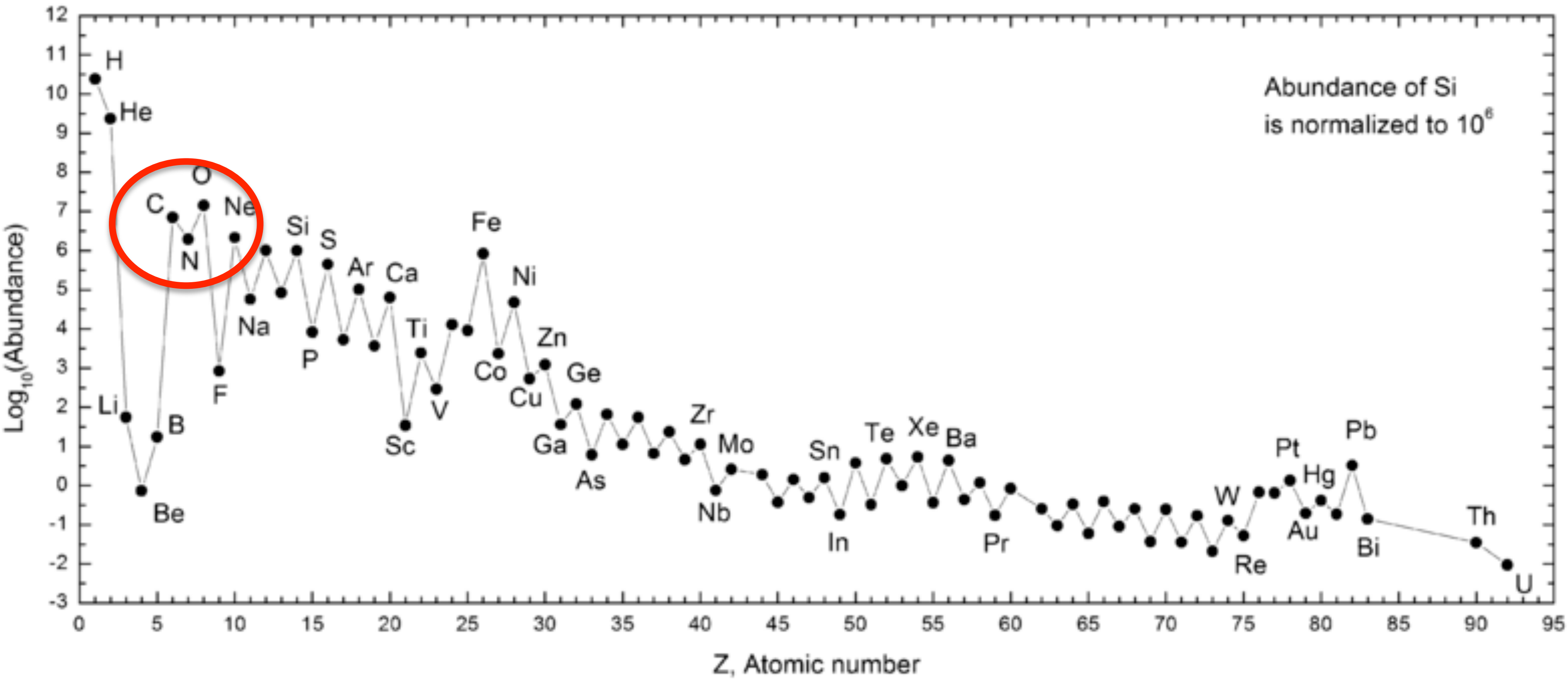
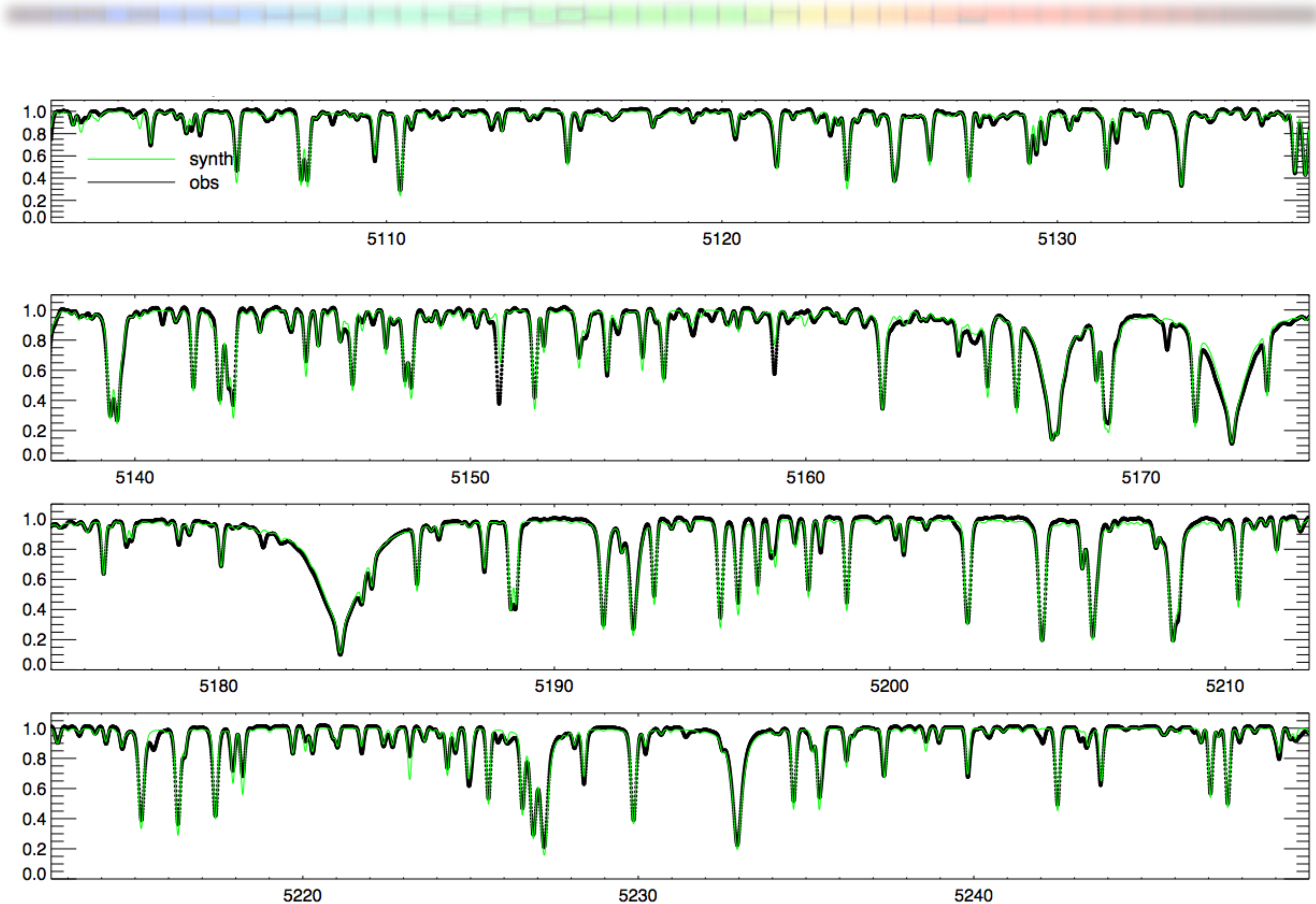
Solar abundance problem

Maria Bergemann

Solar abundances

- Solar Chemical Composition (**SCC**) is a fundamental reference in astrophysics





