Oxygen in the Sun

Martin Asplund

THE AUSTRALIAN NATIONAL UNIVERSITY

Australian Government
Australian Research Council

Main partners in crime

Åke Nordlund

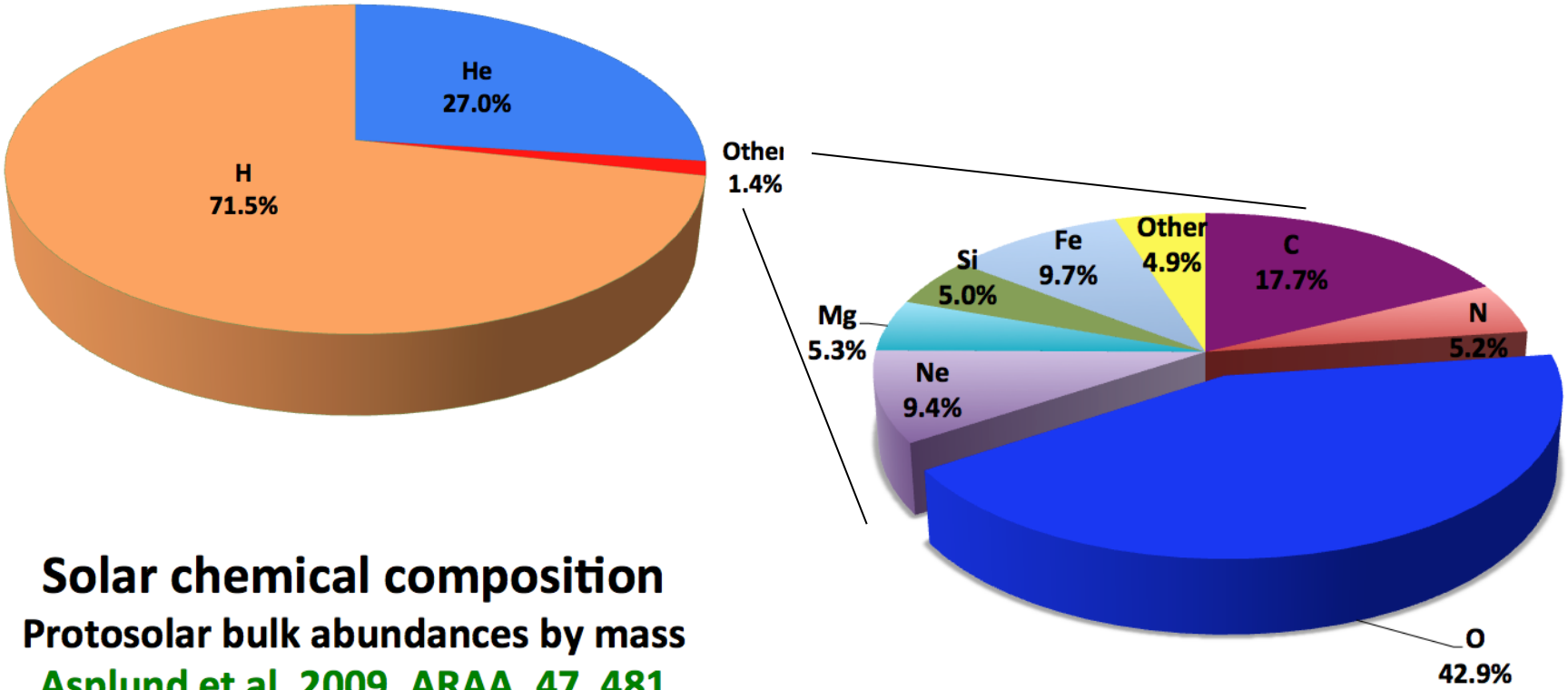
Nicolas Grevesse

(+ many collaborators)

Past and present PhD students + postdocs:
Patrick Baumann, Remo Collet, Wolfgang Hayek, Karin Lind, Jorge Melendez, Tiago Pereira, Ivan Ramirez, Pat Scott, Regner Trampedach etc

Solar abundances

The solar chemical composition is a fundamental yardstick for almost all astronomy

