The Sun in the context of stellar abundance work

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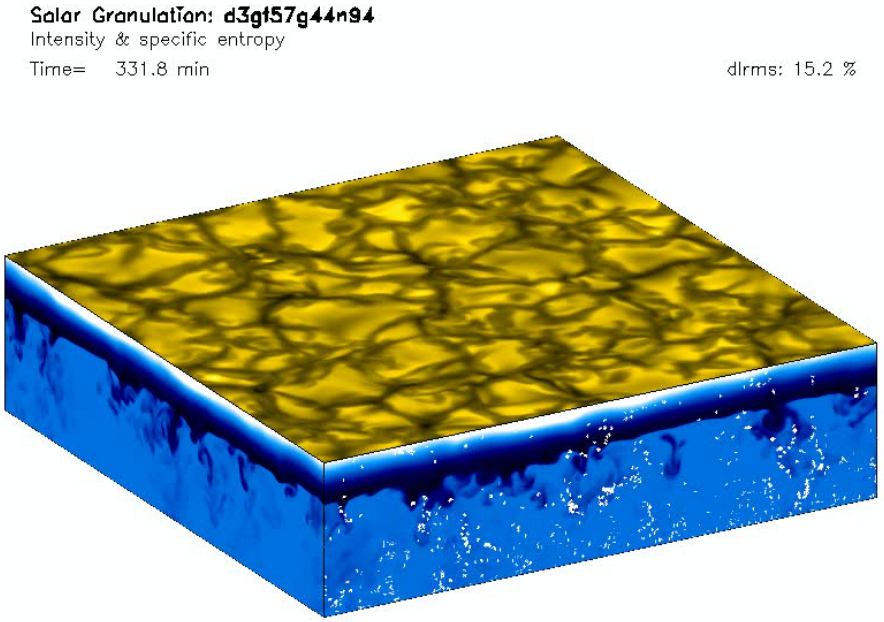
Overview

- CO^{5}BOLD models in the stellar context
  - CO^{5}BOLD? What's that?
  - CIFIST+ 3D model atmosphere grid
- 3D model systematics, comparison to others
- The solar oxygen abundance
  - Quote from the book "Oxygen in the Universe" (Stasinska et al. 2011) from the section on the solar photospheric abundance of oxygen:

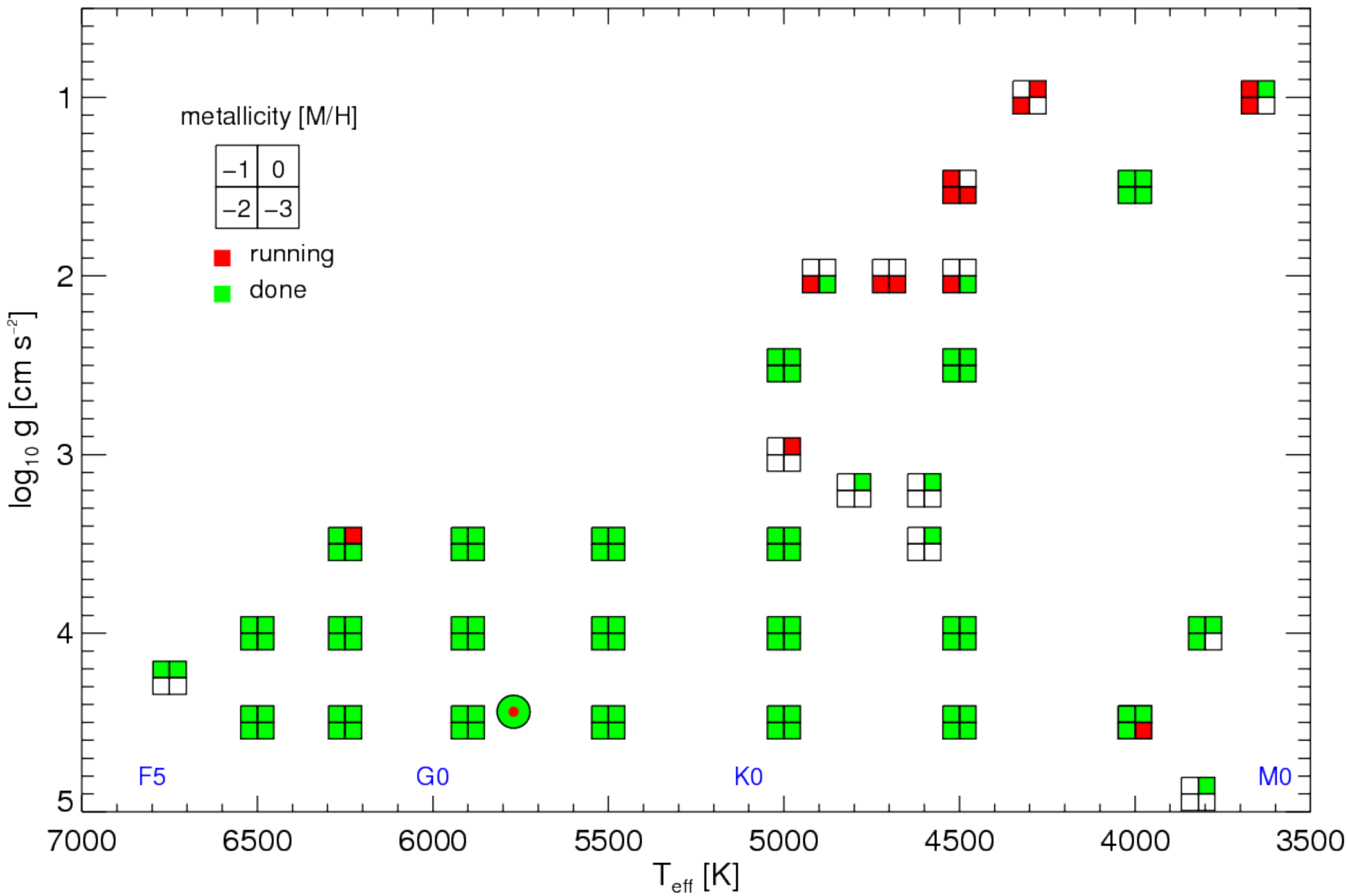
    In this section the team of authors ran into the awkward situation that there was no unanimous opinion among the team members about the best procedure of its determination and ultimately best estimate of the oxygen abundance in the solar atmosphere.
- More on solar abundances, successes and lingering problems
- Some – but not all – aspects intended as message to solar astronomers