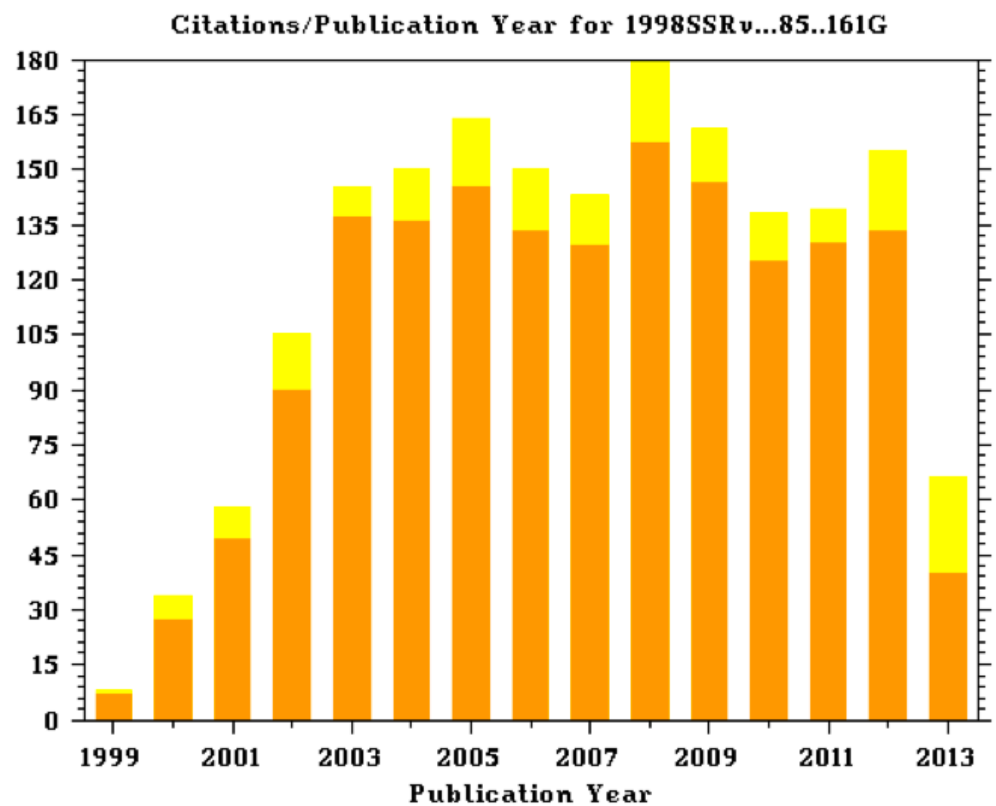
synth
obs
1.0
0.8
0.6
0.4
0.2
0.0
5110
5120
5130
5140
5150
5160
5170
5180
5190
5200
5210
5220
5230
5240

History

Seminal papers by Grevesse & Noels (1993), Grevesse & Sauval (1998)

- 1D hydrostatic solar models
- LTE

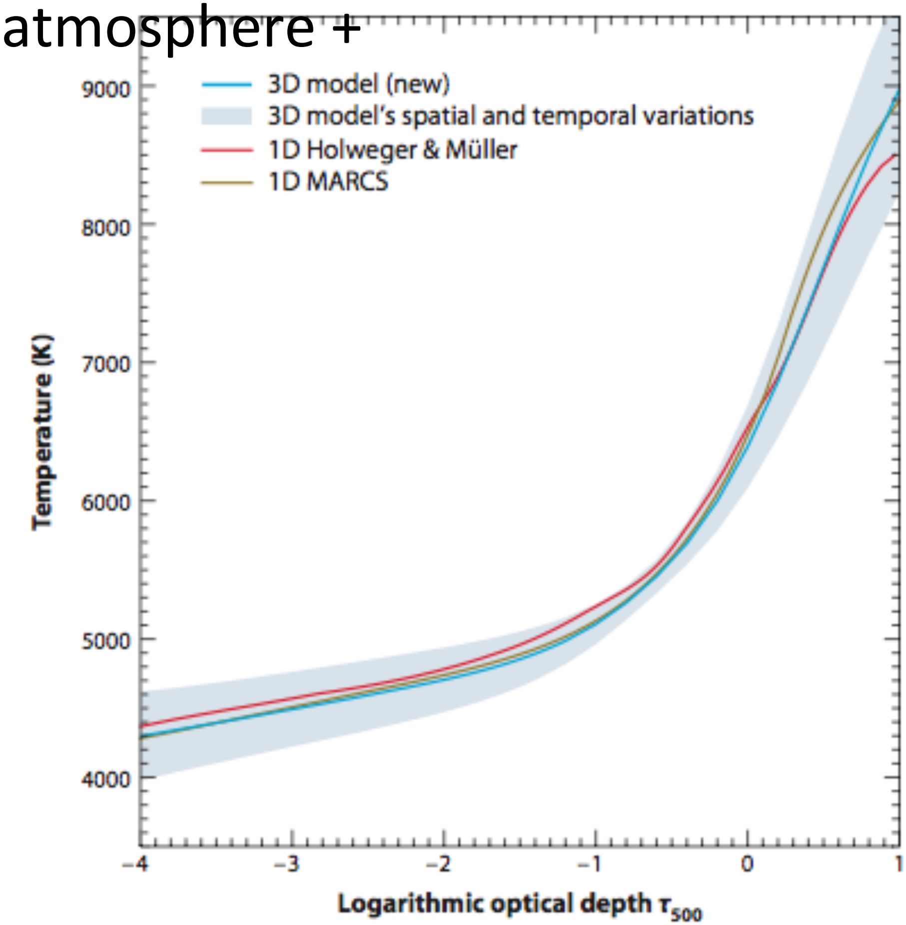
Compilation of atomic data from different literature sources



New 3D NLTE solar abundances

Asplund, Grevesse, Sauval, Scott, 2009, ARAA

3D hydrodynamical solar model atmosphere +
NLTE, where available



New 3D NLTE solar abundances

Asplund, Grevesse, Sauval, Scott, 2009, ARAA

3D hydrodynamical solar model atmosphere + NLTE, where available

Lines	$\log\epsilon_{C,N,O}$ 3D	$\log\epsilon_{C,N,O}$ ⟨3D⟩	$\log\epsilon_{C,N,O}$ HM	$\log\epsilon_{C,N,O}$ MARCS
[C I]	8.41	8.40	8.41	8.38
C I	8.42 ± 0.05	8.47 ± 0.04	8.45 ± 0.04	8.39 ± 0.04
CH $\Delta v = 1$	8.44 ± 0.04	8.44 ± 0.04	8.53 ± 0.04	8.44 ± 0.04
CH A-X	8.43 ± 0.03	8.42 ± 0.03	8.51 ± 0.03	8.40 ± 0.03
C_2 Swan	8.46 ± 0.03	8.46 ± 0.03	8.51 ± 0.03	8.46 ± 0.03
N I	7.78 ± 0.04	7.89 ± 0.04	7.88 ± 0.04	7.78 ± 0.04
NH $\Delta v = 0$	7.83 ± 0.03	7.94 ± 0.02	8.02 ± 0.02	7.97 ± 0.02
NH $\Delta v = 1$	7.88 ± 0.03	7.91 ± 0.03	8.01 ± 0.03	7.91 ± 0.03
[O I]	8.70 ± 0.05	8.70 ± 0.05	8.73 ± 0.05	8.69 ± 0.05
O I	8.69 ± 0.05	8.73 ± 0.05	8.69 ± 0.05	8.62 ± 0.05
OH $\Delta v = 0$	8.69 ± 0.03	8.75 ± 0.03	8.83 ± 0.03	8.78 ± 0.03
OH $\Delta v = 1$	8.69 ± 0.03	8.74 ± 0.03	8.86 ± 0.03	8.75 ± 0.03

