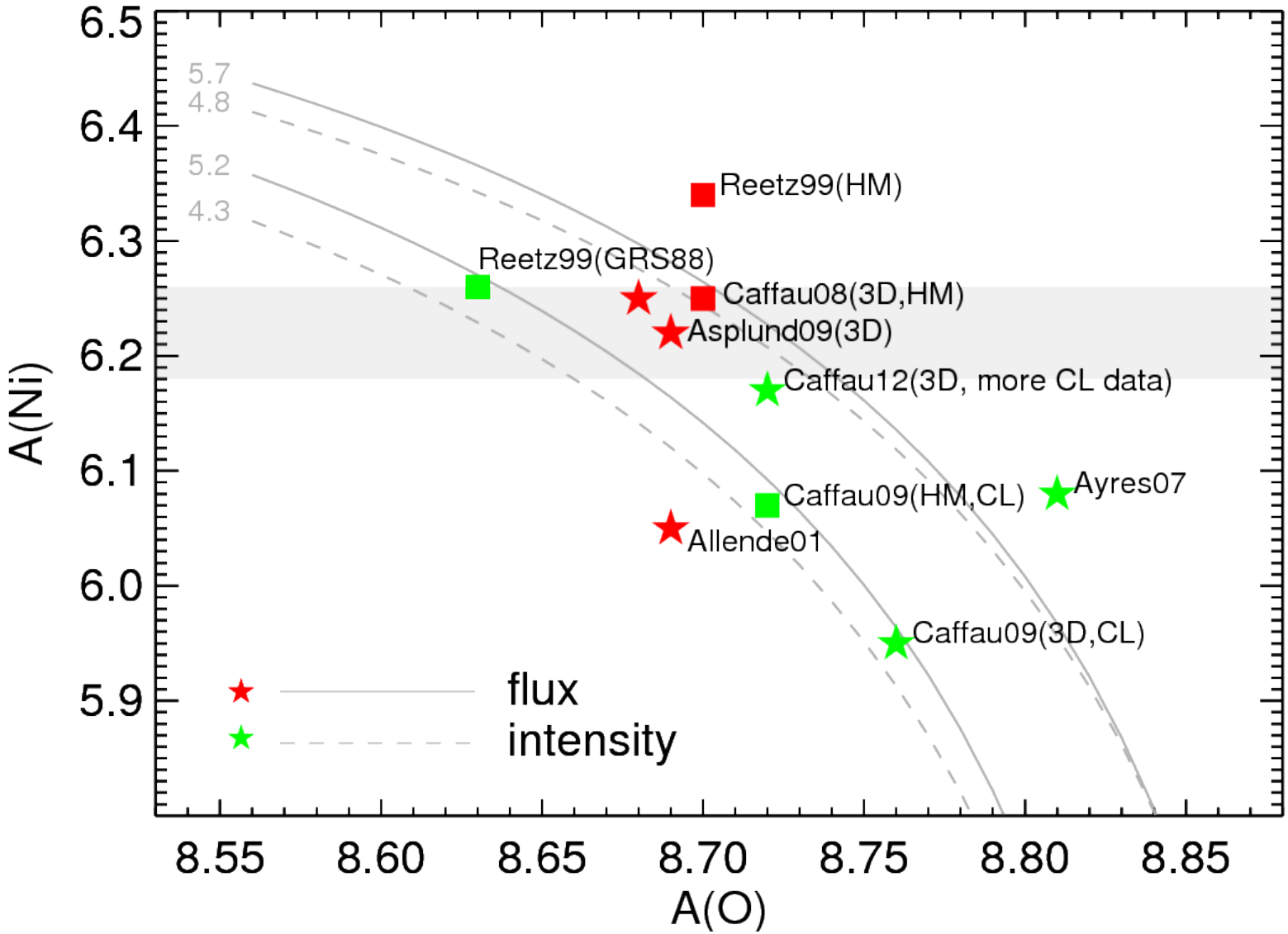
The [OI]+Ni I feature at 630 nm



synthesis for disk-center, dashed: Ni only, solid: O+Ni

- Prime abundance indicator for O in the Sun and late-type stars, immune to NLTE
- Blended by a Ni line, gf measured by Johansson et al. 2003

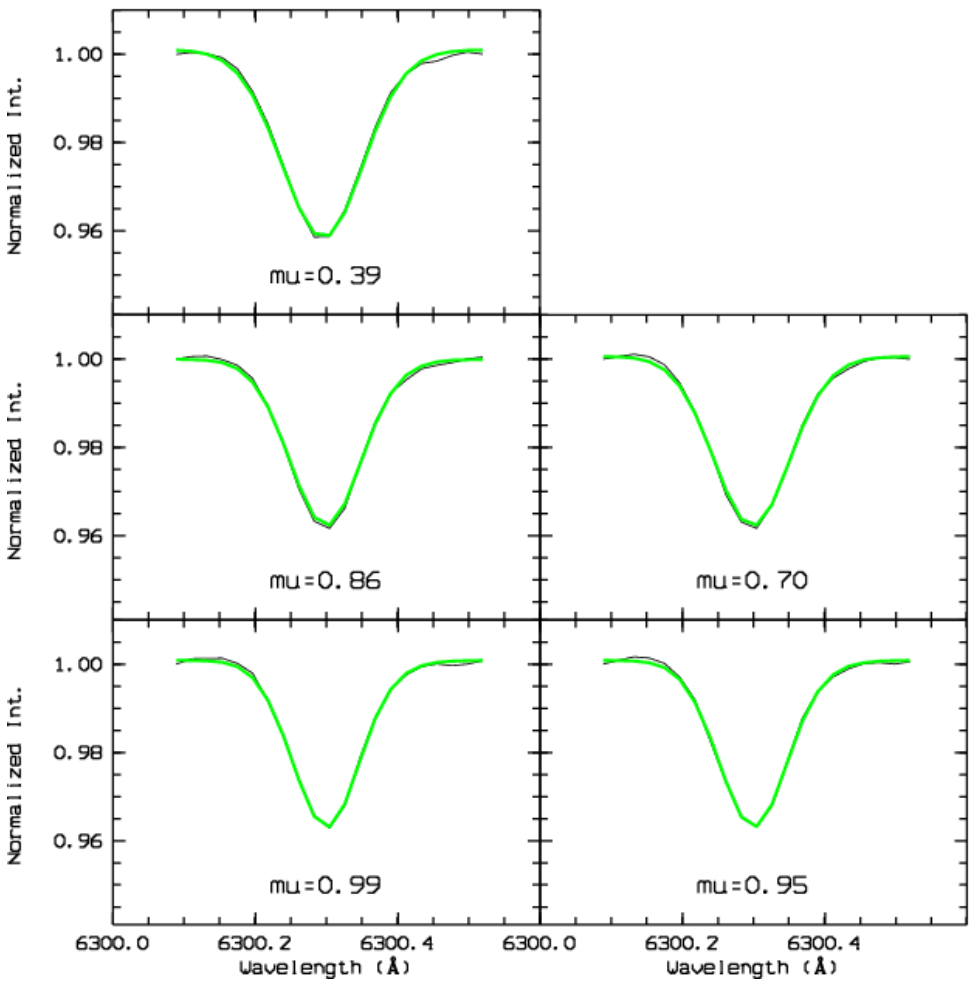
Short, incomplete history of disentangling the [OI]+Ni I feature