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

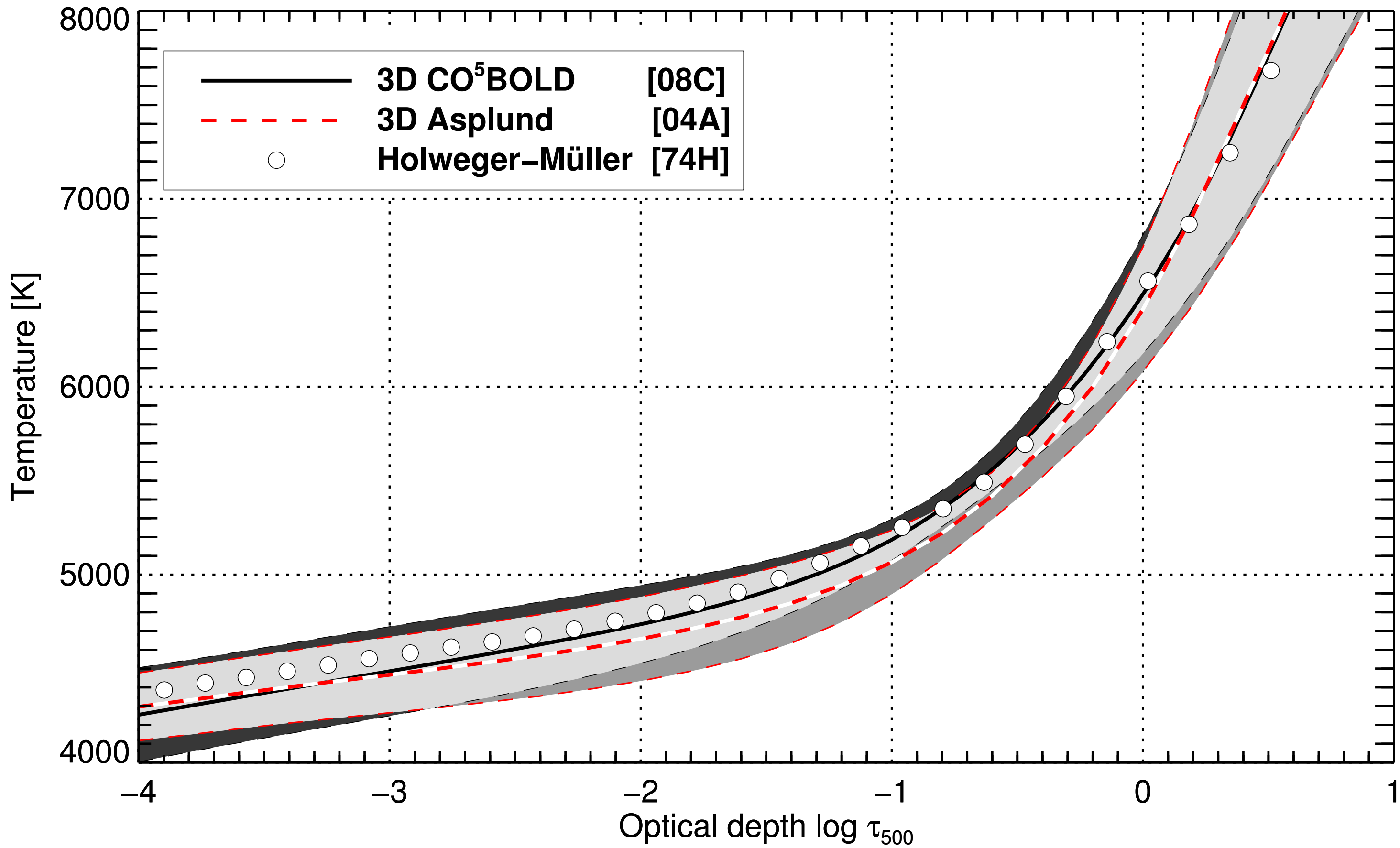
CIFIST+ 3D model atmosphere grid



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

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

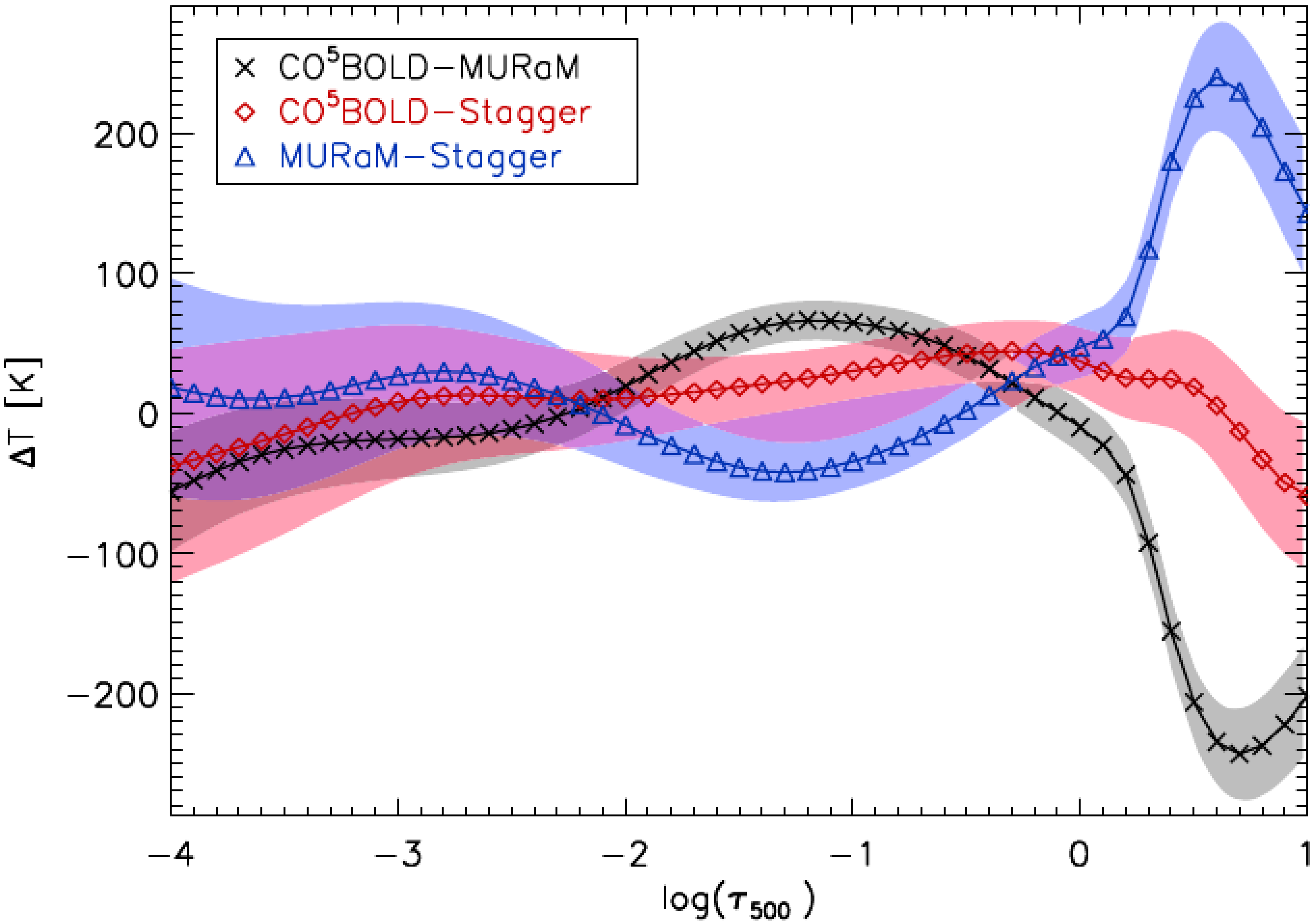
3D model systematics: differences in 3D models



(Figure courtesy M. Steffen)

- Solar CO^{5}BOLD and Asplund et al. (2004) model differ by $\approx 100\,\mathrm{K}$

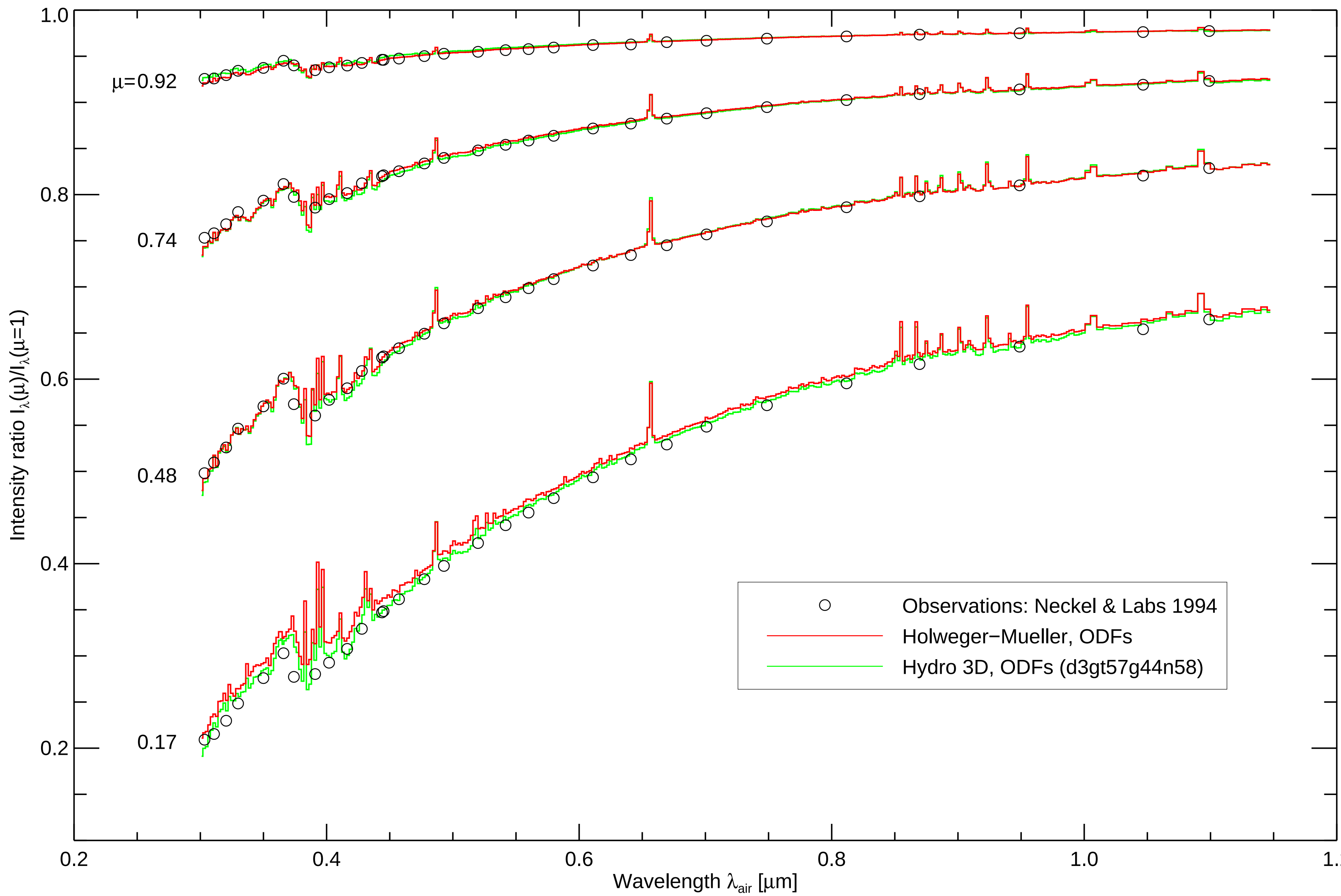
3D model systematics: 3D models move closer



(Figure from Beeck et al. 2012)

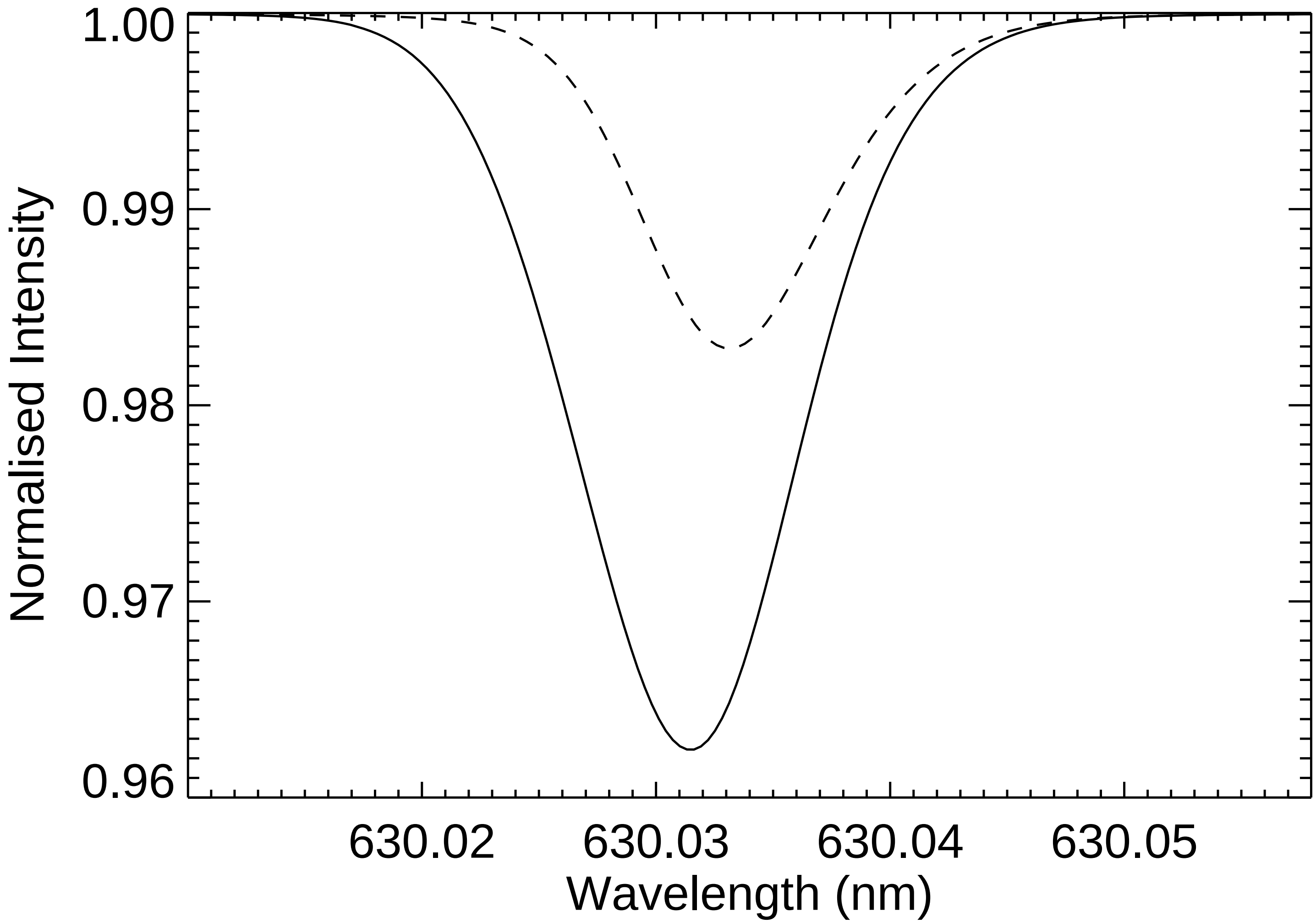
- CO^{5}BOLD and STAGGER (Collet et al. 2011) agree within 50 K for $\tau_{500} < 1$
- Discrepancies reduced by about factor 2

3D model versus semi-empirical Holweger-Müller model



- Theory challenges precision of semi-empirical models and observations!
- Absolute intensities at disk-center measured to 1–2 %, higher precision possible?