New 3D NLTE solar abundances

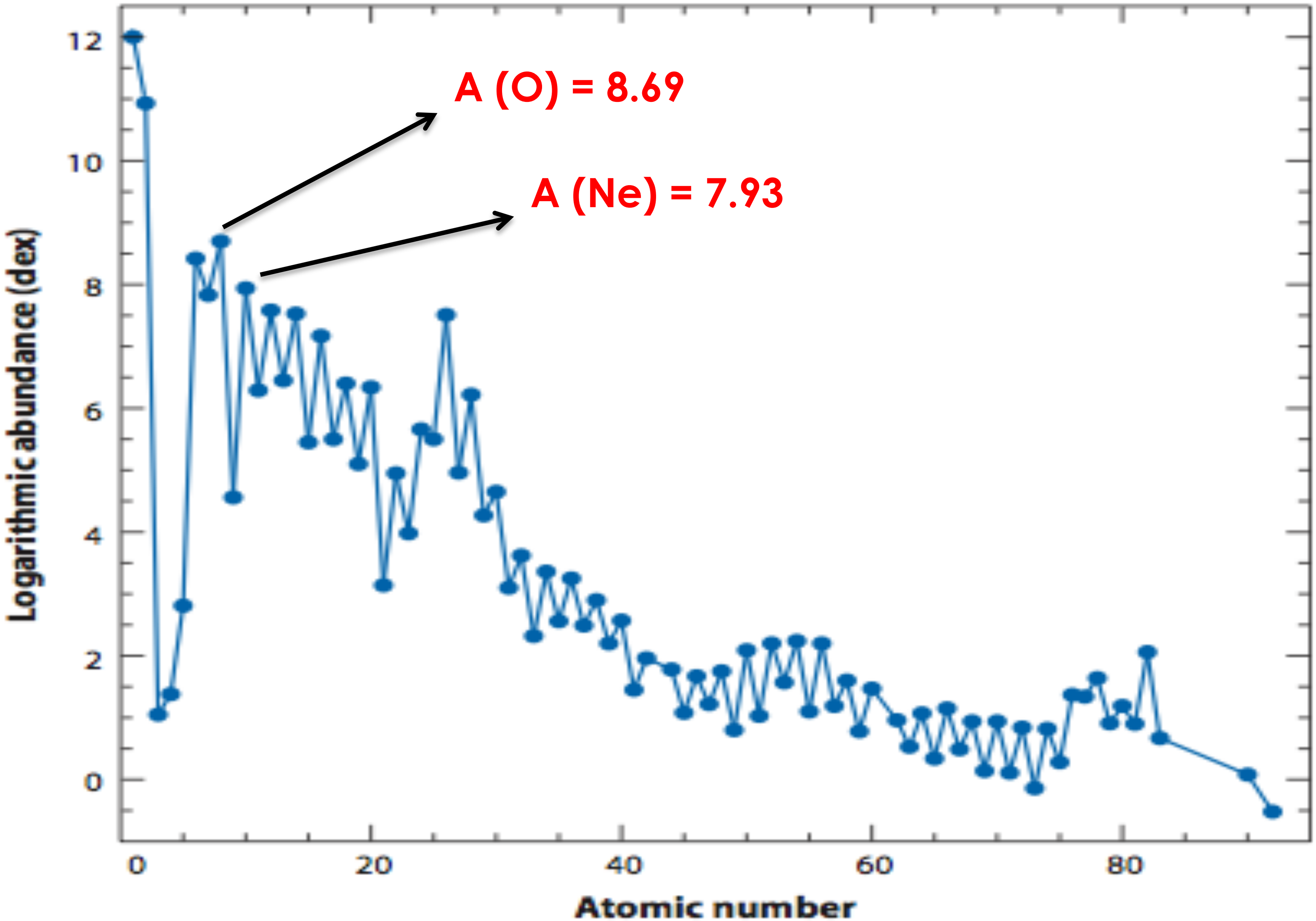
Asplund, Grevesse, Sauval, Scott, 2009, ARAA

3D hydrodynamical solar model atmosphere + NLTE, where available

Different lines of the same element give smaller dispersion of abundances when fitted with 3D models

Lines	$\log\epsilon_{C,N,O}$ 3D	$\log\epsilon_{C,N,O}$ ⟨3D⟩	$\log\epsilon_{C,N,O}$ HM	$\log\epsilon_{C,N,O}$ MARCS
[illegible]	[illegible]	[illegible]	8.41	8.38
[illegible]	[illegible]	[illegible] ± 0.04	8.45 ± 0.04	8.39 ± 0.04
[illegible]	[illegible]	[illegible] ± 0.04	8.53 ± 0.04	8.44 ± 0.04
[illegible]	[illegible]	[illegible] ± 0.03	8.51 ± 0.03	8.40 ± 0.03
[illegible]	[illegible]	[illegible] ± 0.03	8.51 ± 0.03	8.46 ± 0.03
[illegible]	[illegible]	[illegible] ± 0.04	7.88 ± 0.04	7.78 ± 0.04
[illegible]	[illegible]	[illegible] ± 0.02	8.02 ± 0.02	7.97 ± 0.02
NH $\Delta v = 1$	7.88 ± 0.03	7.91 ± 0.03	8.01 ± 0.03	7.91 ± 0.03
[O I]	8.70 ± 0.05	8.70 ± 0.05	8.73 ± 0.05	8.69 ± 0.05
O I	8.69 ± 0.05	8.73 ± 0.05	8.69 ± 0.05	8.62 ± 0.05
OH $\Delta v = 0$	8.69 ± 0.03	8.75 ± 0.03	8.83 ± 0.03	8.78 ± 0.03
OH $\Delta v = 1$	8.69 ± 0.03	8.74 ± 0.03	8.86 ± 0.03	8.75 ± 0.03

New 3D NLTE solar abundances



Meteoritic abundances

- CI Chondrites

✓ Mass spectroscopy very accurate!

✓ But volatile elements (form gaseous components) are depleted

H, He, C, N, O and Ne

need a conversion factor from the solar to meteoritic scale

Meteoritic abundances

- CI Chondrites

depleted in **H** → coupling meteoritic abundances to astronomical scale using **Si**

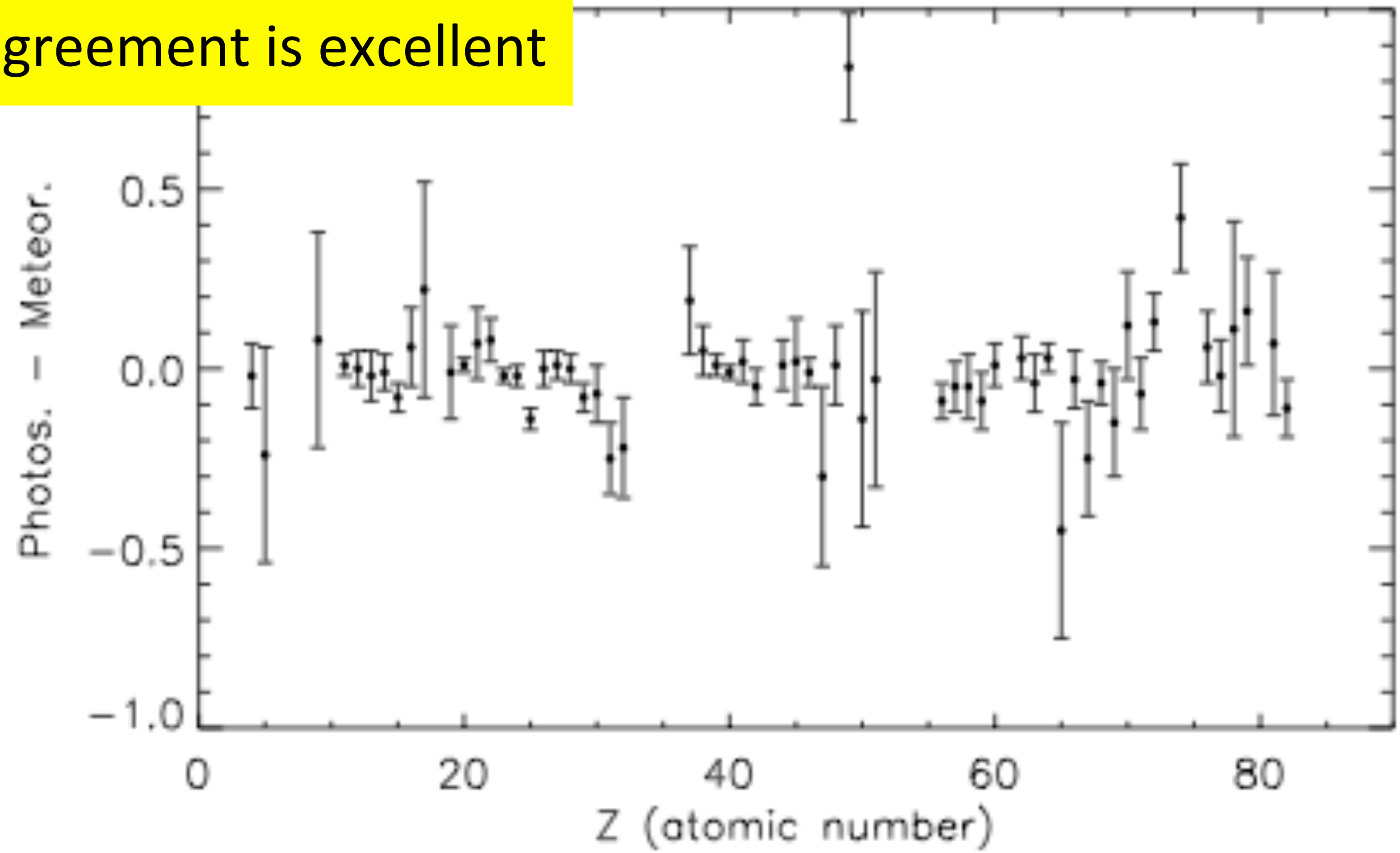
A (el) = const + log N (el)