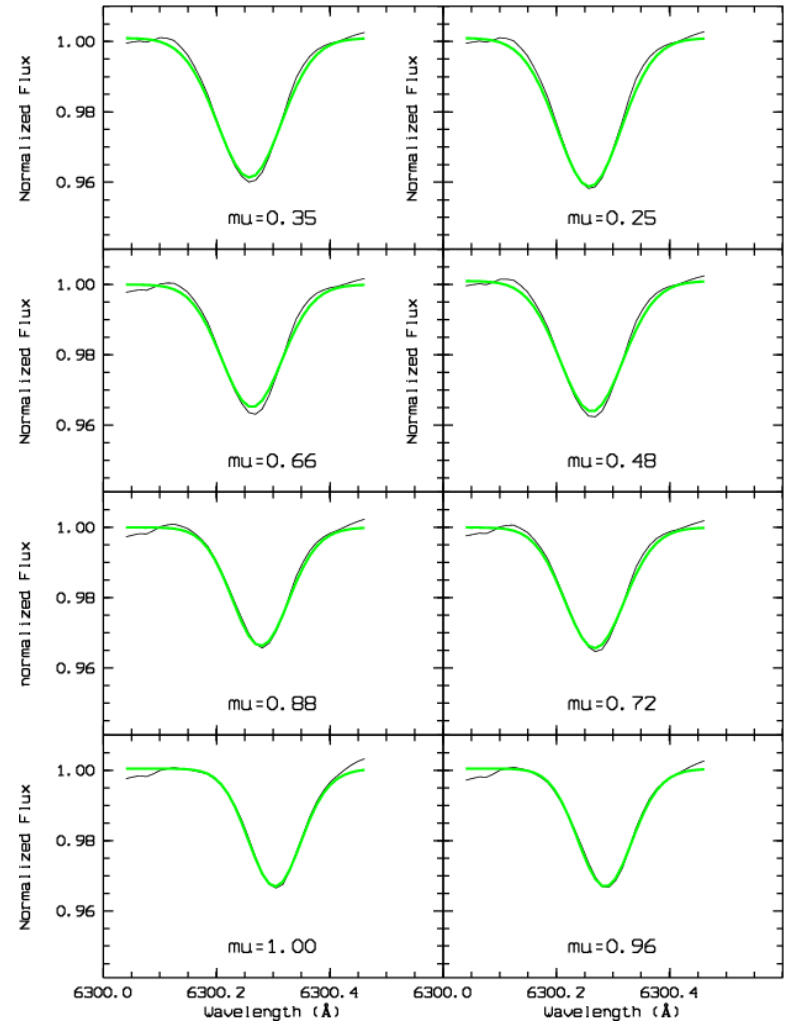


(dashed/green: disk-center, solid/red: disk-integrated; star: 3D, square: 1D model; grey bar: Ni range)

- Recognition of possible Ni blend → low-O abundance from feature

Contributions derived from center-to-limb variation?