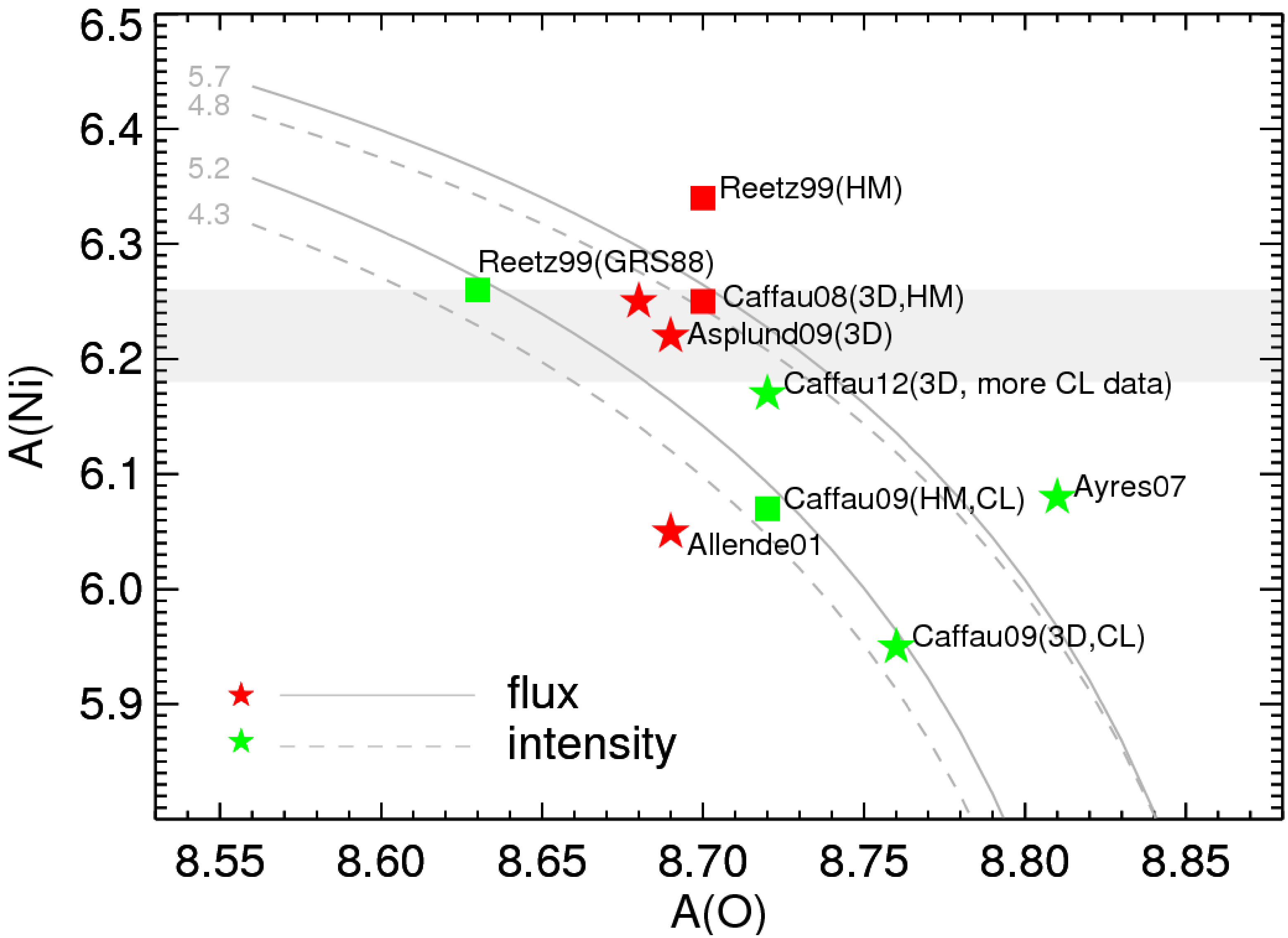
The [OI]+Ni I feature at 630 nm



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

Questions we are confronted with:

- Which is the chemical composition of the solar photosphere?
- Are 3D models important in the abundances determination?
  - yes because:
    - 3D correction can be as large as 0.1 dex
    - no necessity to fix α_{MLT} and ξ_{micro} important for some elements
- Are 3D models responsible for the downward revision of the solar metallicity?
  - no because usually abundances from 3D model larger than from 1D reference model
  - exceptions:
    - Th, because on red wing of strong blend
    - N, lines with high $\mathrm{E}_{\mathrm{low}}$ formed deep in the photosphere
  - this answer depends on the reference 1D model
- How to put the chemical analysis of the Sun with respect to the chemical analysis of other stars

CO5BOLD solar abundances

Photospheric solar abundance of 13 elements

EL	N	CO^5BOLD	AG89	GS98	AGS05	AGSS09
Li	1	1.03 ± 0.03	1.16 ± 0.10	1.10 ± 0.10	1.05 ± 0.10	1.05 ± 0.10
C	43	8.50 ± 0.06	8.56 ± 0.04	8.52 ± 0.06	8.39 ± 0.05	8.43 ± 0.05
N	12	7.86 ± 0.12	8.05 ± 0.04	7.92 ± 0.06	7.78 ± 0.06	7.83 ± 0.05
O	10	8.76 ± 0.07	8.93 ± 0.035	8.83 ± 0.06	8.66 ± 0.05	8.69 ± 0.05
P	5	5.46 ± 0.04	5.45 ± 0.04	5.45 ± 0.04	5.36 ± 0.04	5.41 ± 0.03
S	9	7.16 ± 0.05	7.21 ± 0.06	7.33 ± 0.11	7.14 ± 0.05	7.12 ± 0.03
K	6	5.11 ± 0.09	5.12 ± 0.13	5.12 ± 0.13	5.08 ± 0.07	5.03 ± 0.09
Fe	15	7.52 ± 0.06	7.67 ± 0.03	7.50 ± 0.05	7.45 ± 0.05	7.50 ± 0.04
Zr	15	2.62 ± 0.06	2.60 ± 0.03	2.60 ± 0.02	2.59 ± 0.05	2.58 ± 0.04
Eu	5	0.52 ± 0.03	0.51 ± 0.08	0.51 ± 0.08	0.52 ± 0.06	0.52 ± 0.04
Hf	4	0.87 ± 0.04	0.88 ± 0.08	0.88 ± 0.08	0.88 ± 0.08	0.85 ± 0.04
Os	3	1.36 ± 0.19	1.45 ± 0.10	1.45 ± 0.10	1.45 ± 0.10	1.25 ± 0.07
Th	1	0.08 ± 0.03	0.12 ± 0.06	*0.09 ± 0.02*	*0.06 ± 0.05*	0.02 ± 0.10
Z		0.0154	0.0189	0.0171	0.0122	0.0134
Z/X		0.0211	0.0267	0.0234	0.0165	0.0183

AG89 Anders & Grevesse Geochemica et Cosmochimica acta, 1989 Vol. 53

GS98: Grevesse et Sauval; Space Science Reviews 85: 161-174, 1998

AGS05: Asplund et al; ASP Conferences Series, Vol. 336, 2205

AGGS09: Asplund, Grevesse, Sauval, & Scott, ARA&A 2009

3D abundance corrections

- 3D abundance corrections take into consideration hydro-effects on the abundance determination.

- The abundance of Y being A(Y)$=\log\frac{n_{\rm Y}}{n_{\rm H}}+12$
  - quantity related to the line strength:
    - a ratio of a quantity related to the line opacity $n_{\rm Y}$ over one related to the continuum opacity mainly due to H^- in the cool dwarfs.

- We define them as:
  - $\mathrm{A(Y)}_{\rm 3D} - \mathrm{A(Y)}_{\rm 1D_{LHD}}$
    takes into consideration the effects of convection on 3D temperature structure

  - $\mathrm{A(Y)}_{\rm 3D} - \mathrm{A(Y)}_{\langle\rm 3D\rangle}$
    takes into consideration effects of fluctuations around the mean stratification

Both are function of micro-turbulence and the first one of the mixing length parameter.

3D effects on solar abundances

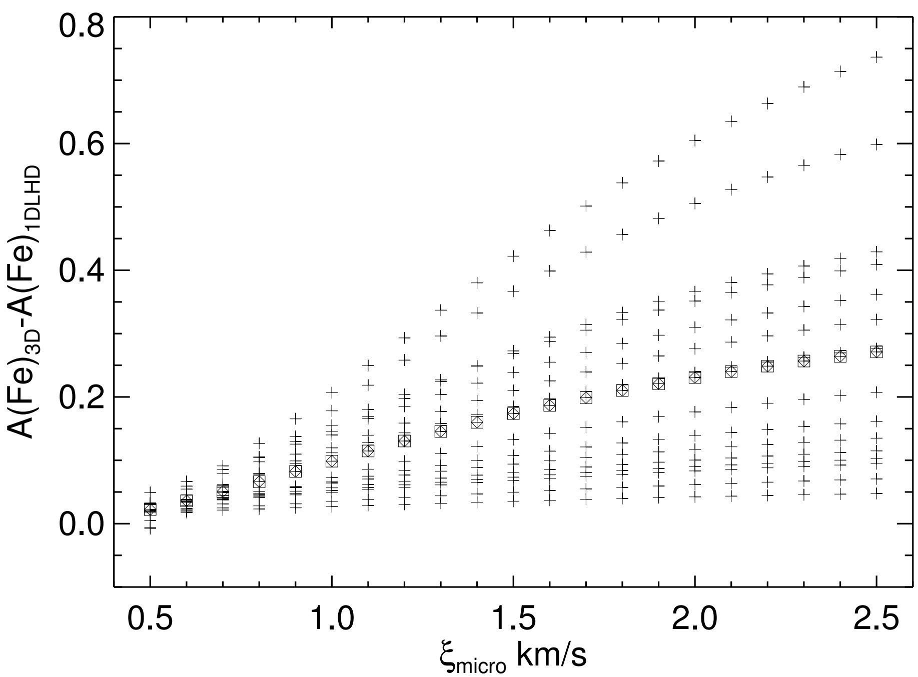
- Generally 3D-effects for the abundance determination in the Sun are small
- Th, Fe are exception