assuming A(Si) = 7.54
const = 1.54 to match Si abundance on both scales

Meteoritic vs old 1D LTE solar

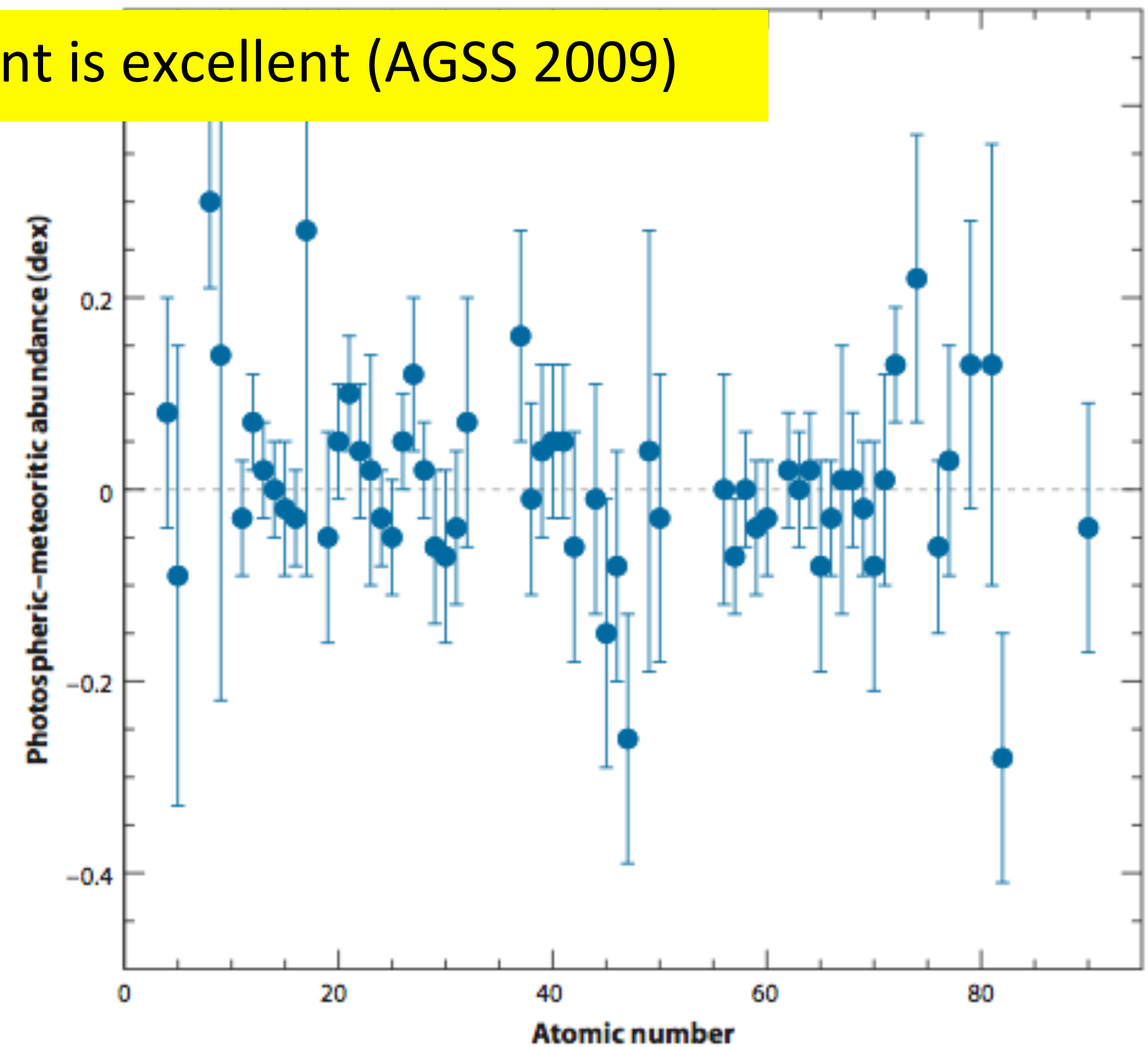
Grevesse & Noels (1993), Grevesse & Sauval (1998)

The agreement is excellent



Meteoritic vs new 3D NLTE solar

The agreement is excellent (AGSS 2009)



Grevesse & Sauval (1989)