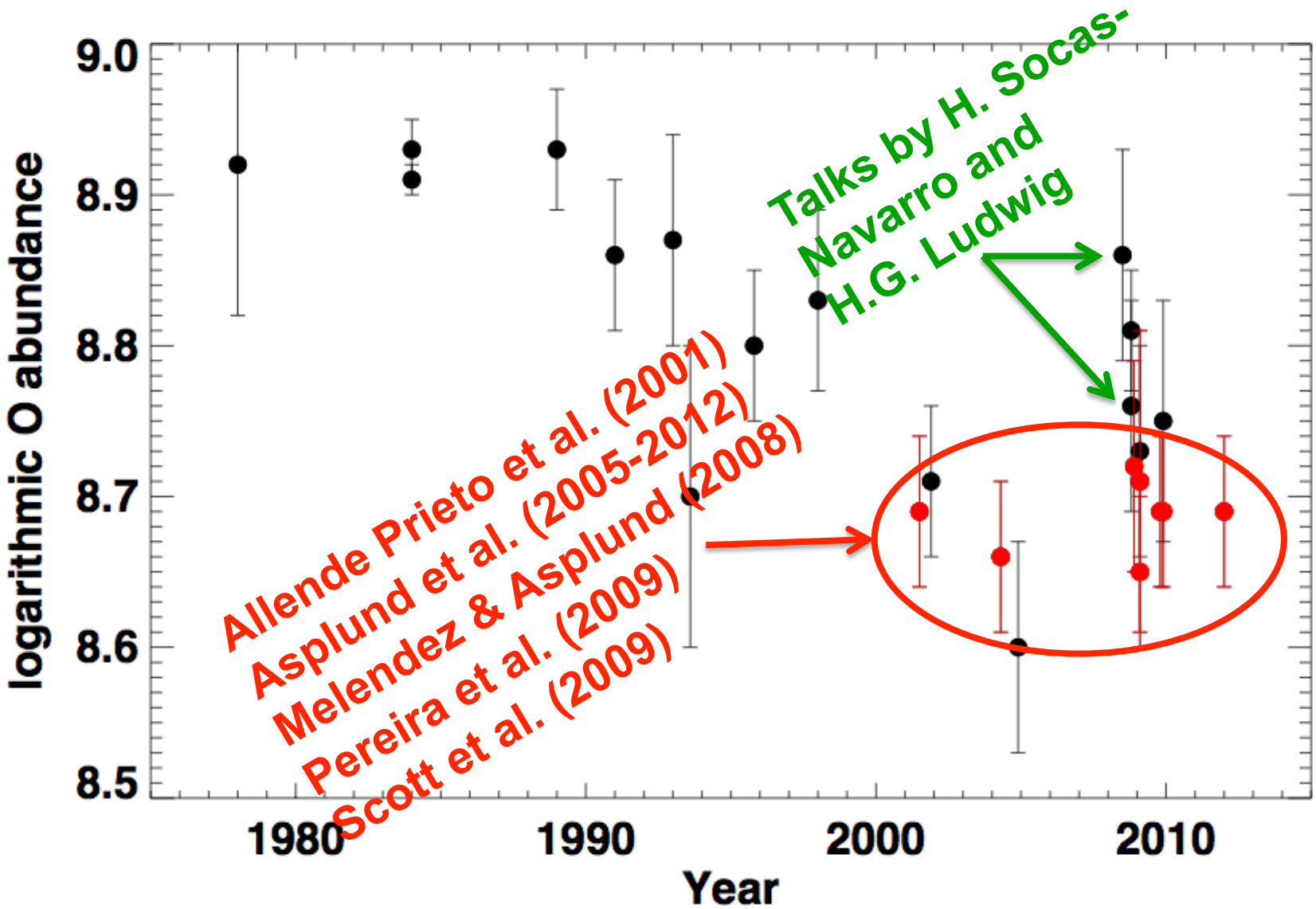


Solar chemical composition

Protosolar bulk abundances by mass

Asplund et al. 2009, ARAA, 47, 481

Running out of oxygen?