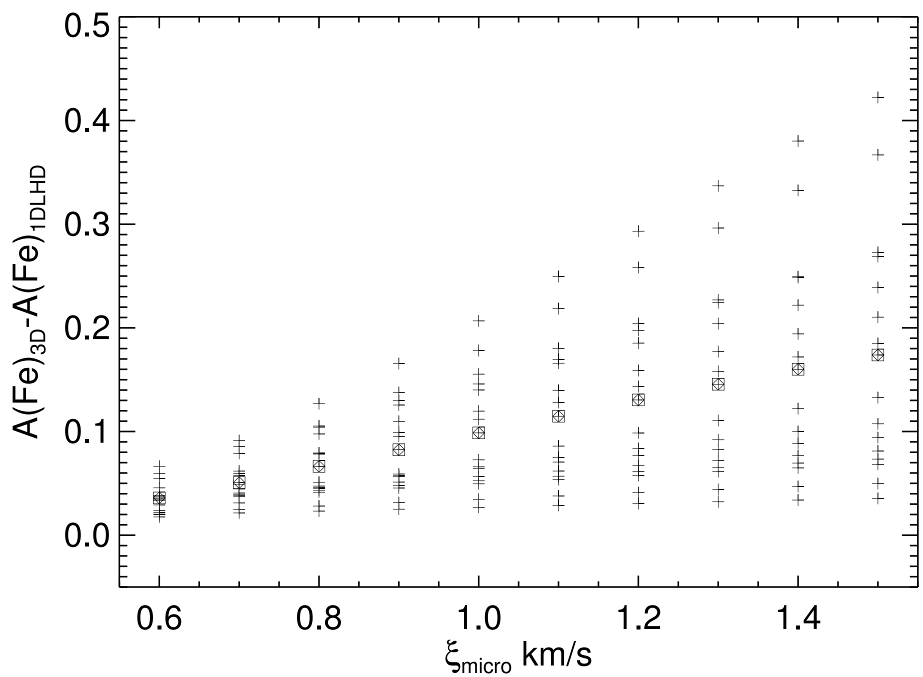
EL	N	ion		CO^{5}BOLD	3D-1D$_{\mathrm{LHD}}$	3D-$\langle$3D$\rangle$	role of 3D
Li	1	Li I	I/F	1.02 ± 0.02			3D-NLTE
C	43	C I	I/F	8.50 ± 0.11	+0.02	–0.03	ξ_{micro}
N	12	N I	I	7.86 ± 0.12	–0.05	–0.01	α_{MLT}
O	10	O I	I/F	8.76 ± 0.07	+0.05	+0.01	ξ_{micro}
P	5	P I	I/F	5.46 ± 0.04	+0.03	+0.01	
S	6	S I	F	7.15 ± 0.06	+0.04	+0.01	ξ_{micro}
Fe	38	Fe I	I	7.45 ± 0.06	+0.11	+0.03	ξ_{micro}
Fe	15	Fe II	I/F	7.51 ± 0.08	+0.08	+0.05	ξ_{micro}
Zr	15	Zr II	I/F	2.62 ± 0.06	+0.01	–0.00	ξ_{micro}
Eu	5	Eu II	I/F	0.52 ± 0.03	+0.01	+0.02	
Hf	4	Hf II	I/F	0.87 ± 0.04	+0.02	+0.01	
Th	1	Th II	I/F	0.08 ± 0.03	–0.10		Line asymmetry

Average over several lines

3D Corrections a function of micro-turbulence

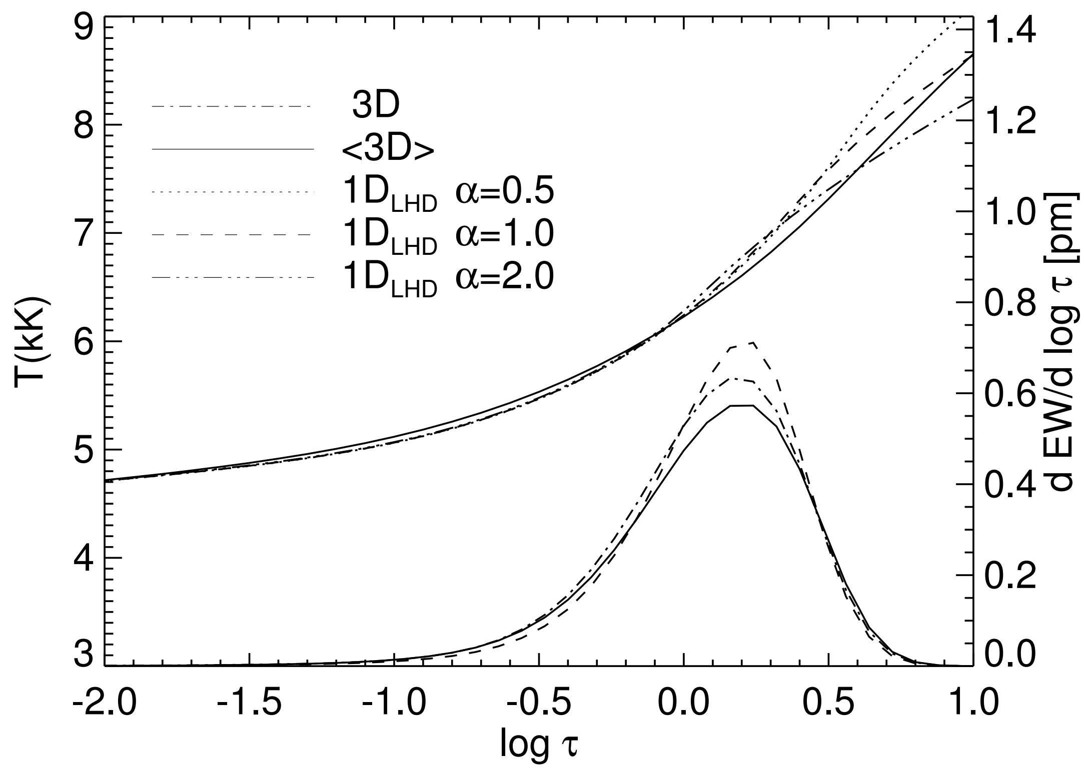
- In a reasonable range of micro-turbulence 3D correction can change up to 0.1 dex
  - 15 Fe II lines, 0.8 pm<EW<8.8 pm
  - Disc-centre
    - $\xi = 0.6 \mathrm{km\,s^{-1}}$, $\mathrm{A(Y)_{3D} - A(Y)_{1D_{LHD}} = +0.036}$
    - $\xi = 1.2 \mathrm{km\,s^{-1}}$, $\mathrm{A(Y)_{3D} - A(Y)_{1D_{LHD}} = +0.130}$
  - Disc-integrated
    - $\xi = 0.9 \mathrm{km\,s^{-1}}$, $\mathrm{A(Y)_{3D} - A(Y)_{1D_{LHD}} = +0.037}$
    - $\xi = 1.5 \mathrm{km\,s^{-1}}$, $\mathrm{A(Y)_{3D} - A(Y)_{1D_{LHD}} = +0.139}$





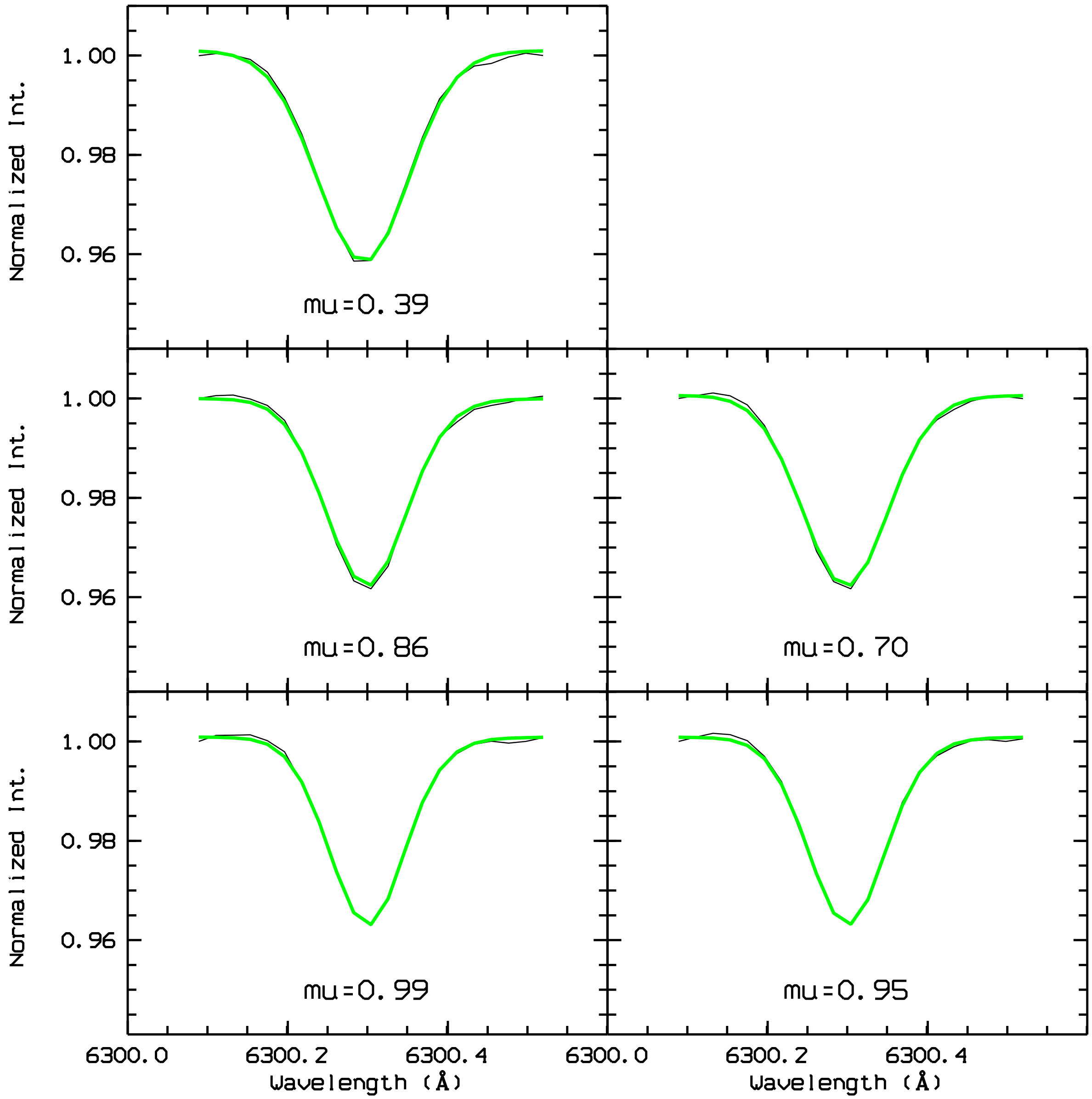
3D Corrections a function of the mixing length parameter