- 1D hydrostatic solar model
- LTE

old 1D LTE

Asplund, Grevesse, Sauval, Scott, 2009, ARAA

- 3D hydrodynamical solar model
- NLTE, where available

new 3D NLTE

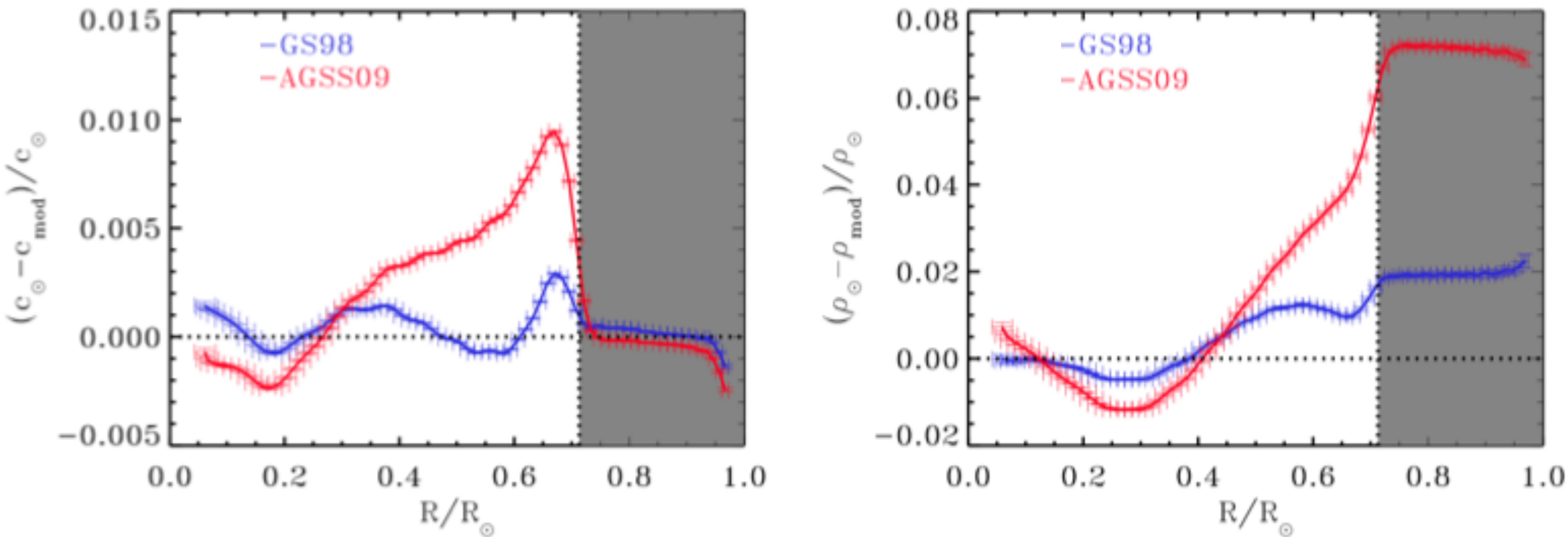
Element	GS98	AGSS09
C	8.52	8.43
N	7.92	7.83
O	8.83	8.69
Ne	8.08	7.93
Mg	7.58	7.53
Si	7.56	7.51
Ar	6.40	6.40
Fe	7.50	7.45
Z/X	0.0229	0.0178

Significantly lower solar **metal mass fraction Z**

- **Z=0.0169** (GS 1998)
- **Z=0.0134** (AGSS 2009)

The solar abundance problem

major difficulty to reconcile them with stellar evolution



Wrong sound speed

Wrong depth of the convective zone

Wrong surface He abundance

Serenelli et al. 2011

	GS98	AGSS09	Helios.
$(Z/X_\odot)$	0.0229	0.0178	—
$R_{CZ}/R_\odot$	0.712	0.723	0.713 ± 0.001
Y_S	0.2429	0.2319	0.2485 ± 0.0034
$\langle \delta c/c \rangle$	0.0009	0.0037	—
$\langle \delta \rho/\rho \rangle$	0.011	0.040	—

The solar abundance problem

- The standard solar models with the 'old 1D LTE' solar abundances (GS 1998) agree well with helioseismology

but

- the new (3D, NLTE) abundances destroy the agreement

Solar photospheric spectrum – not all elements can be measured

He

H II regions or B stars, helioseismology

A(He) = 10.99

Ne, Ar

only from solar wind, flares, sunspots

usually need some reference element, e.g. Ne/Mg or Ne/O

Caffau et al. 2010

- 3D hydro solar model (CO5BOLD)
- approximate treatment of NLTE

Element	Ion. state	Abundance	N lines
Li	*I*	1.03 ± 0.03	1
C	*I*	8.50 ± 0.06	45
N	*I*	7.86 ± 0.12	12
O	*I*	8.76 ± 0.07	10
P	*I*	5.46 ± 0.04	5
S	*I*	7.16 ± 0.05	7
K	*I*	5.11 ± 0.09	6
Fe	*II*	7.52 ± 0.06	15

Z/X = 0.0209

Asplund et al. 2009, ARAA

- 3D hydro solar model (Stagger)
- NLTE, where available

Element	GS98	AGSS09
C	8.52	8.43
N	7.92	7.83
O	8.83	8.69
Ne	8.08	7.93
Mg	7.58	7.53
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Ar	6.40	6.40
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Z/X	0.0229	0.0178

Explanations?

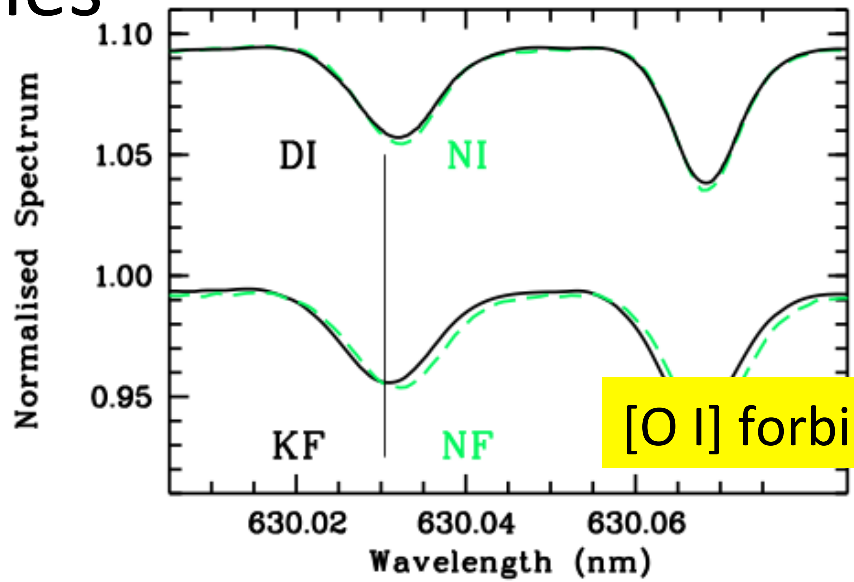
Asplund et al. 2009 Z/X = 0.0178

Caffau et al. 2010 Z/X = 0.0209

“The differences reflects the differences in the T structure of the CO5BOLD and Stagger” (Caffau et al.)