Solar system abundances

Meteorites

Mass spectroscopy

Very high accuracy

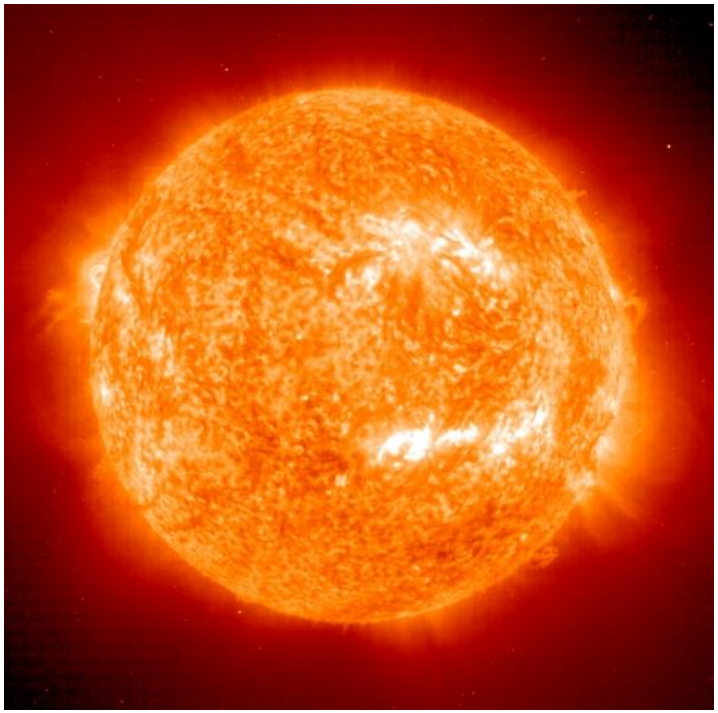
Element depletion

Solar atmosphere

Solar spectroscopy

Modelling-dependent