- A change in the α parameter produces a change in the abundance from $1\mathrm{D}_{\mathrm{LHD}}$ model, and as a consequence a change in the 3D correction
- this effect evident for lines from transition of "high" $\mathrm{E}_{\mathrm{low}}$
- for a sample of 12 N I lines: $\alpha = 1.0^{+1.0}_{-0.5} \quad \Rightarrow \mathrm{A(N)}_{1\mathrm{D}_{\mathrm{LHD}}} = 7.89^{-0.09}_{+0.05}\ \mathrm{dex}$



Unresolved problems

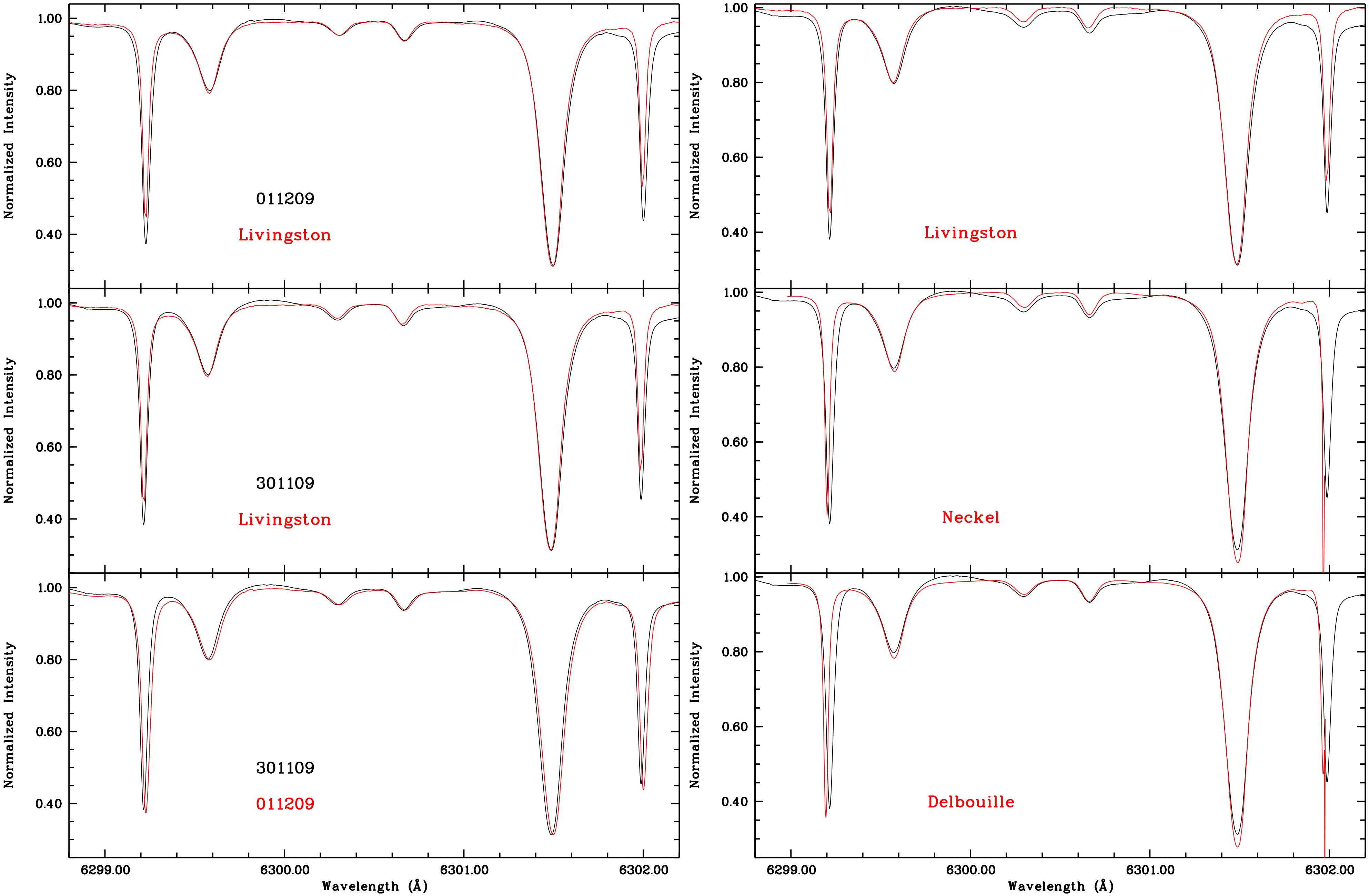
Centre-disc [OI] 630 nm line



HINODE

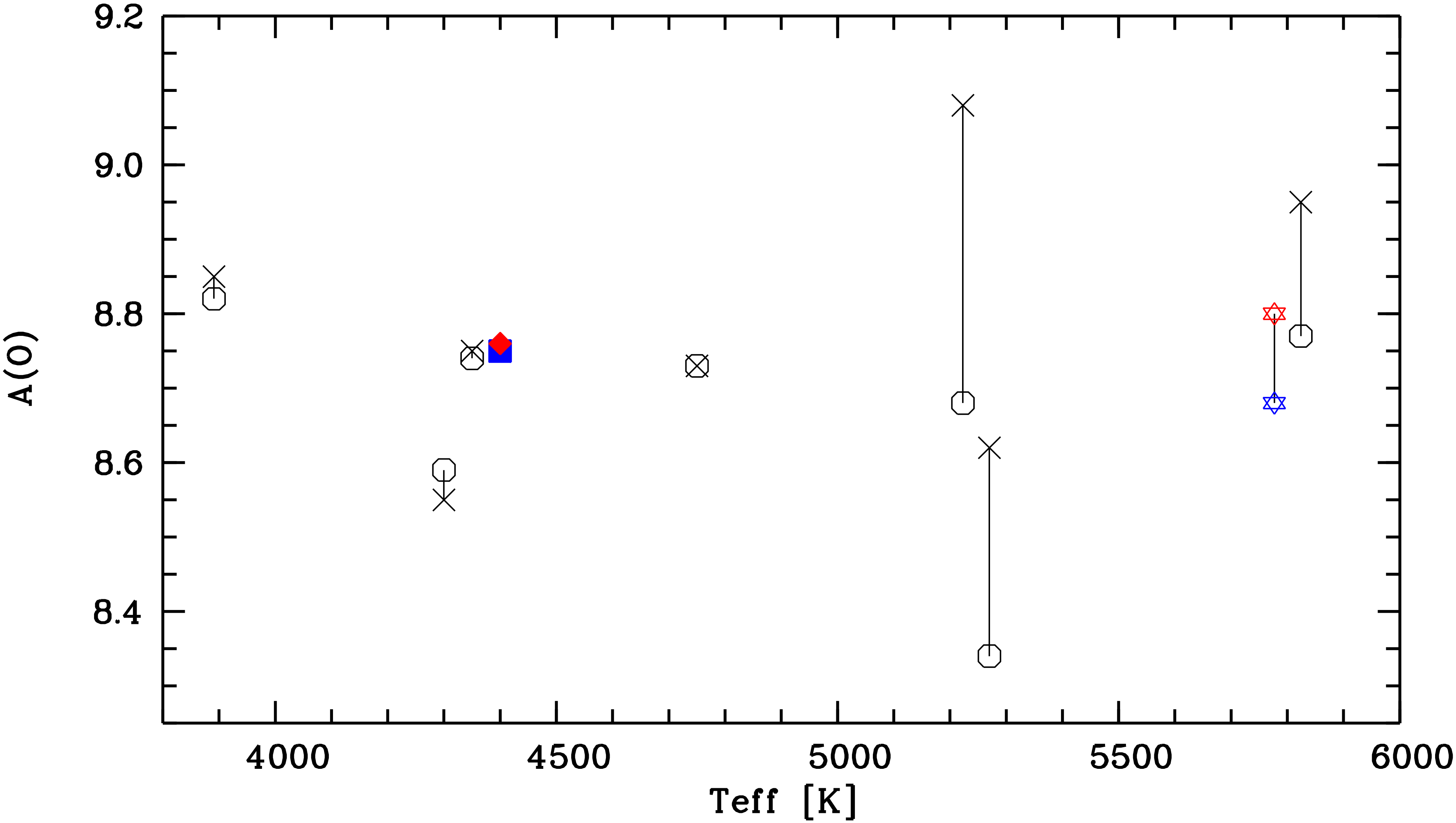
- $A(O) = 8.71$
- $A(Ni) = 6.17$

Centre-disc [OI] 630 nm line



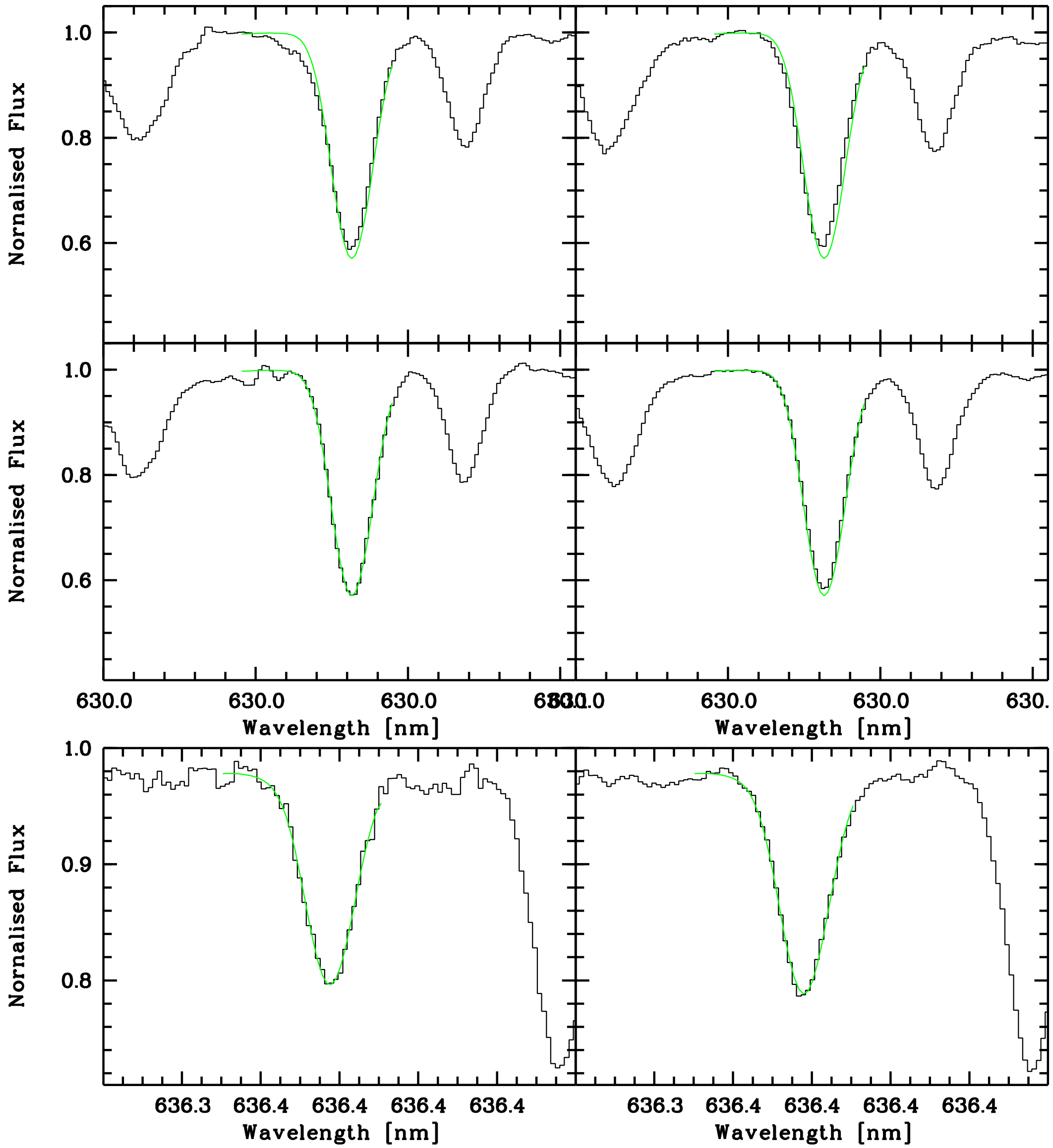
[OI] 630 - 636 nm lines

The two [OI] lines do not give same A(O) in dwarf stars.