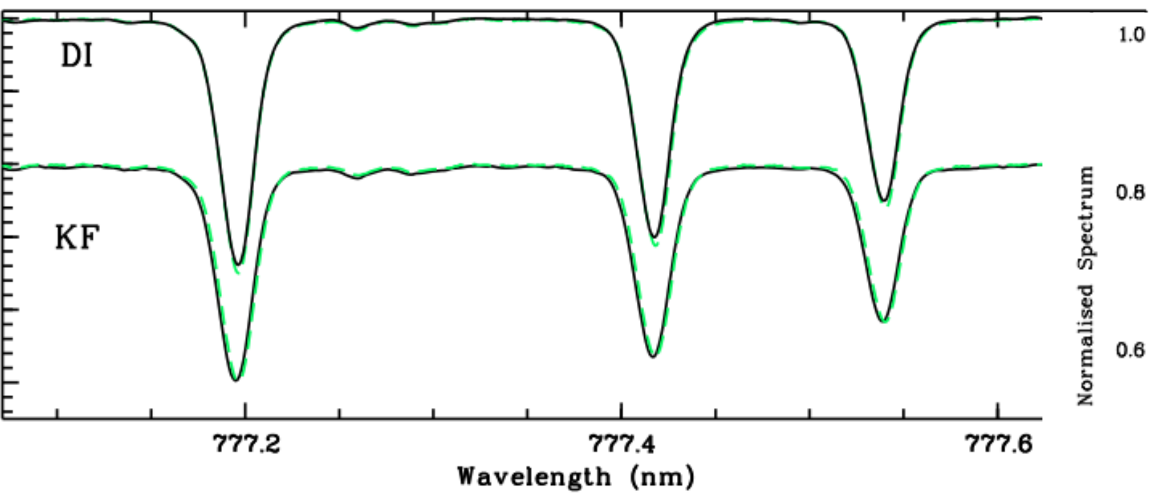
O diagnostics lines

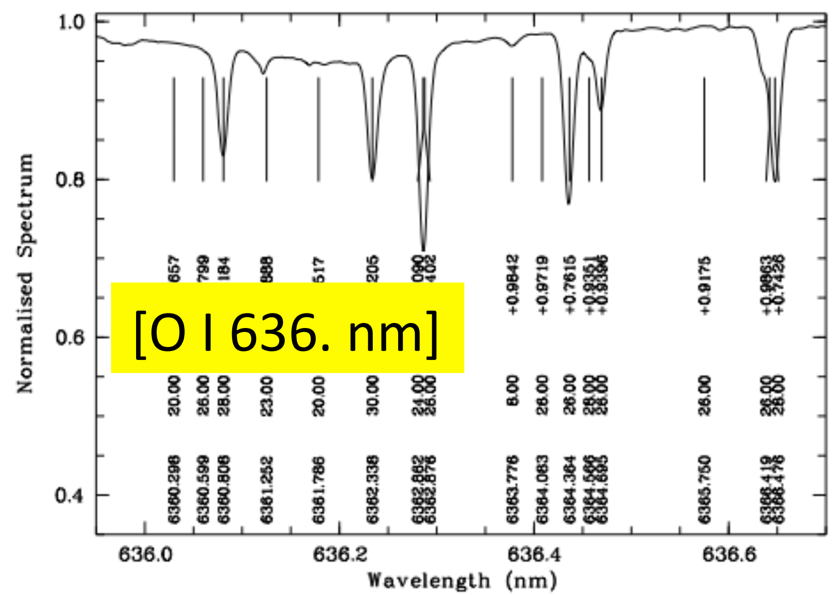
OH molecular lines
~ 80 in the IR



[O I] forbidden line

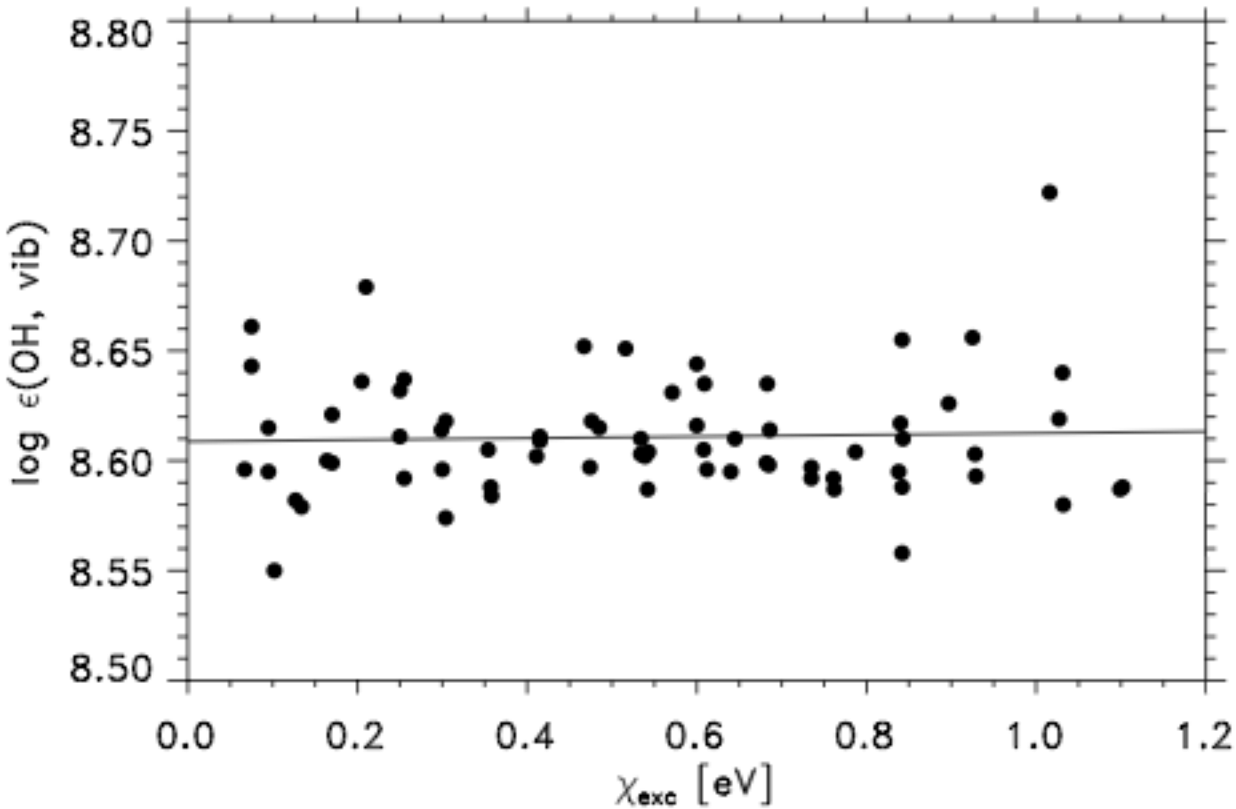
O I atomic lines





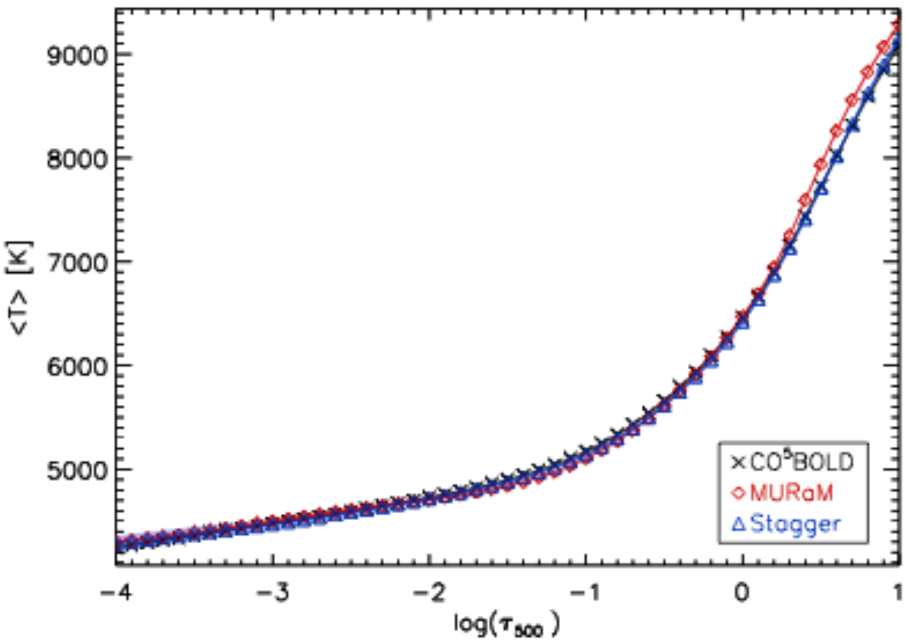
[O I 636. nm]

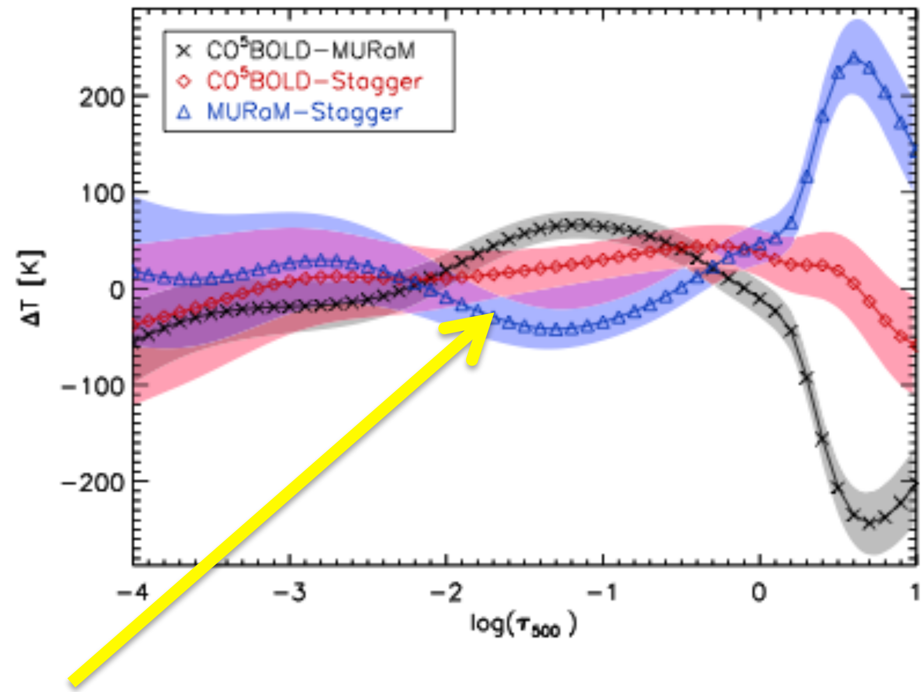
OH vibration-rotation lines: extremely sensitive to 3D effects