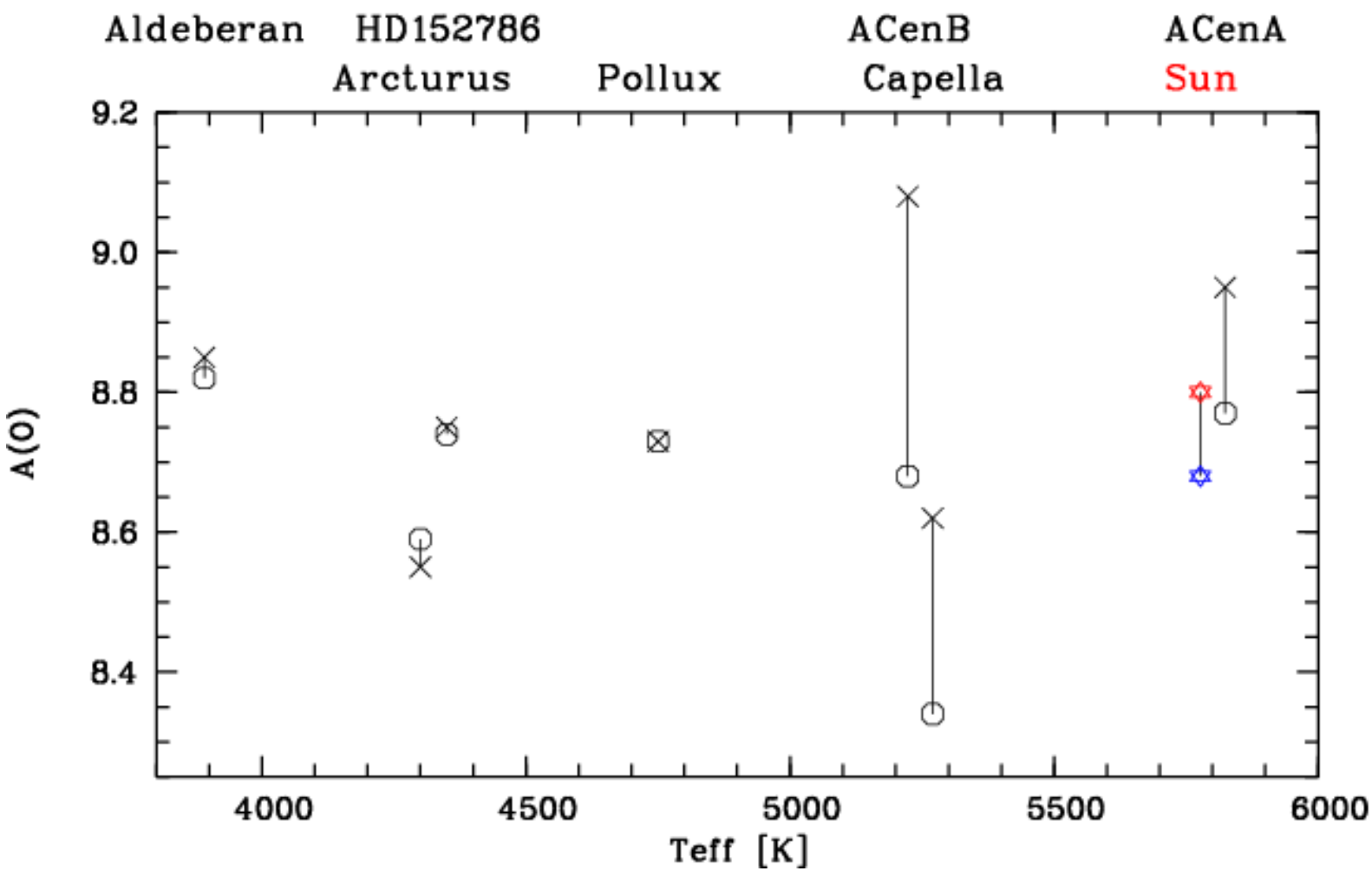




Left: HINODE, J.-M. Malherbe **Right**: THEMIS, Tenerife, J.-M. Malherbe

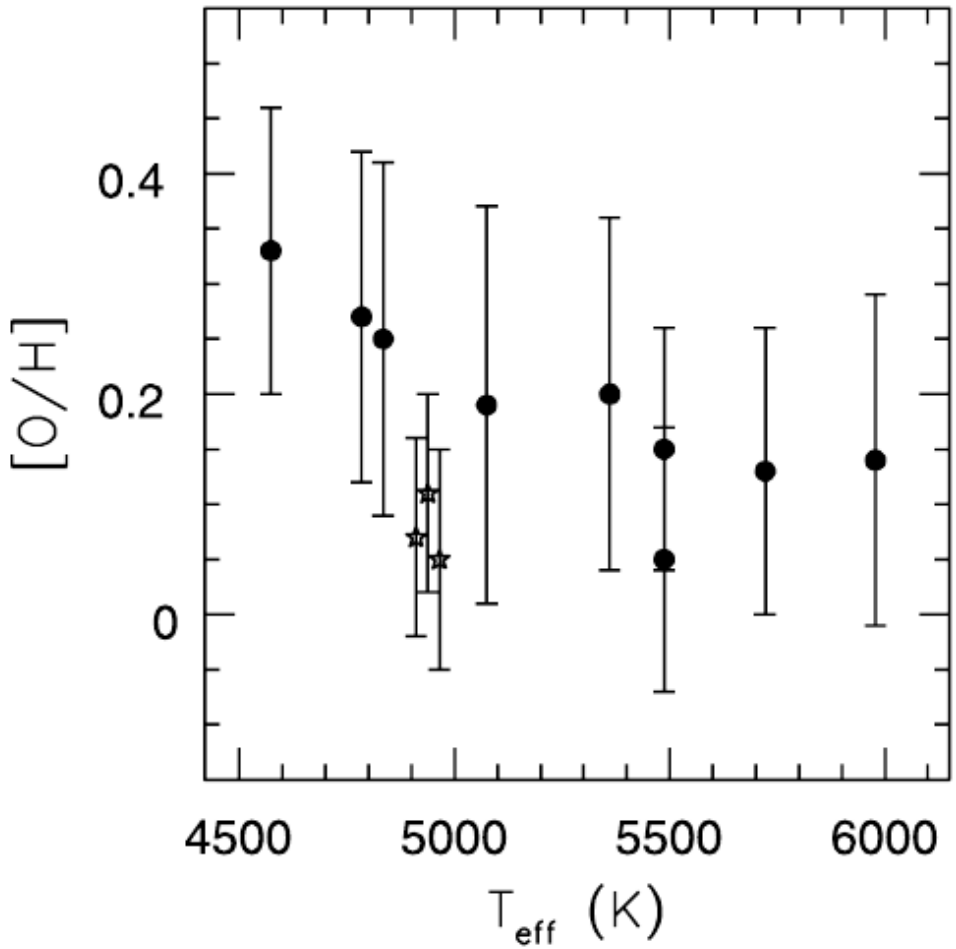
- Ni: $\chi_{\rm low} = 4.3\,{\rm eV}$, O: $\chi_{\rm low} = 0.0\,{\rm eV}$ $\rightarrow$ line formation with different T-response
- HINODE data: A(O)=8.71, A(Ni)=6.17; THEMIS data: A(O)=8.61, A(Ni)=6.25

Abundance discrepancy 630 vs 636 nm – a look at stars



- Archival UVES and HARPS spectra, new THEMIS(!) spectra
- 1D analysis with ATLAS/SYNTHE suite
  → correlation with effective temperature???

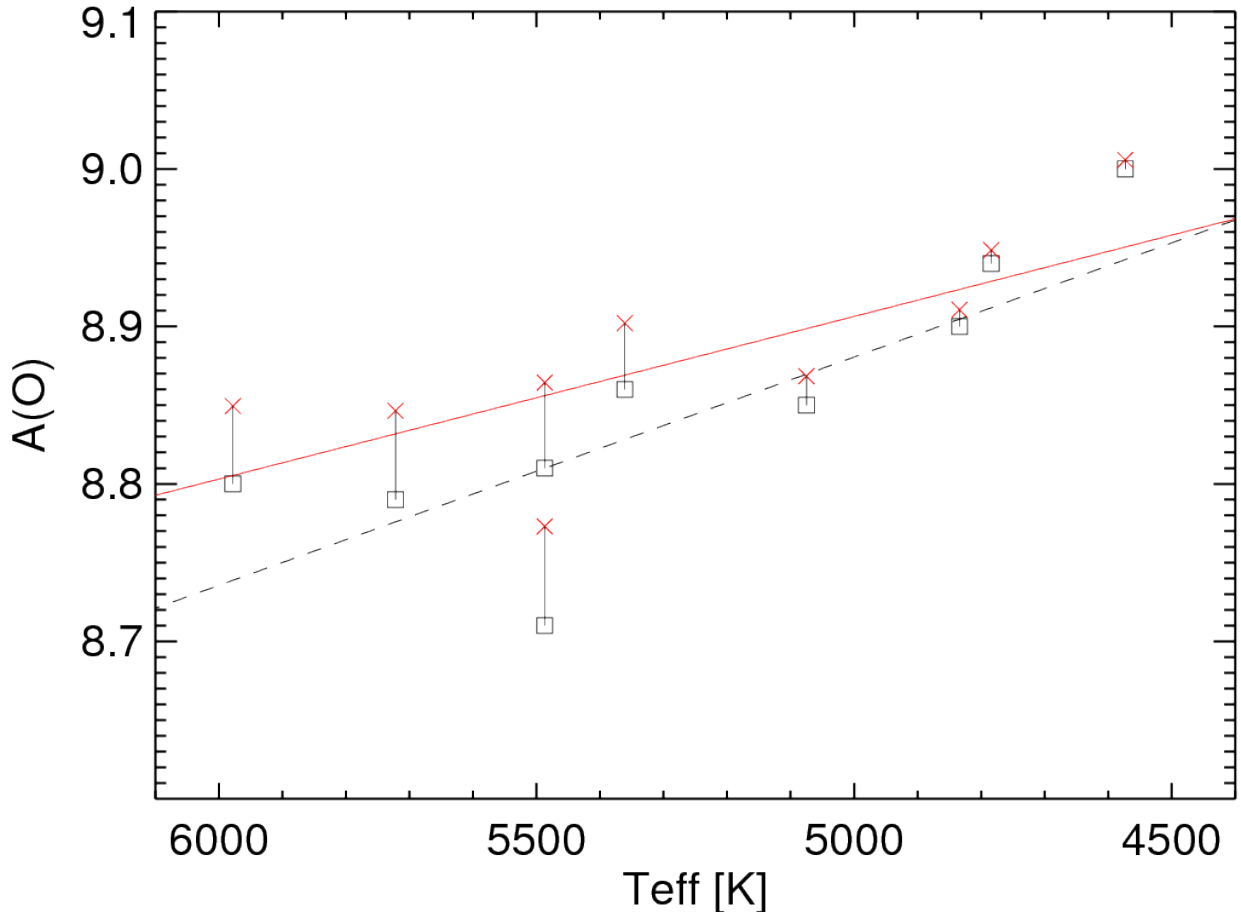
Hyades: chemical homogeneity versus model problems



(from Schuler et al. 2006, dwarfs dots, giants stars)

- Oxygen from forbidden 630 nm feature in Hyades
- Chemical inhomogeneous or modelling deficit?

3D abundance corrections to 630 nm feature for Hyades dwarfs



- Hotter dwarfs have noticeable corrections
- Overall trend reduced but not at all eliminated
- Chemical homogeneity of stellar clusters? Chemical tagging?