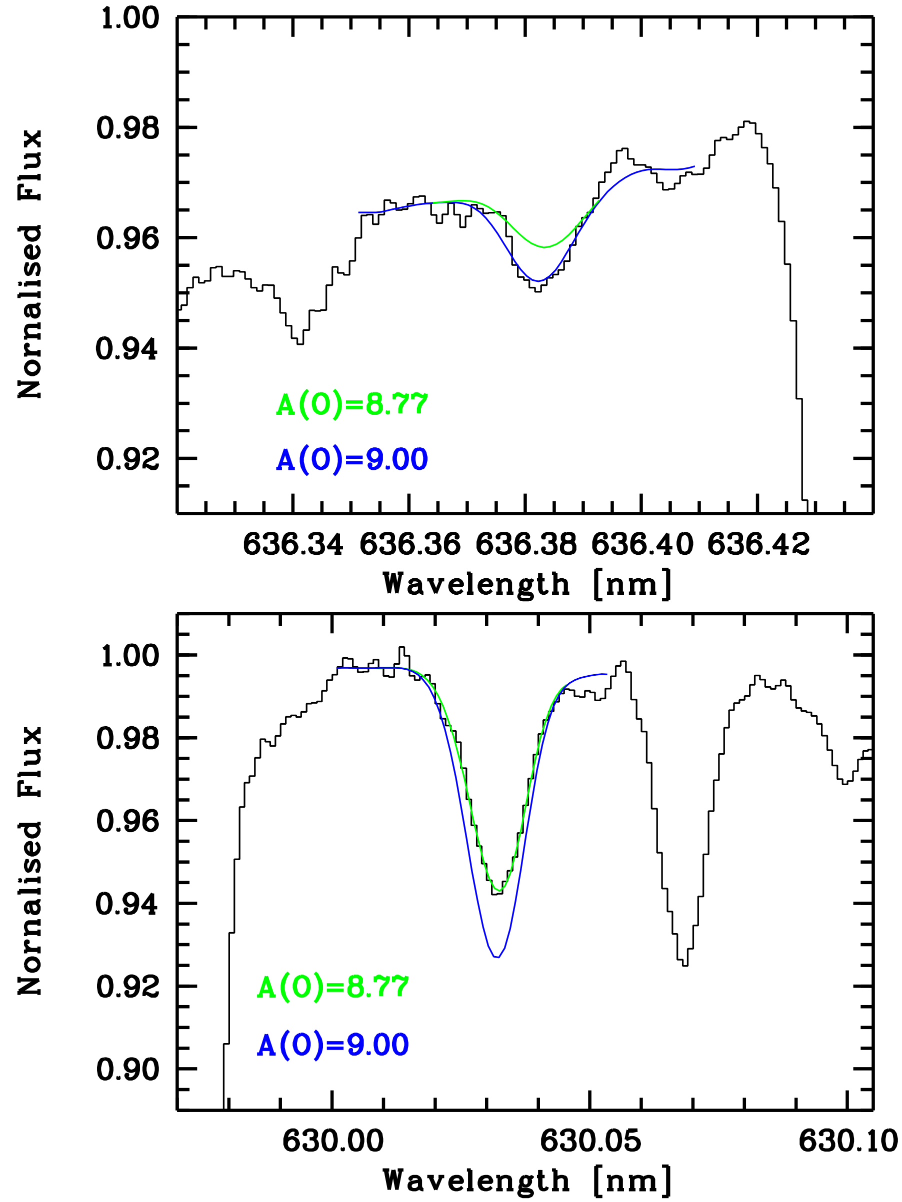


A(O) from [OI] lines, 630 nm circles and 636 nm crosses

[OI] 630 - 636 nm lines



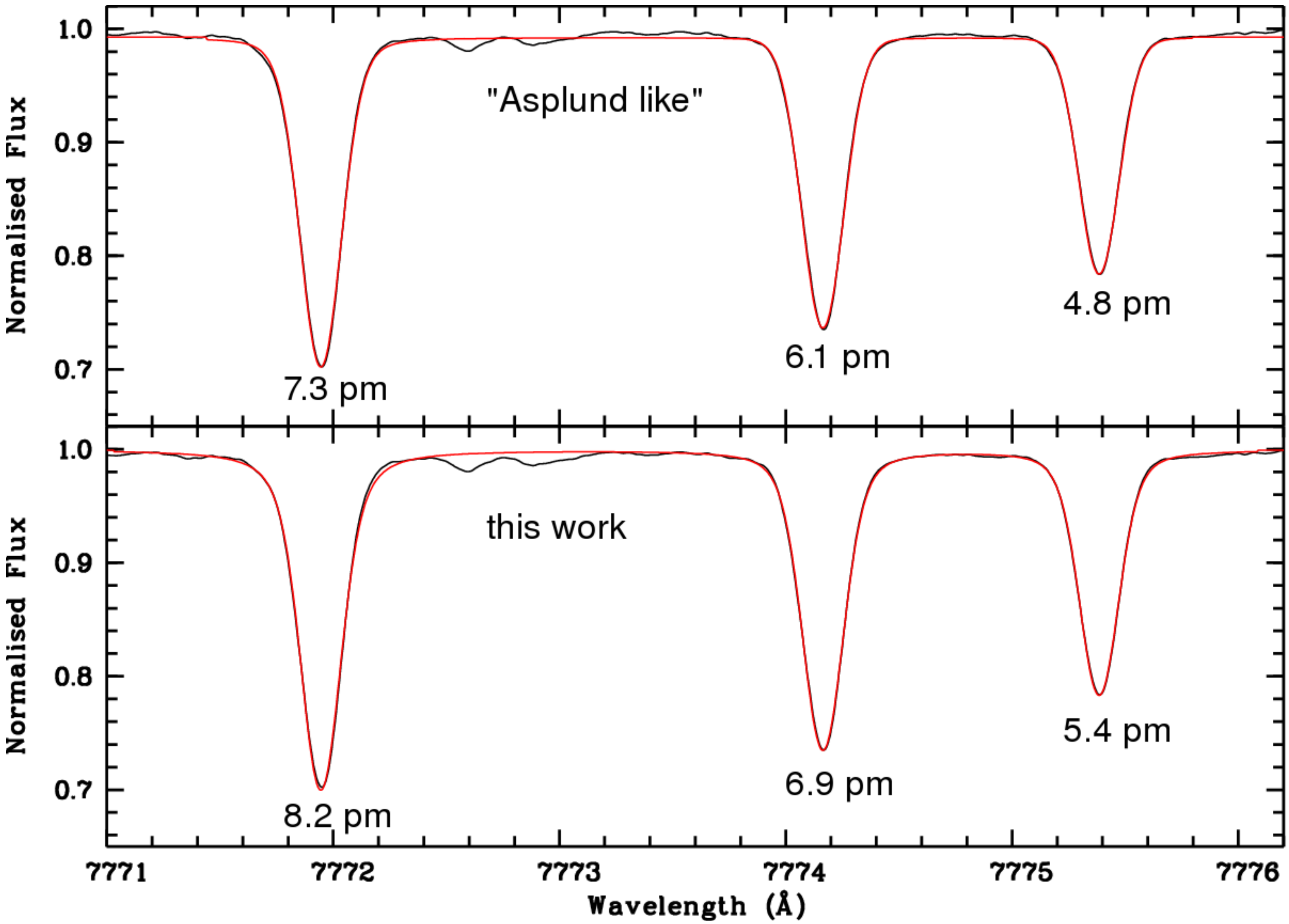
Arcturus



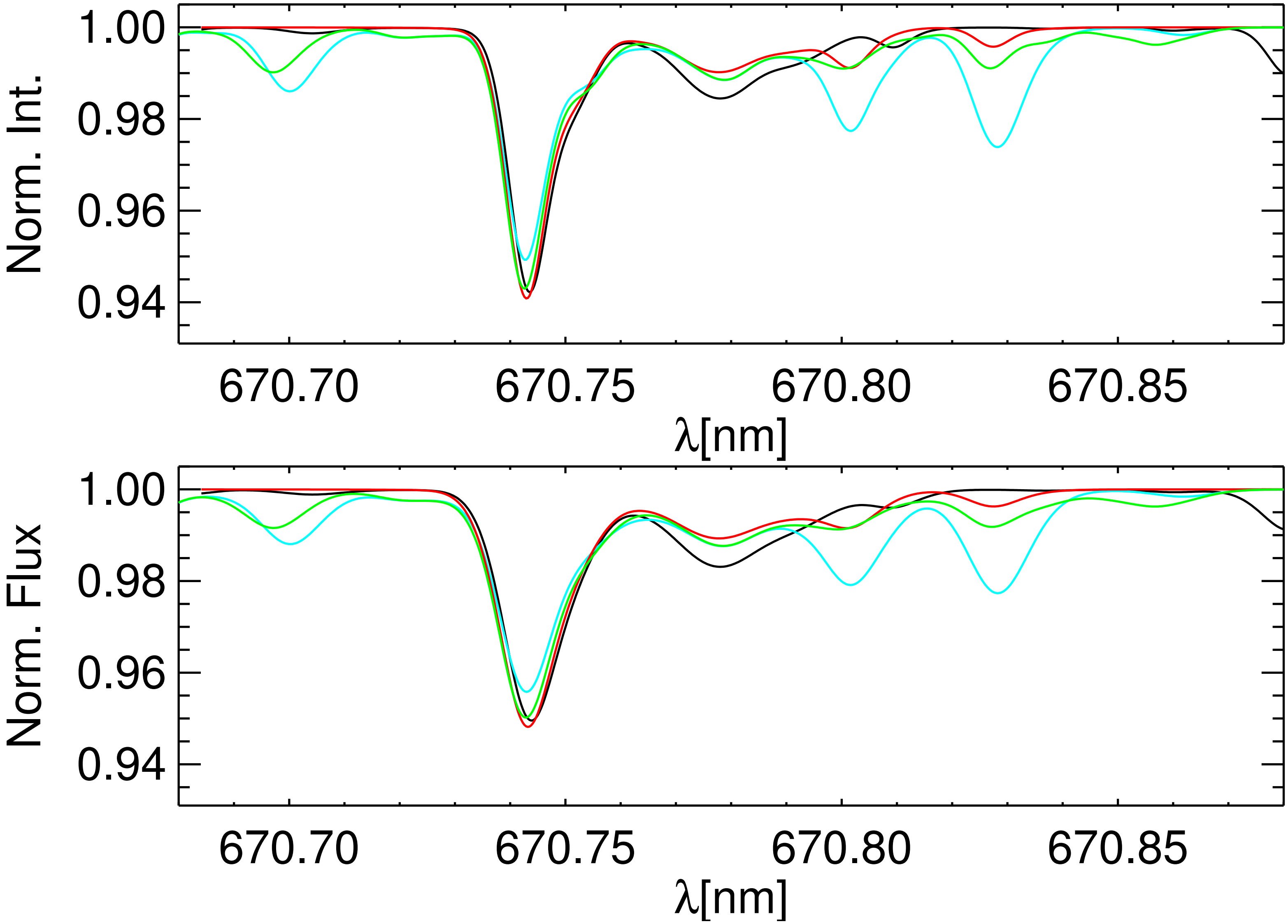
α Cen A

Differences in EW measurements