Very little depletion



Solar system abundances

Meteorites

Mass spectroscopy

Very high accuracy

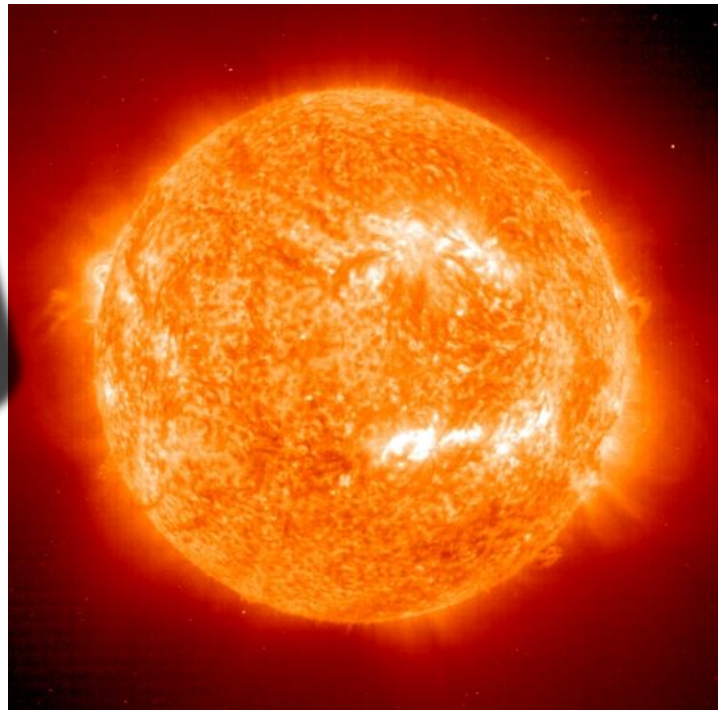
Element depletion

Solar atmosphere