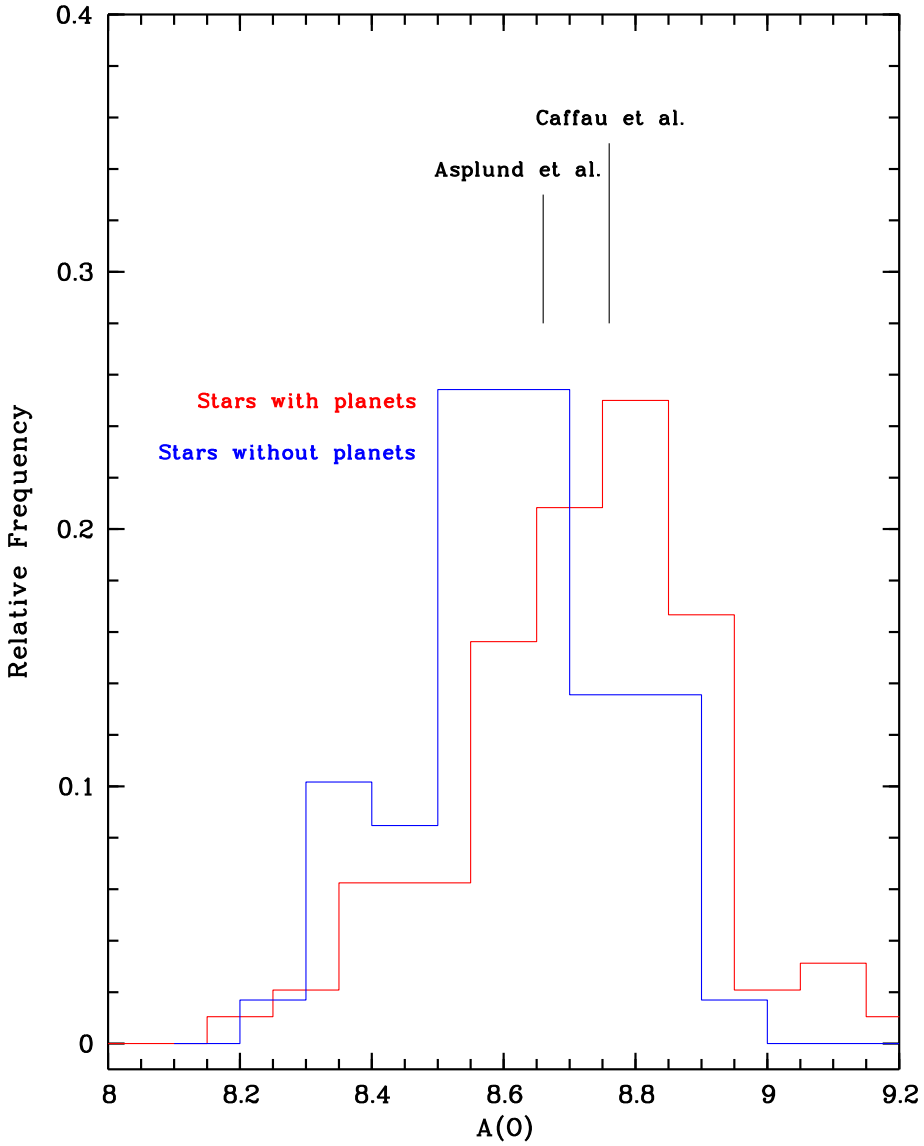
Take away ...

- There is a (slow) convergence towards a 3D concordance value of the solar oxygen abundance
  - the solar photosphere has a "lowish" oxygen abundance
- Low S_{H} and slightly lower EW of triplet lines than assumed in Caffau et al. (2008)

A(O) = 8.73±0.04	$\mathrm{S_H} = 0$
A(O) = 8.76±0.04	$\mathrm{S_H} = 1/3$
A(O) = 8.79±0.04	$\mathrm{S_H} = 1$

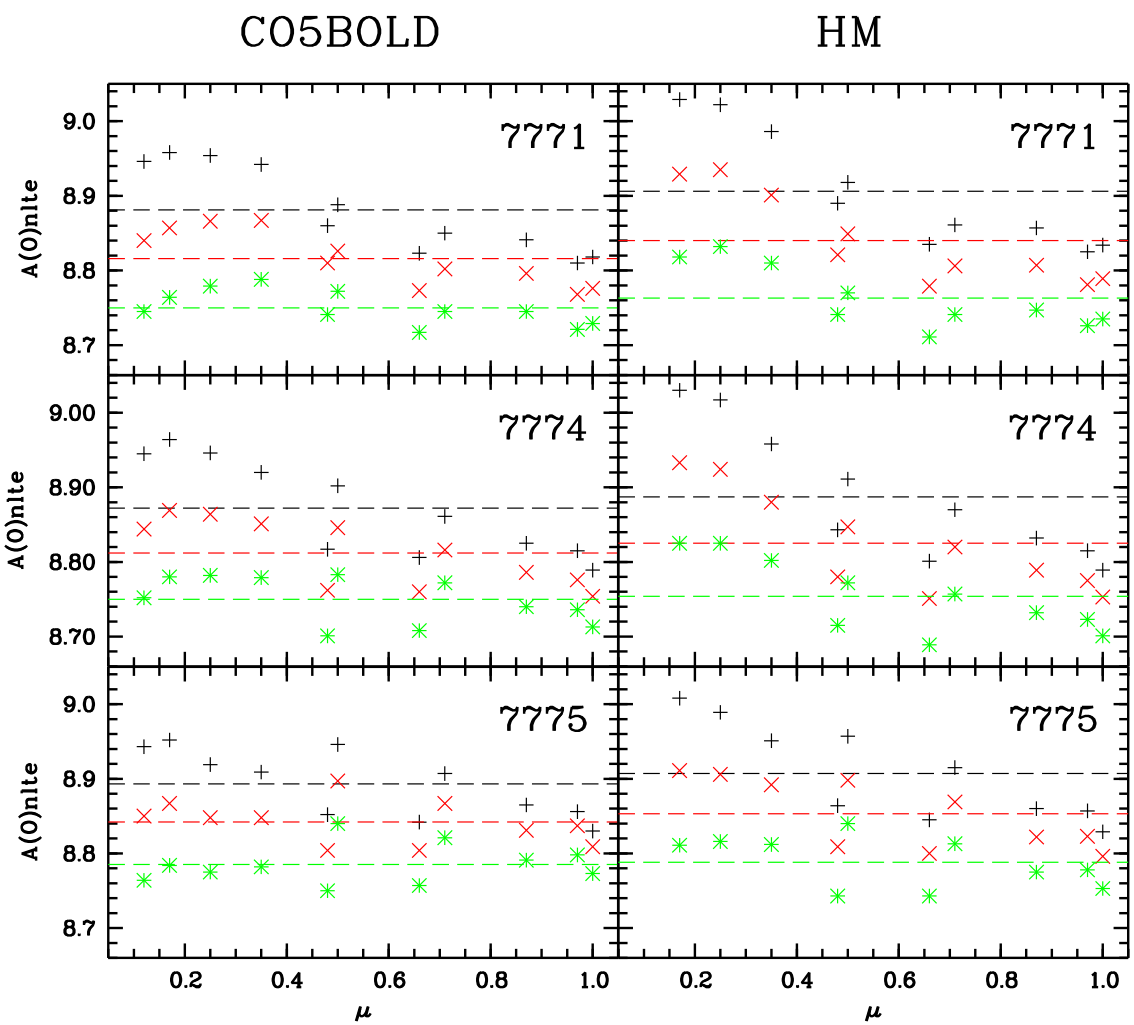
- Remaining questions ...
  - discrepancy of abundances derived from 630 nm and 636 nm forbidden lines
  - molecular abundance indicators (CO, OH)?
- There are repercussions on the determination of stellar O-abundances

Is the chemical composition of the Sun atypical?