Asplund et al. (2004)

The mean differences between the 3D hydro models are small (Beeck et al. 2012): <Δ T> ~ 0



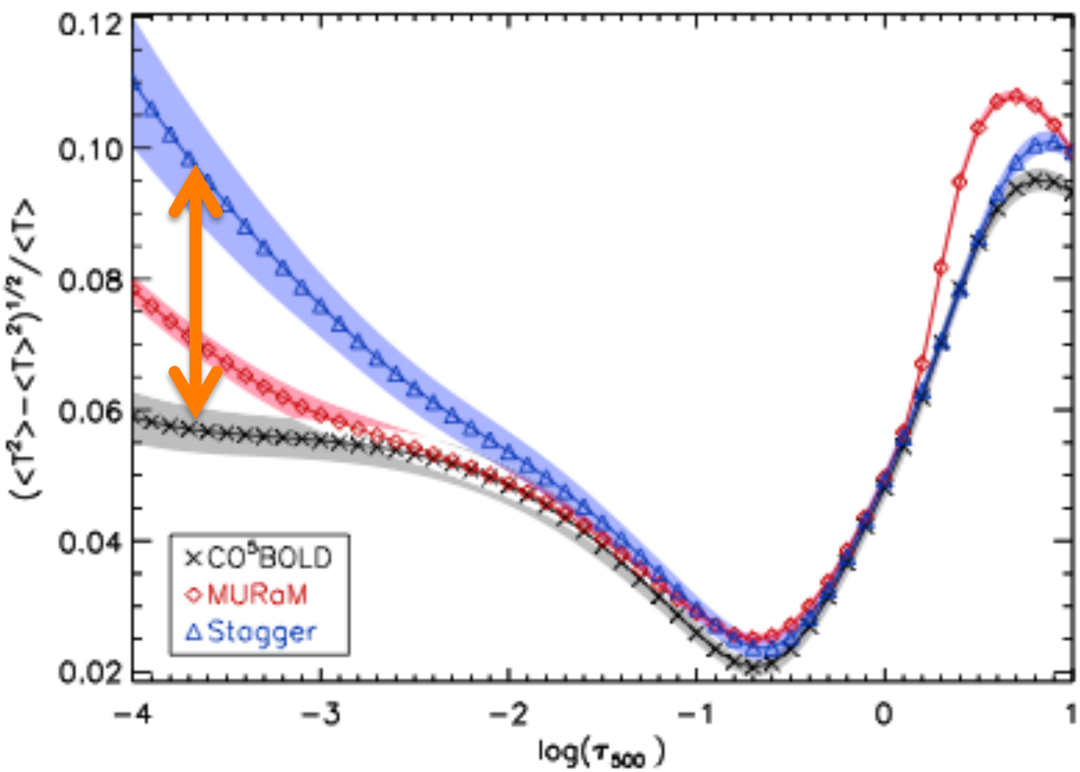


where the line formation takes place

Beeck et al. (2012)

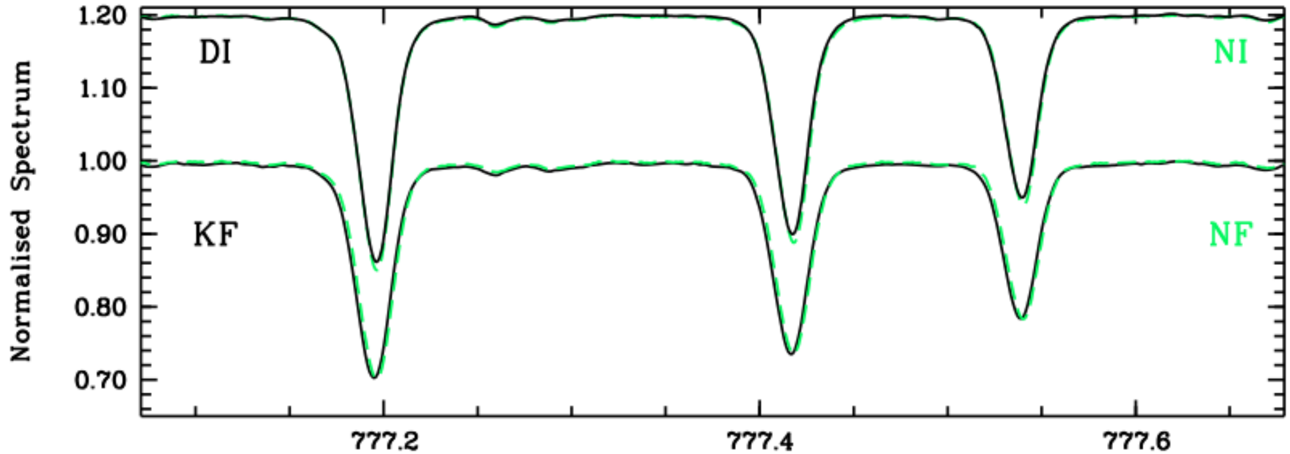
But RMS temperature fluctuations are larger at a given depth in Stagger models

horizontal T and rho in homogeneities contribute strictly positively to the number density of molecules



Lower O abundances from molecular OH lines with CO5BOLD models

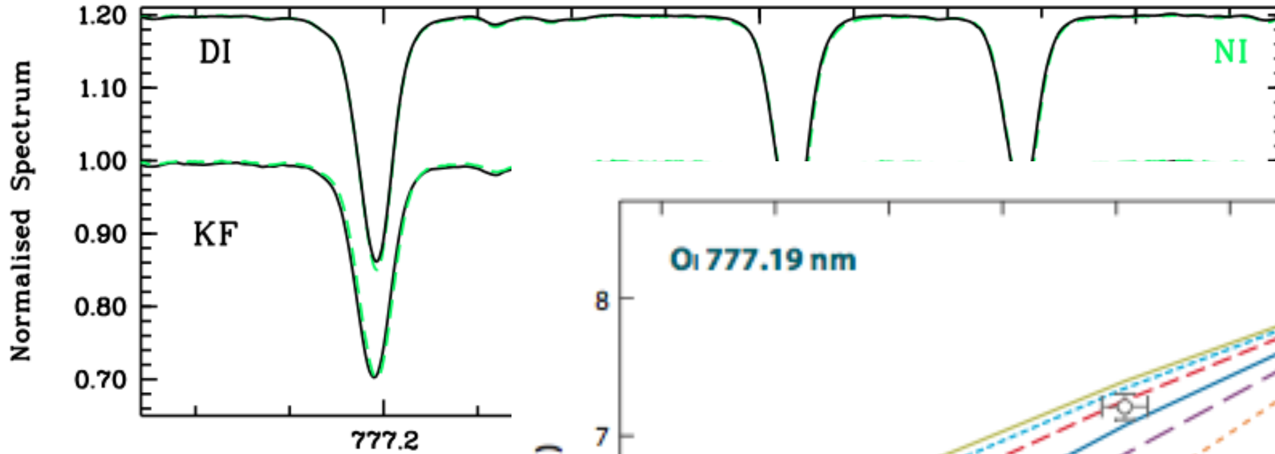
O I atomic lines – severe negative NLTE effects