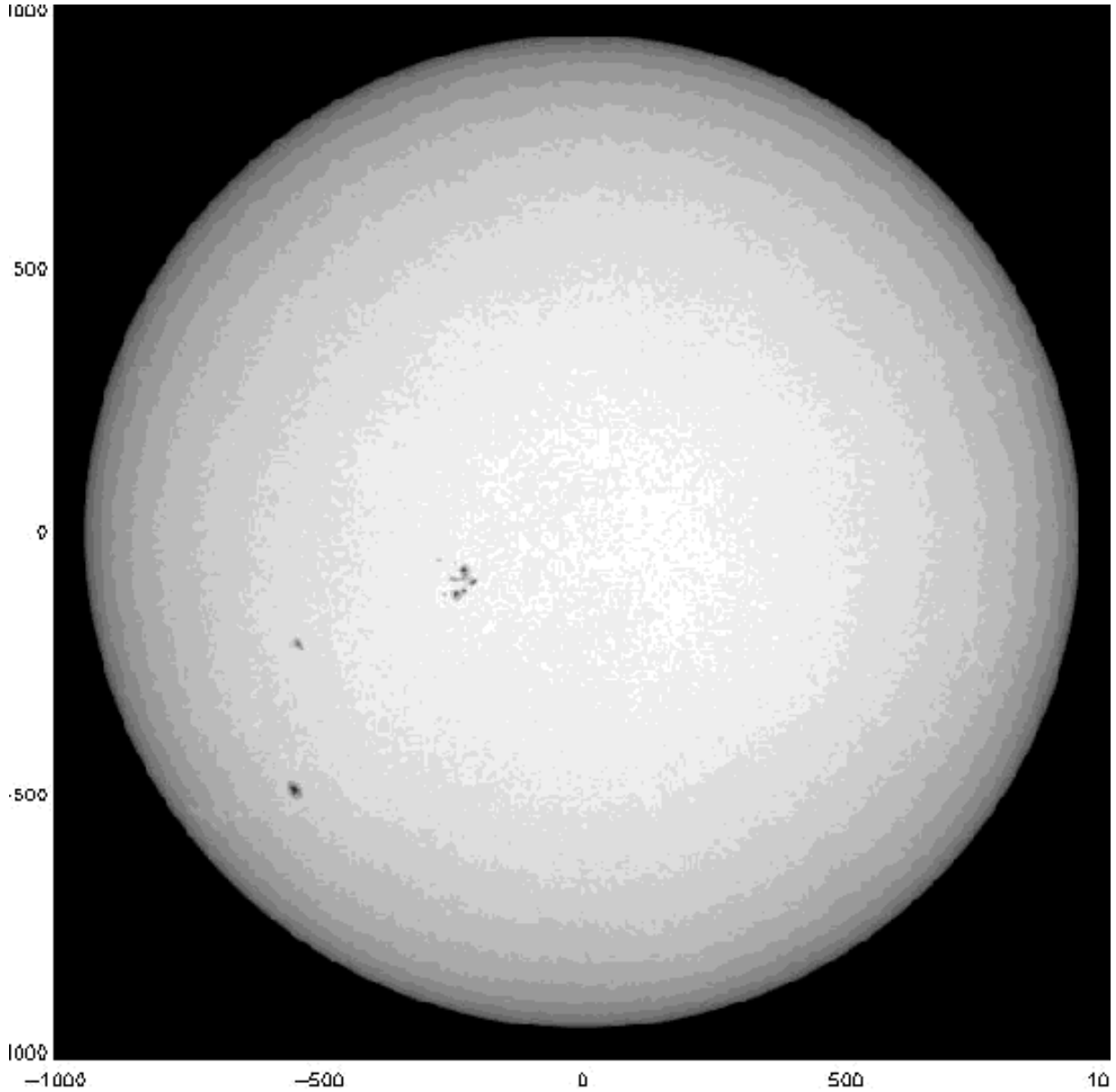
Solar spectroscopy

Modelling-dependent

Very little depletion

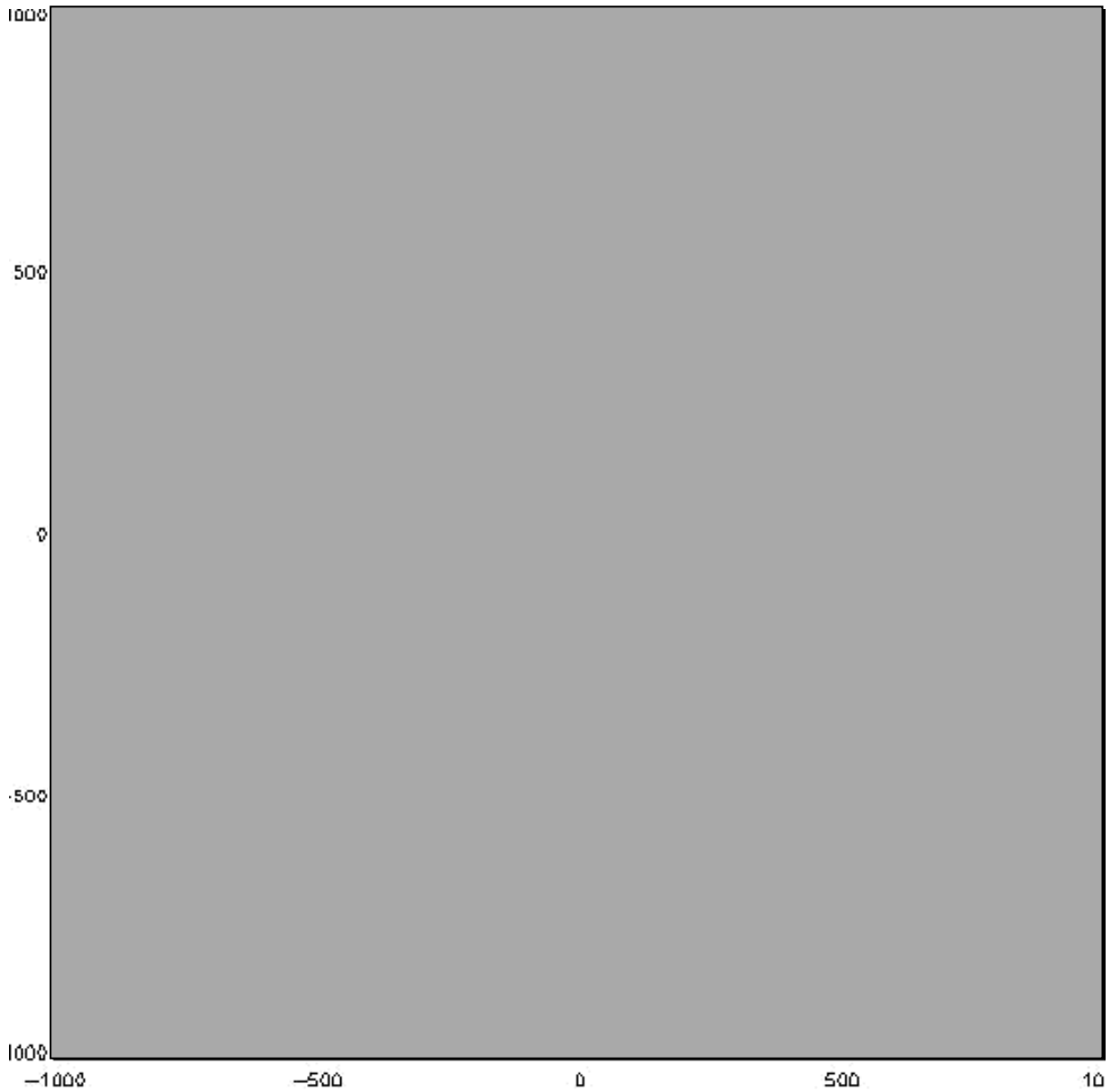


Solar atmosphere



Mats Carlsson (Oslo)