- Local ISM, B-stars show low O abundance
- Ecuvillon et al. (2006)
  - 96 planet hosting stars
  - 59 without planet detection
  - volume limited sample
- O abundance follows trend in overall metallicity
- Higher O abundance plausible for planet hosting stars
- Did the Sun migrate to present galactocentric radius?

Center-to-limb variation of the O triplet lines



- NLTE corrections depending on limb angle $\mu = \cos(\theta)$
- Most homogeneous with $\mathrm{S_H} = 0$
- 3D model outperforms HM
  - scatter $\sigma_{\mathrm{3D}} = 0.032\,\mathrm{dex}$
  - scatter $\sigma_{\mathrm{HM}} = 0.044\,\mathrm{dex}$

black: $\mathrm{S_H} = 1$ red: $\mathrm{S_H} = 1/3$ green: $\mathrm{S_H} = 0$

Are 3D model atmospheres responsible for the low O abundance?

- Confusion due to different reference models
- LHD reference model
  - standard 1D model: hydrostatic, MLT
  - opacities, EOS, radiative transfer scheme identical to 3D

$$\mathrm{A(O)}_{\mathrm{3D}}\text{-}\mathrm{A(O)}_{\mathrm{1D,LHD}}=+0.05\,\mathrm{dex}$$

- All lines except 615.8 nm have a positive 3D-1D correction (α_{MLT} dependent)
- In a strictly differential comparison the 3D model pushes the solar O abundance up relative to the 1D result!

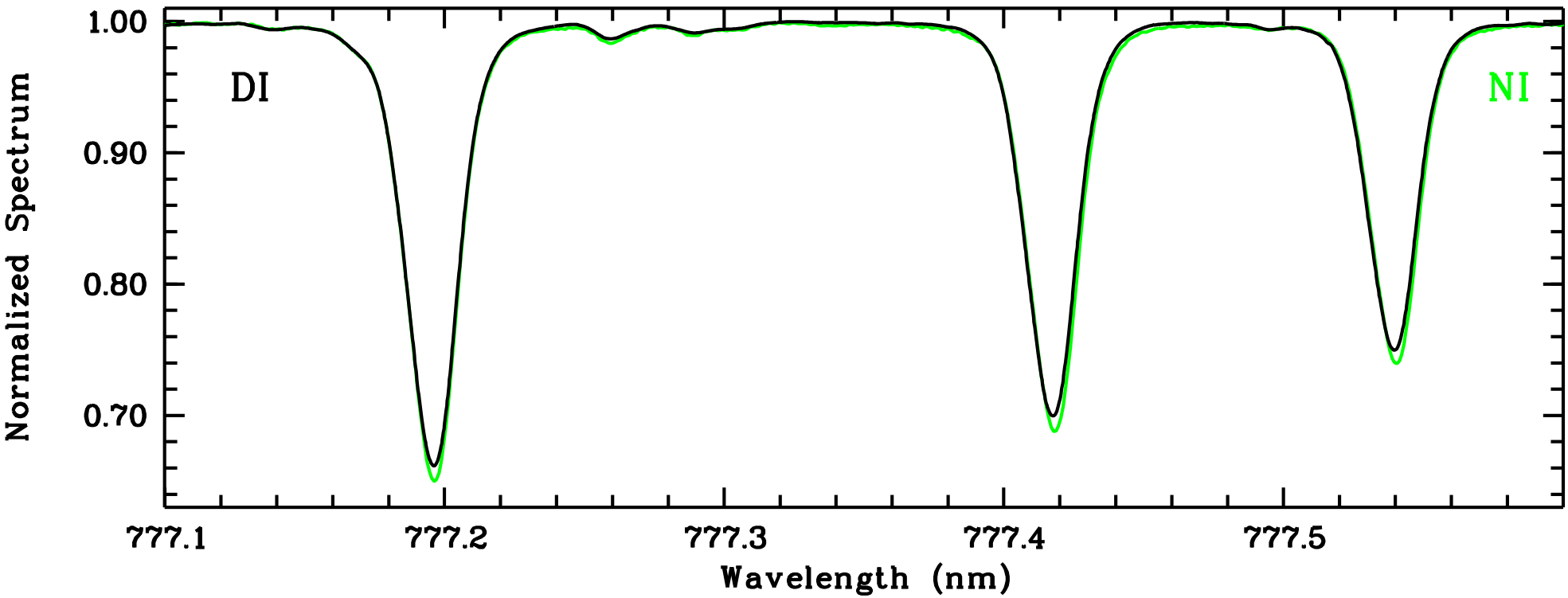
Departures from thermodynamic equilibrium

- All except the forbidden O lines suffer from departures from LTE
  - in particular 777 nm infrared triplet lines
- 1D NLTE computations with Kiel code, model atom of Paunzen at al. 1999
  - solar NLTE for oxygen essentially 1D problem
- Inelastic collisions with neutral H atoms important factor for NLTE corrections

A(O) = 8.73±0.04	$\mathrm{S_H} = 0$
A(O) = 8.76±0.04	$\mathrm{S_H} = 1/3$
A(O) = 8.79±0.04	$\mathrm{S_H} = 1$

- About half of the formal error is related to the uncertainty in the NLTE corrections
- Preferences: Asplund et al. $\mathrm{S_H} = 0$ – while empirically finding $\mathrm{S_H} = 1$