There is some subjectivity in the EW measurements

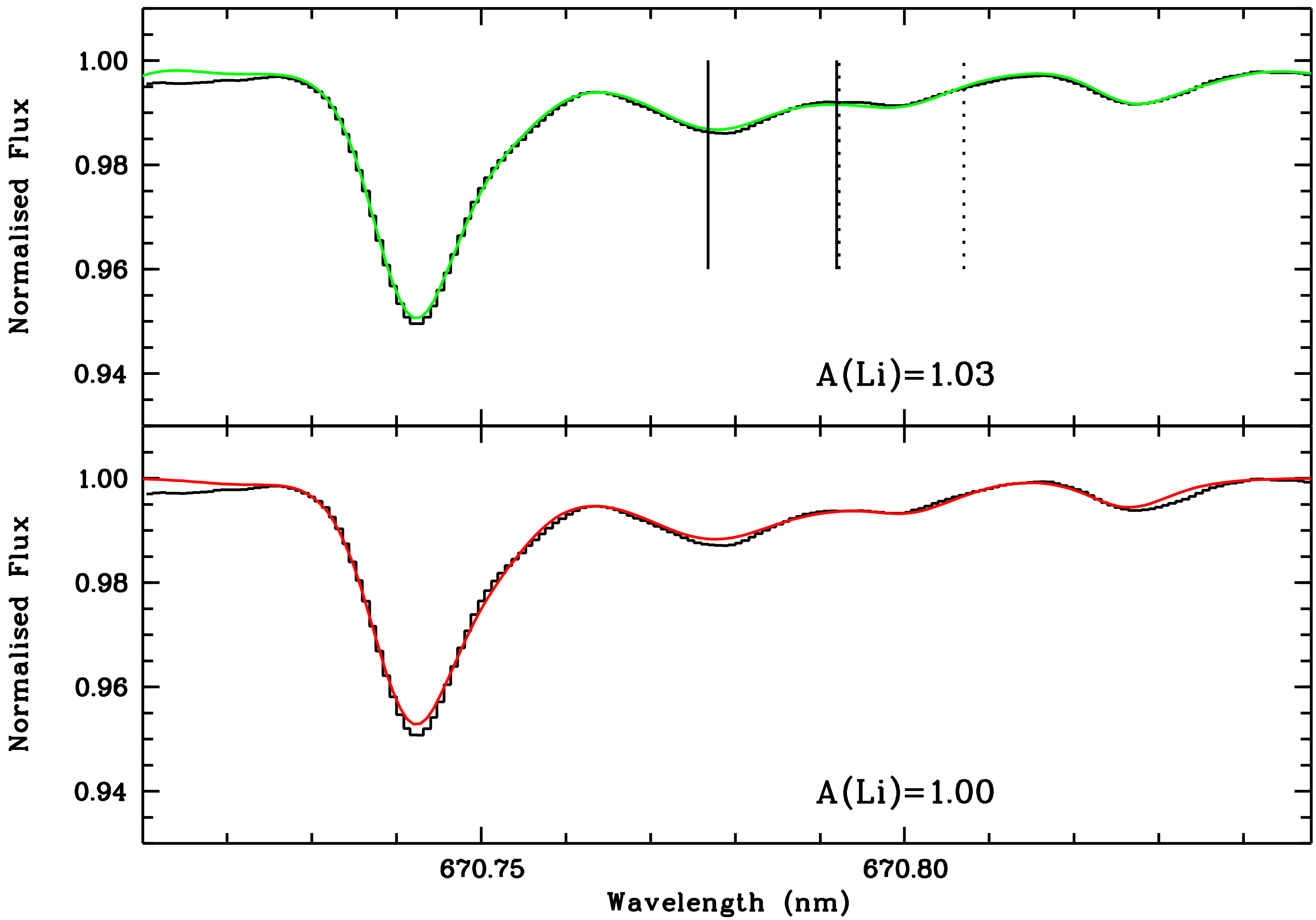


Li



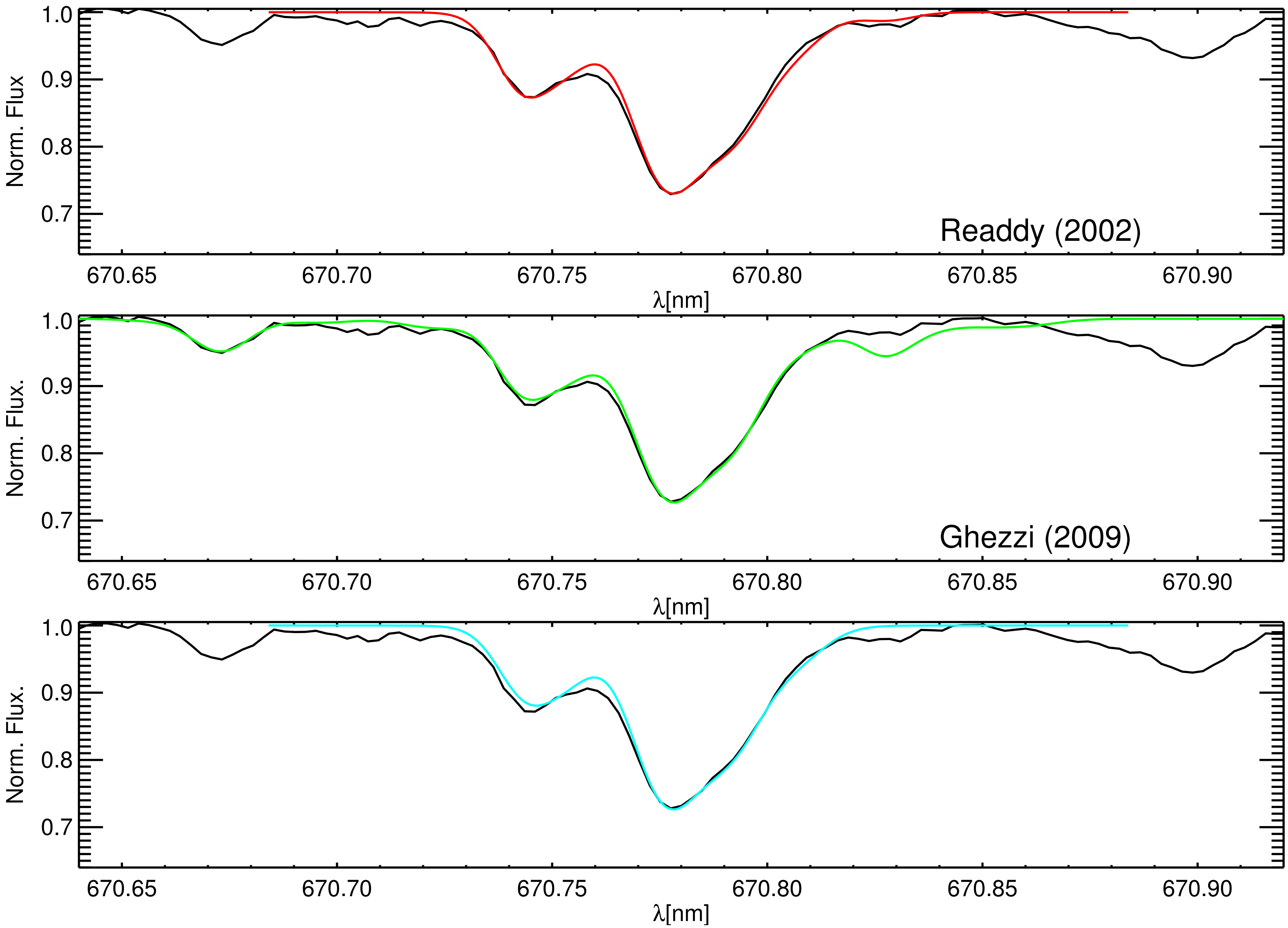
Reddy et al. (2002) Ghezzi et al. (2009) Hiltgen (1996) Mandell et al. (2204)

Li



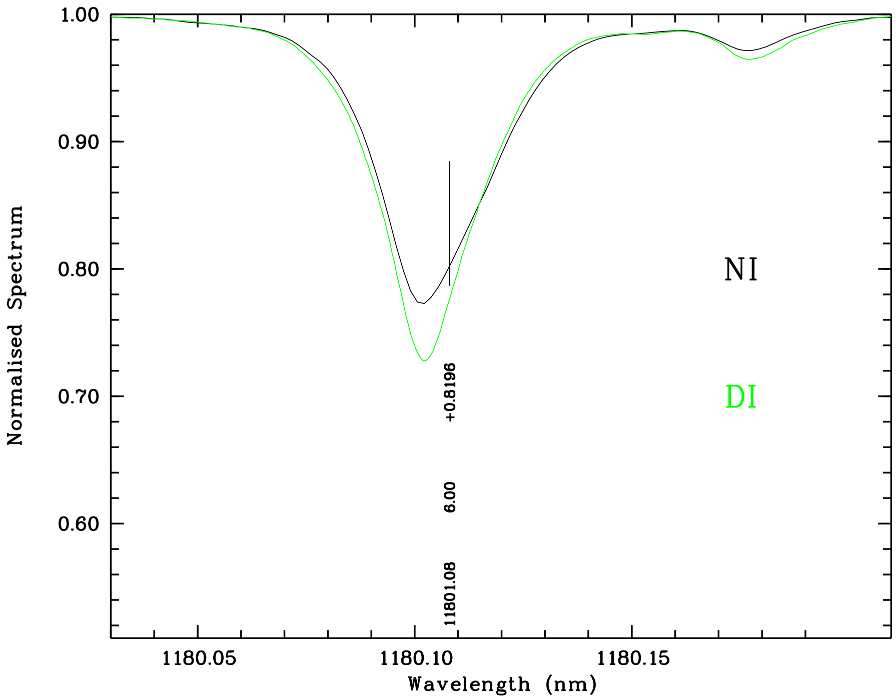
Reddy et al. (2002), Ghezzi et al. (2009)