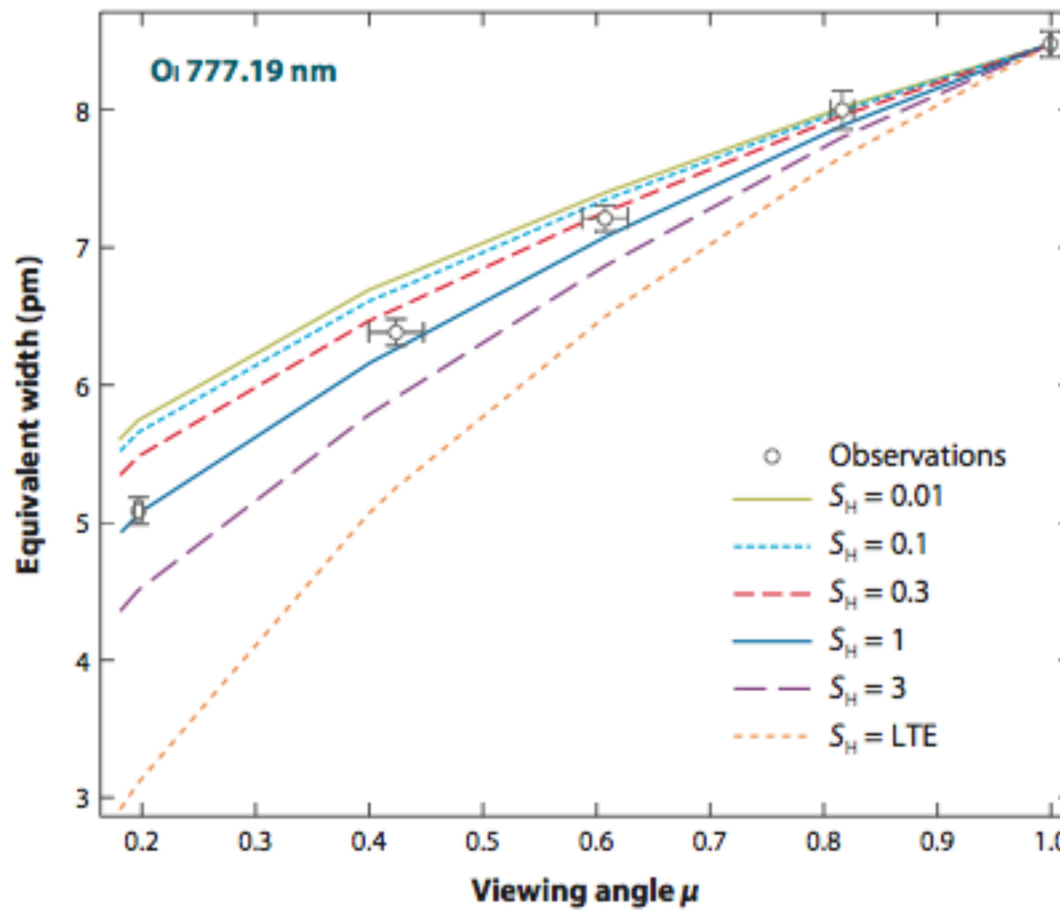


Caffau et al. 2008

lin[e] nm				= 1) corr. HH[a]	NLTE (S_H = 1/3) A(O)	corr.	NLTE (S_H = 0) A(O)	corr.	corr. A04[b]	Flux/Intensity
615.8	8.64	8.64	–0.003		8.64	–0.004	8.64	–0.002	–0.03	F
615.8	8.63	8.62	–0.003	–0.01	8.62	–0.003	8.62	–0.002		I
630.0	8.68	8.68	0.0		8.68	0.0	8.68	0.0		
636.3	8.78	8.78	0.0		8.78	0.0	8.78	0.0		
777.1	9.03	8.87	–0.16		8.81	–0.22	8.75	–0.28	–0.27	F
777.1	8.93	8.85	–0.07	–0.07	8.81	–0.12	8.77	–0.16		I
777.4	8.99	8.84	–0.14		8.79	–0.20	8.74	–0.25	–0.24	F
777.4	8.88	8.80	–0.08	–0.06	8.76	–0.12	8.72	–0.16		I
777.5	8.96	8.85	–0.12		8.80	–0.16	8.75	–0.21	–0.20	F
777.5	8.88	8.82	–0.06	–0.05	8.79	–0.09	8.75	–0.13		I

O I atomic lines – severe negative NLTE effects





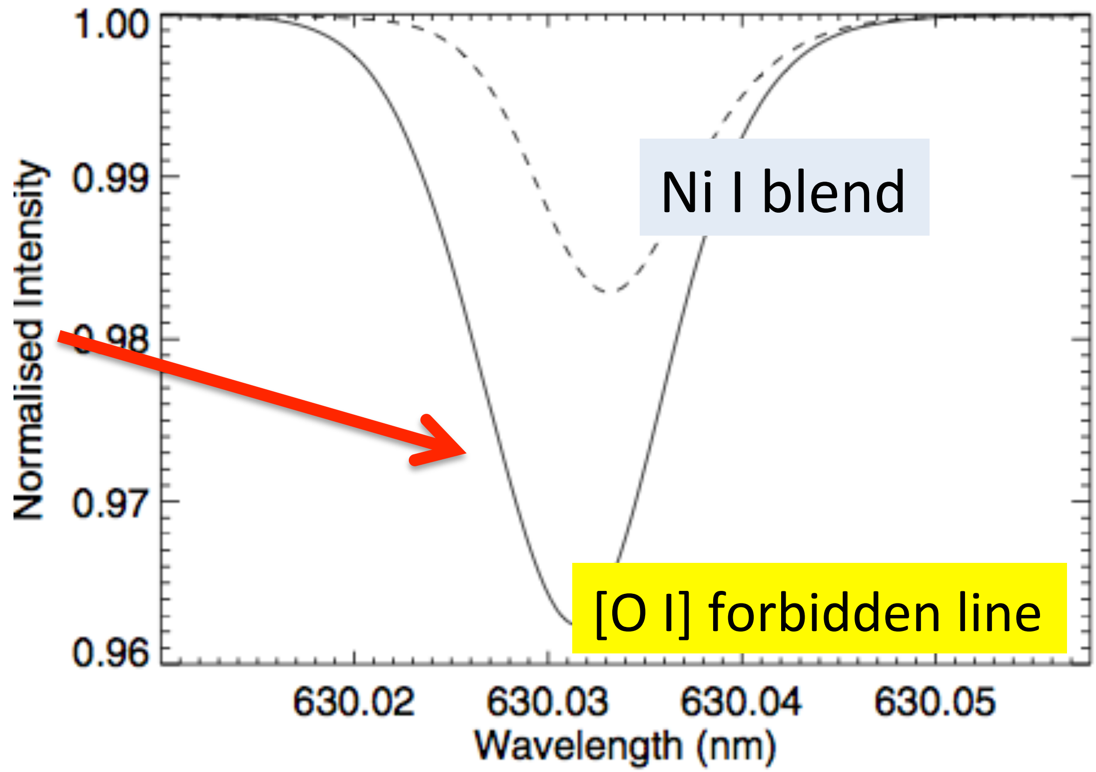
AGSS 2009

careful verification of the NLTE line formation for OI based on the solar limb-darkening

The forbidden [O I] line is blended by a Ni I line

Ni abundance may be affected by NLTE?

So far, only 3D LTE results for Ni



Solutions

Missing opacity? (Christensen-Dalsgaard et al. 2009)

Underestimated element diffusion?

Accretion of low-Z material? (Serenelli et al. 2011)

Underestimated solar Ne abundance? - unclear

Erroneous solar abundances? - unclear

Combination of some of the above?