Imperfect solar observational material

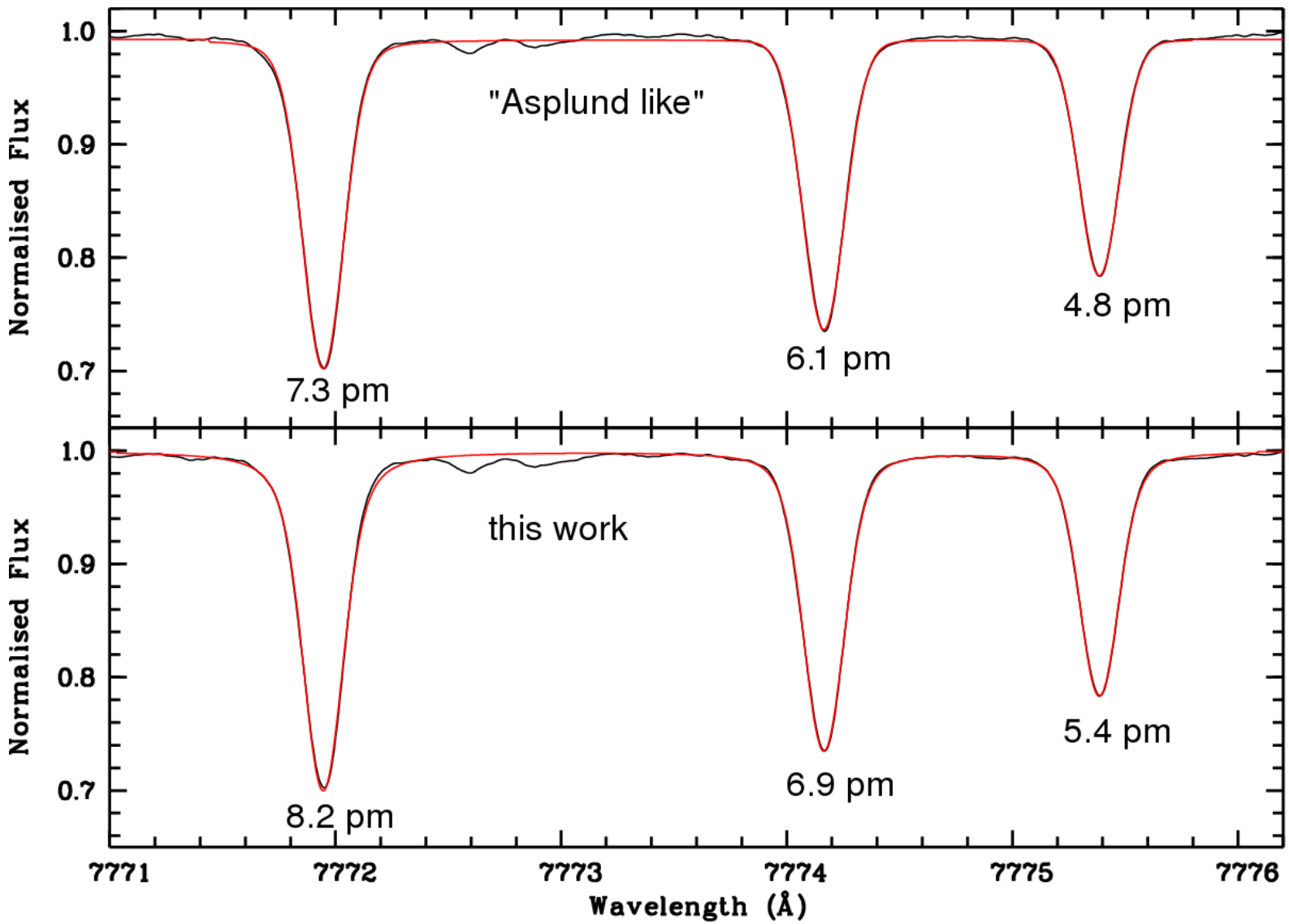


Delbouille disk-center intensity spectrum (DI)
Neckel disk-center intensity spectrum (NI)

EWs differ by 4, 7, 3 %

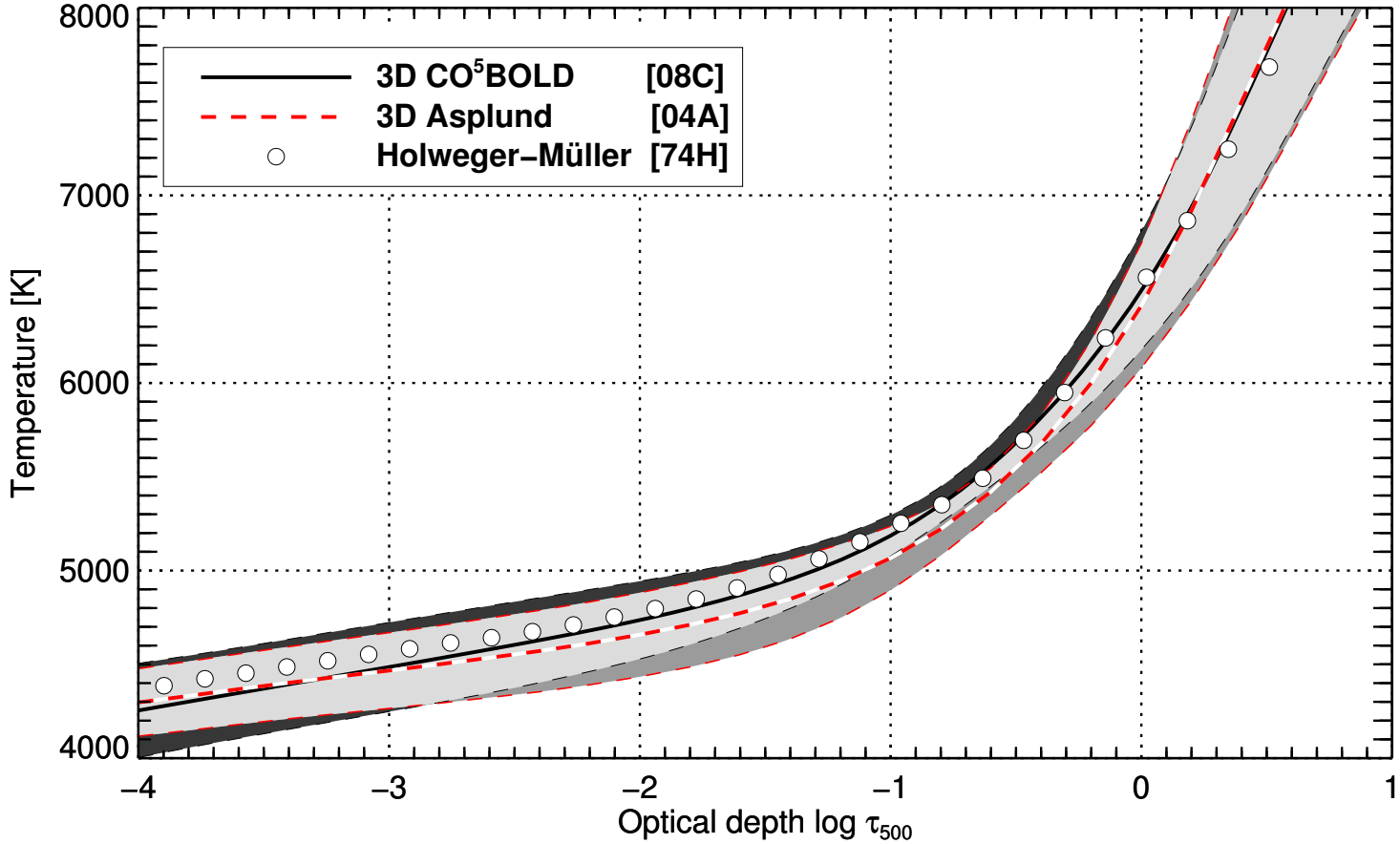
- Surprising differences in high-quality solar atlases

Measurement of equivalent widths



- Treatment of line wings and continuum placement critical, $\approx 12\,\%$ difference