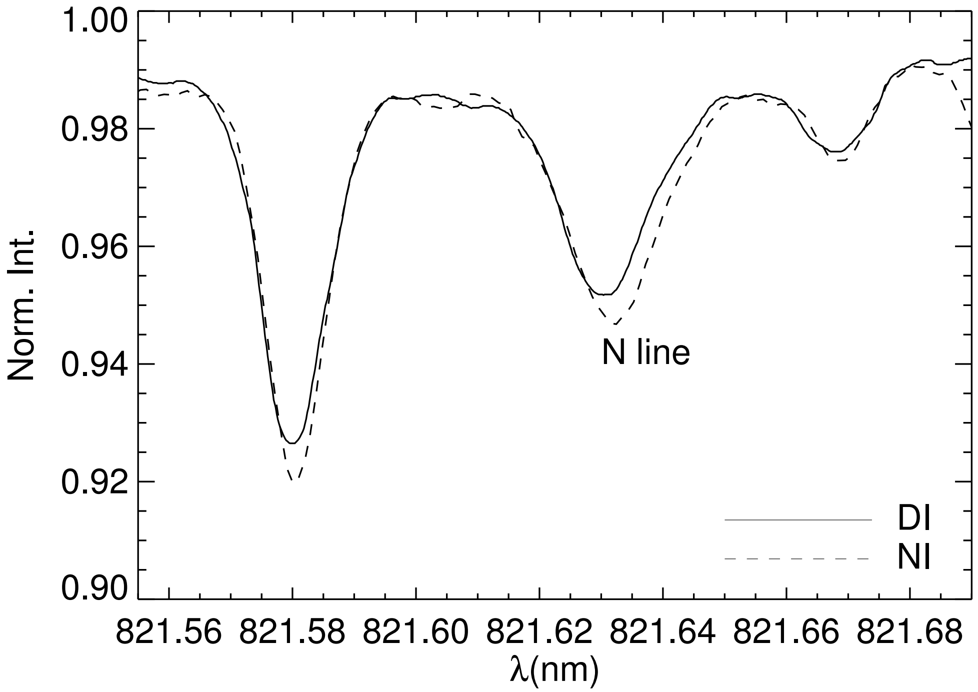
Li



Reddy et al. (2002), Ghezzi et al. (2009), Casares et al. (2007)

Observed spectra: unexplained differences

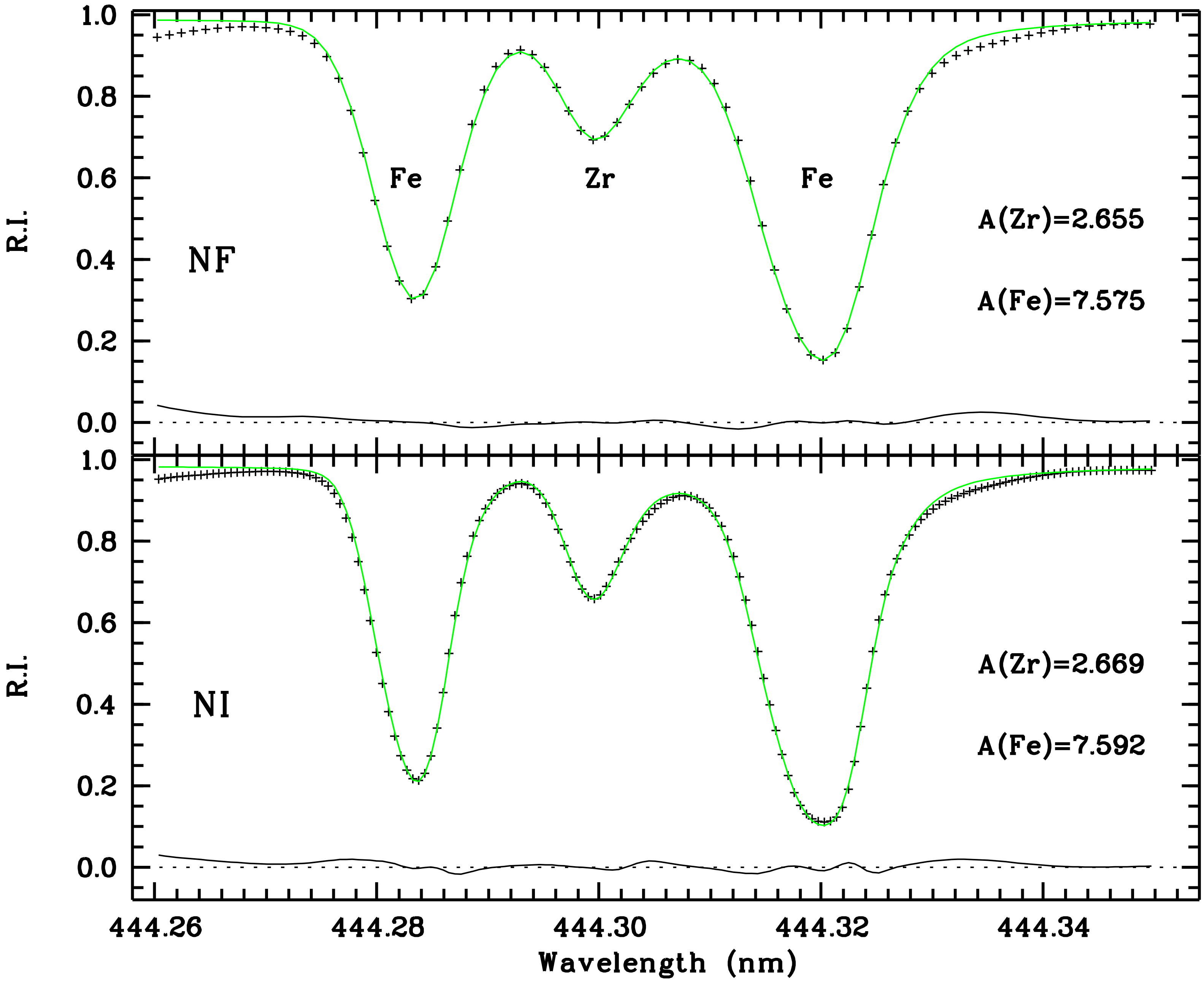




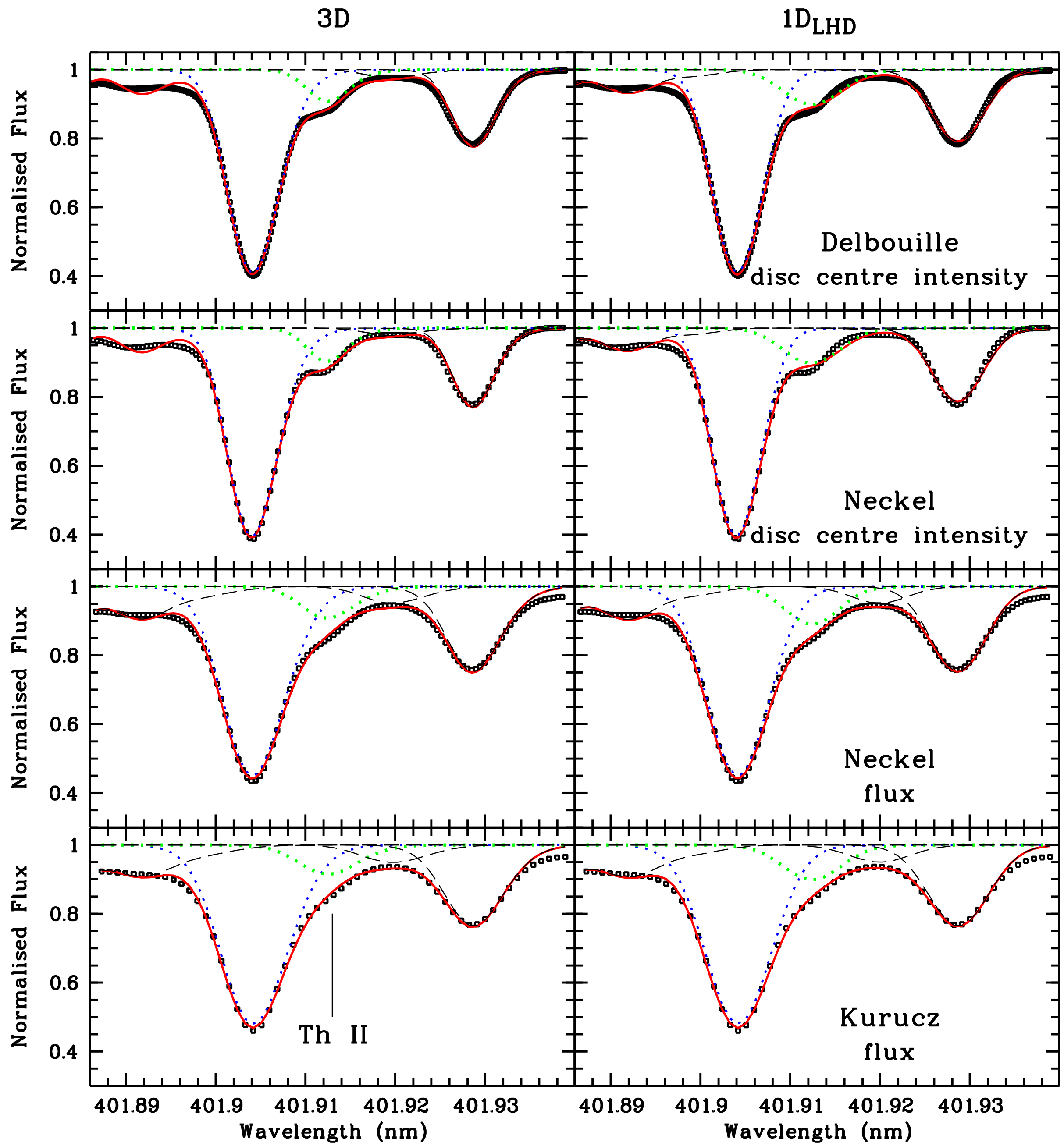
Solar atlases sometimes differ more than expected from S/N and resolution

Good results

Centre-disc Zr II-444.2 nm line



Th abundance, A(Th)=-0.08



Take away

- some work on 3D models necessary
- observational material need improvements
  - reproducibility of observations
  - characterisation of observing conditions (active regions, telluric absorption)
  - characterisation of instruments (instrumental profile, scattered light)
- centre-to-limb observations (in the process of collecting)
- absolute flux calibration