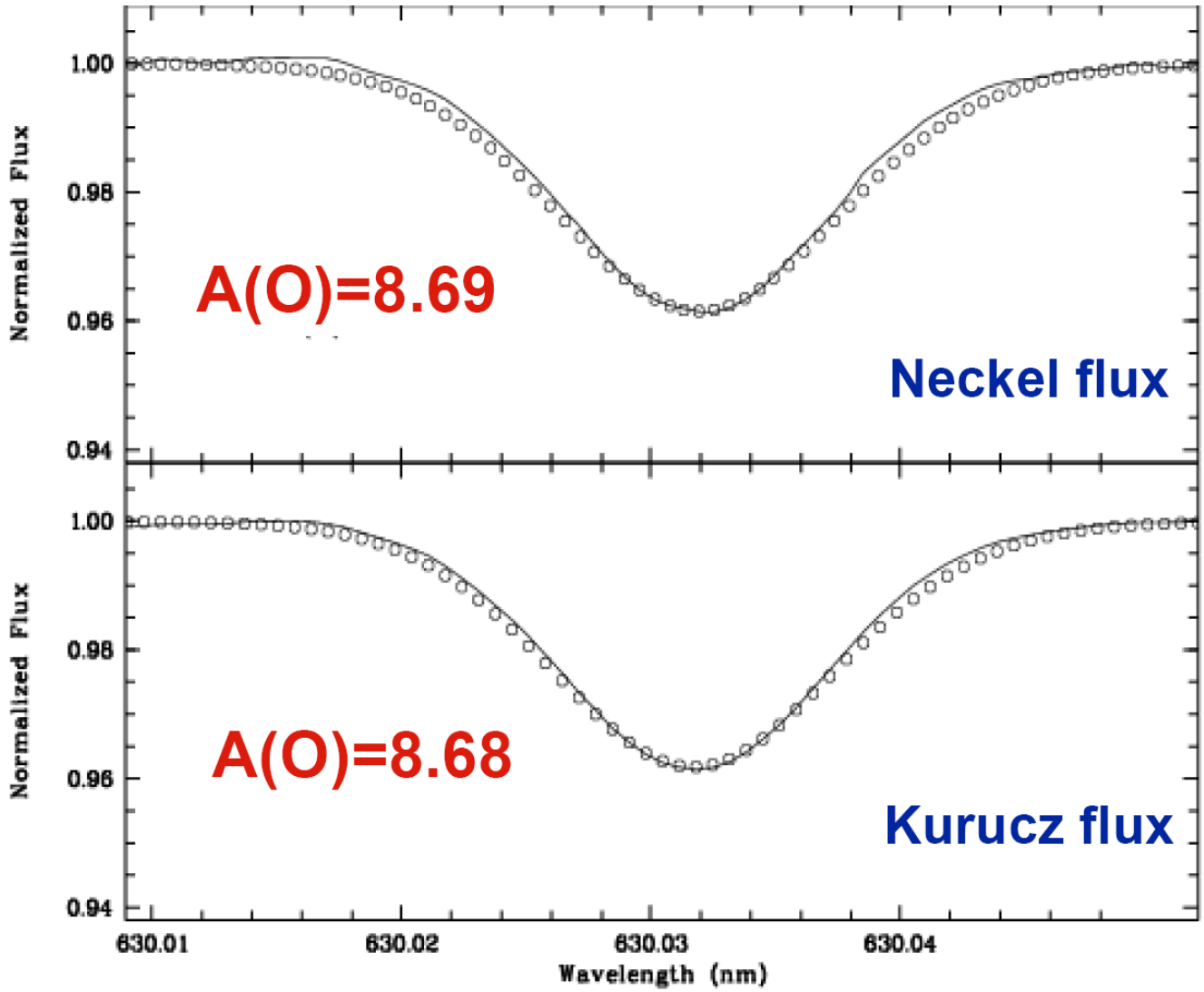
Model systematics: differences in 3D models



(Figure courtesy M. Steffen)

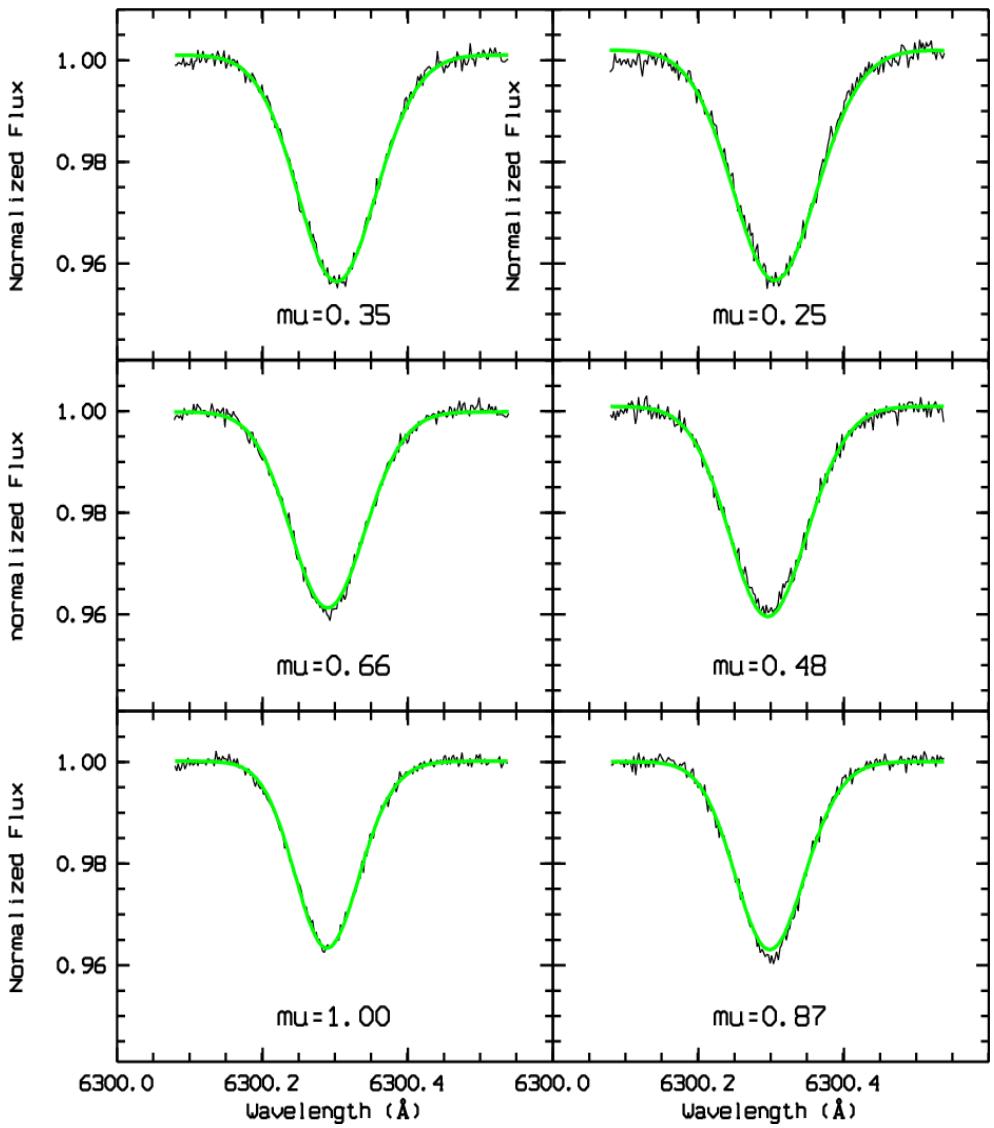
- Solar CO^{5}BOLD and Asplund et al. (2004) model different
- Tests point to noticeable differences due to the spectral synthesis codes

[OI]+Ni blend @ 6300 Å, $\lambda/\Delta\lambda \sim$300 000, S/N$\sim$2000, 3D fit



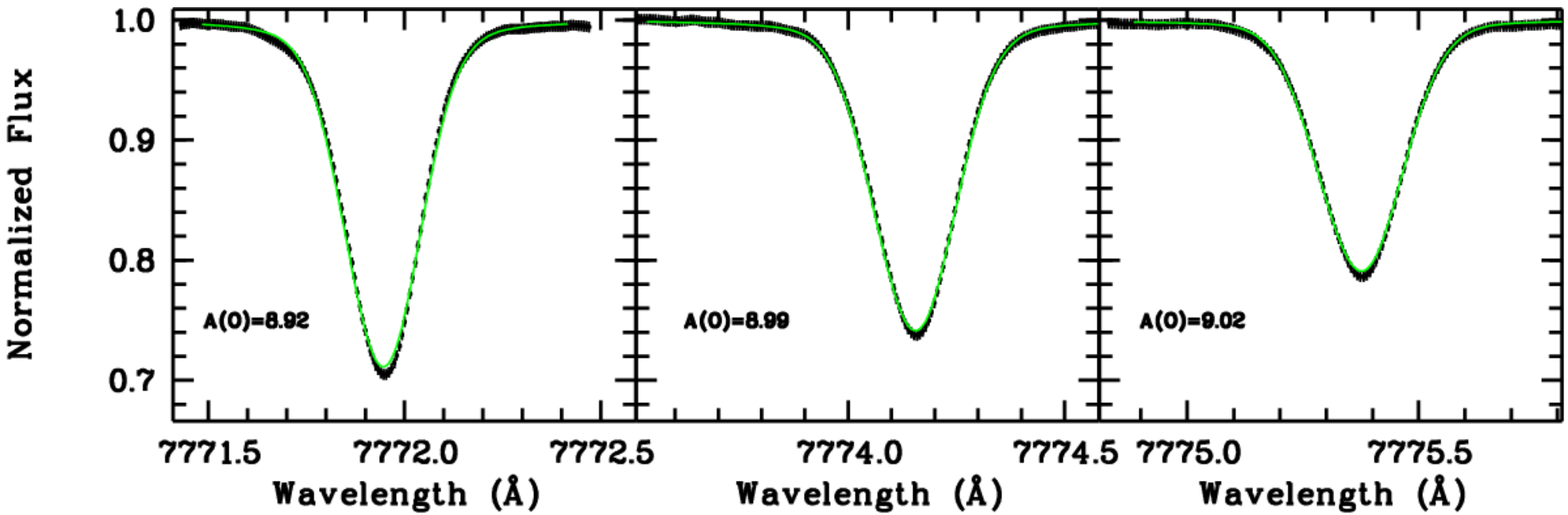
- Important O abundance indicator, separation of O and Ni contribution difficult
- Even for the Sun observational material not perfectly homogeneous and complete

Center-to-limb variation of the [OI]+Ni blend



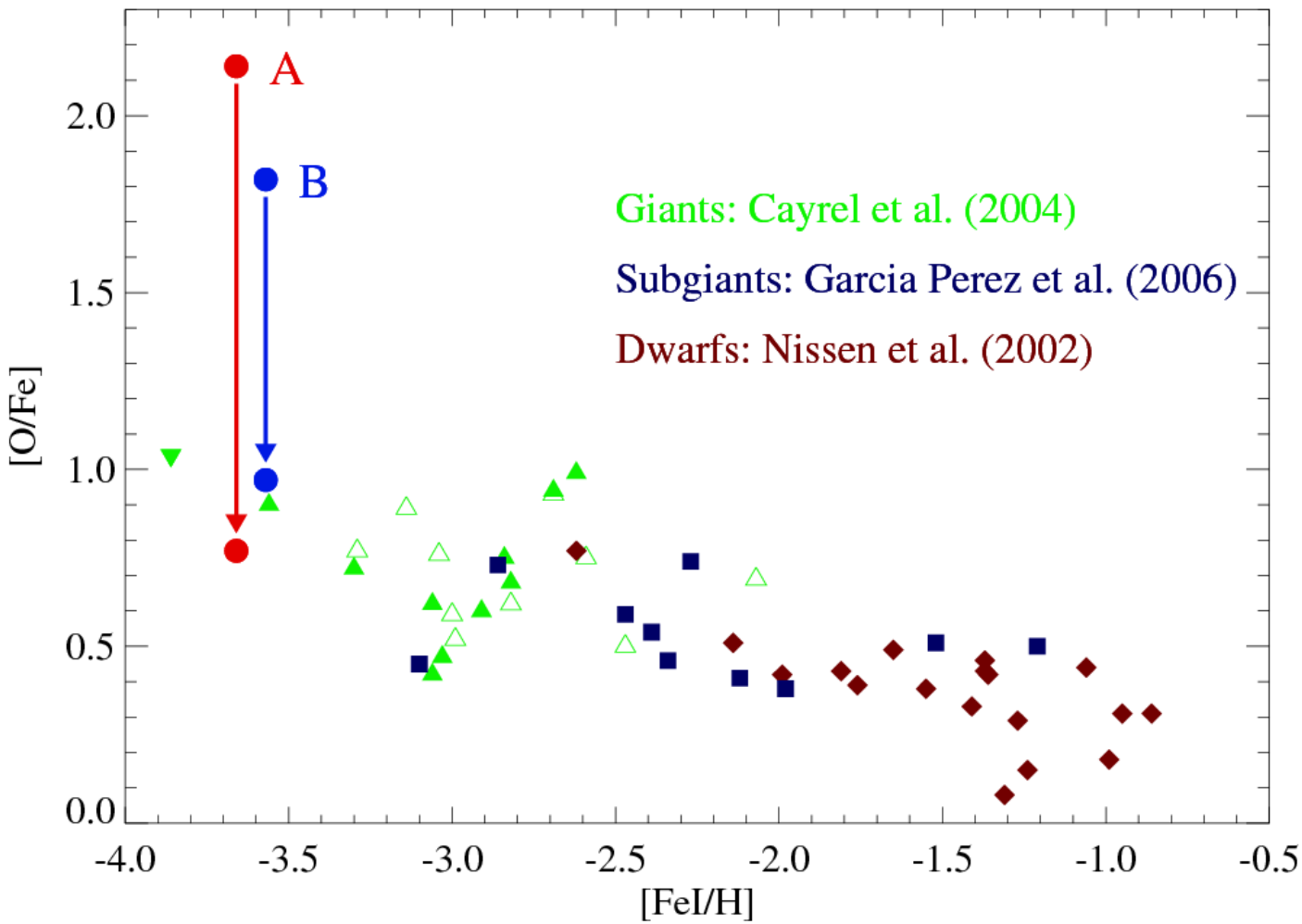
- Spectra different limb-angles μ
- Different thermodynamic formation conditions
- Good fits
- However: degeneracy between contributions of O and Ni not broken

Oxygen near-infrared triplet



- 3D and 1D models provide satisfactory fit to observed line profiles in LTE
- Abundances of individual components of triplet different – and rather high
- High excitation lines, level populations suffer departures from LTE
- How large are the NLTE abundance corrections?
  - poorly known collisional cross sections with neutral hydrogen atoms important

The extremely metal-poor binary CS 22876-032 ([Fe/H]≈ -3.7)



plot courtesy of J. González Hernández

- O abundances from OH lines in the UV, 3D abundance corrections -1.0. . .-1.5 dex
- Other observations based on [OI] 6300 Å line, no 3D abundance corrections applied