Solar atmosphere



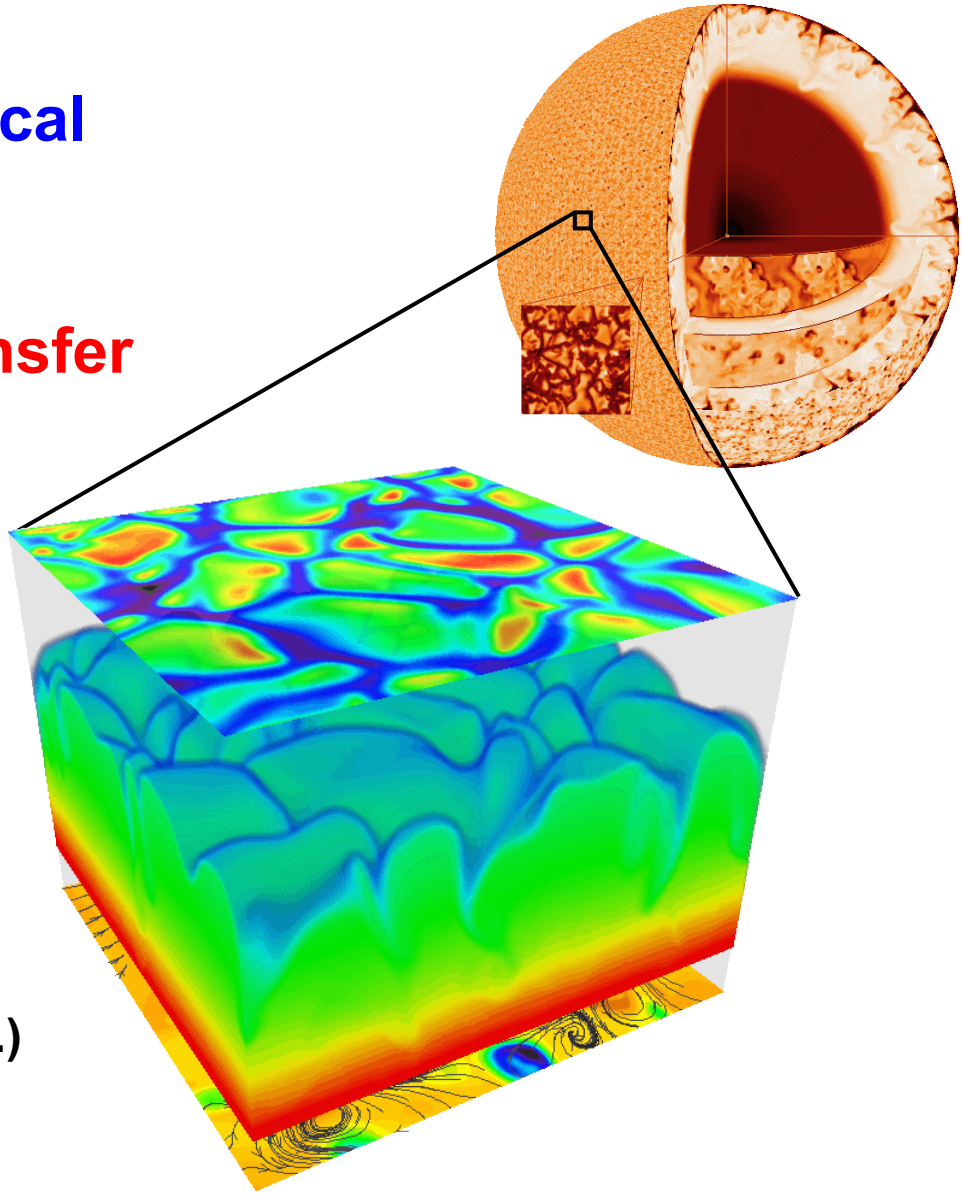
Mats Carlsson (Oslo)

3D solar atmosphere model

Ingredients:

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

Essentially parameter free

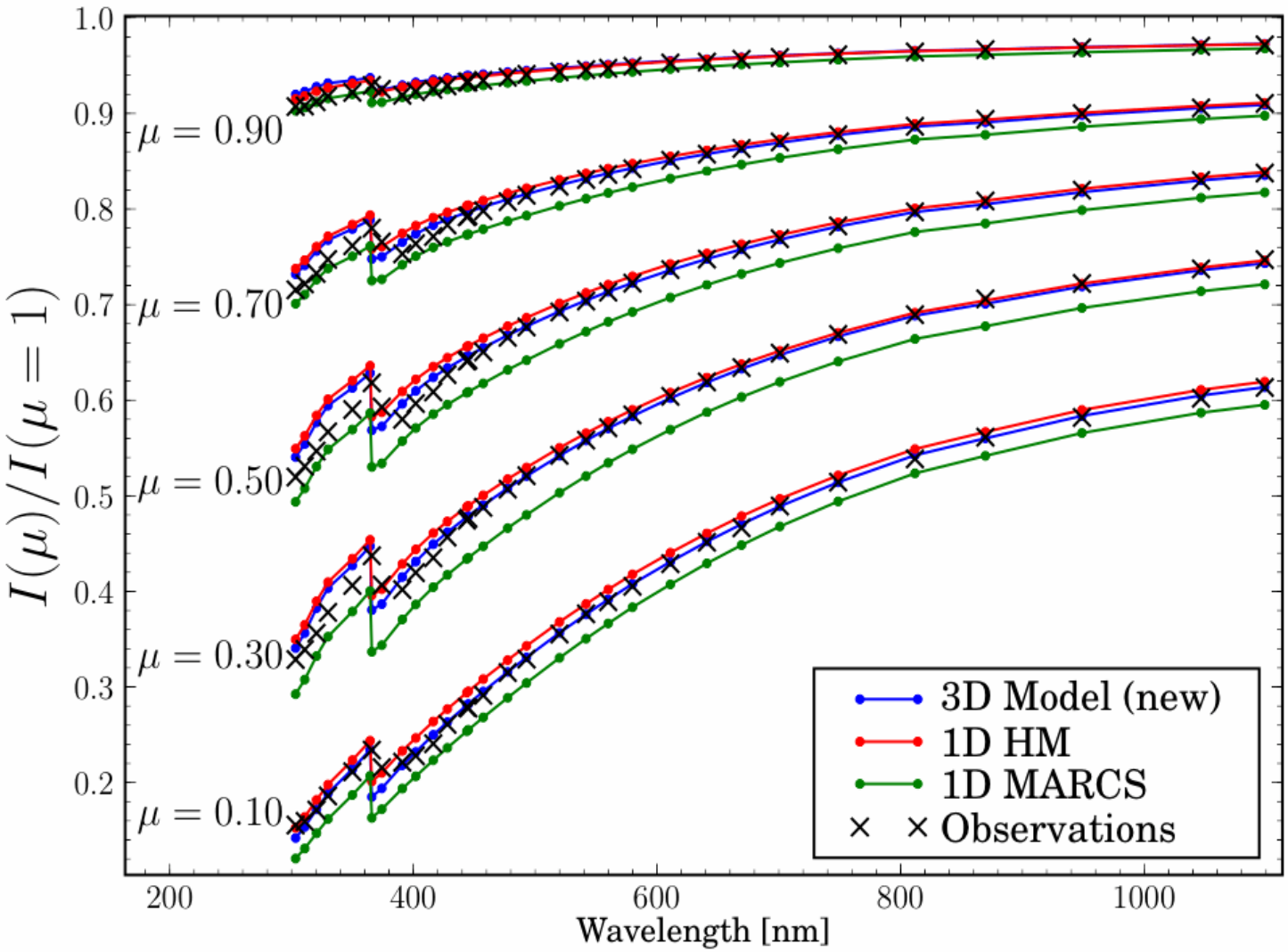


For the aficionados:

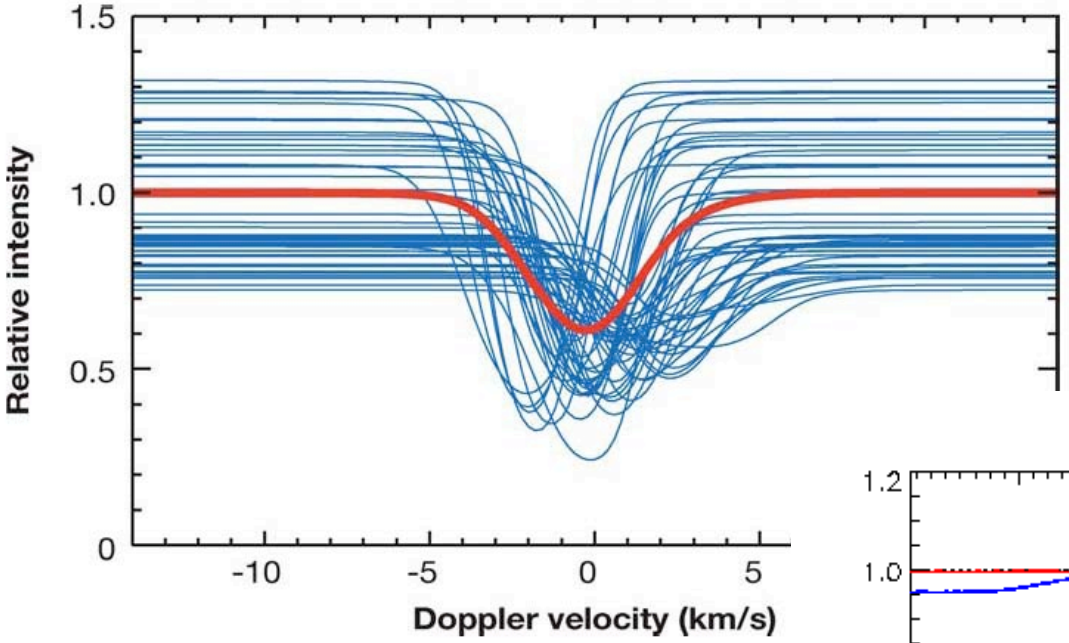
Stagger-code (Nordlund et al.)
MHD equation-of-state (Mihalas et al.)
MARCS opacities (Gustafsson et al.)
Opacity binning (Nordlund)

Temperature structure

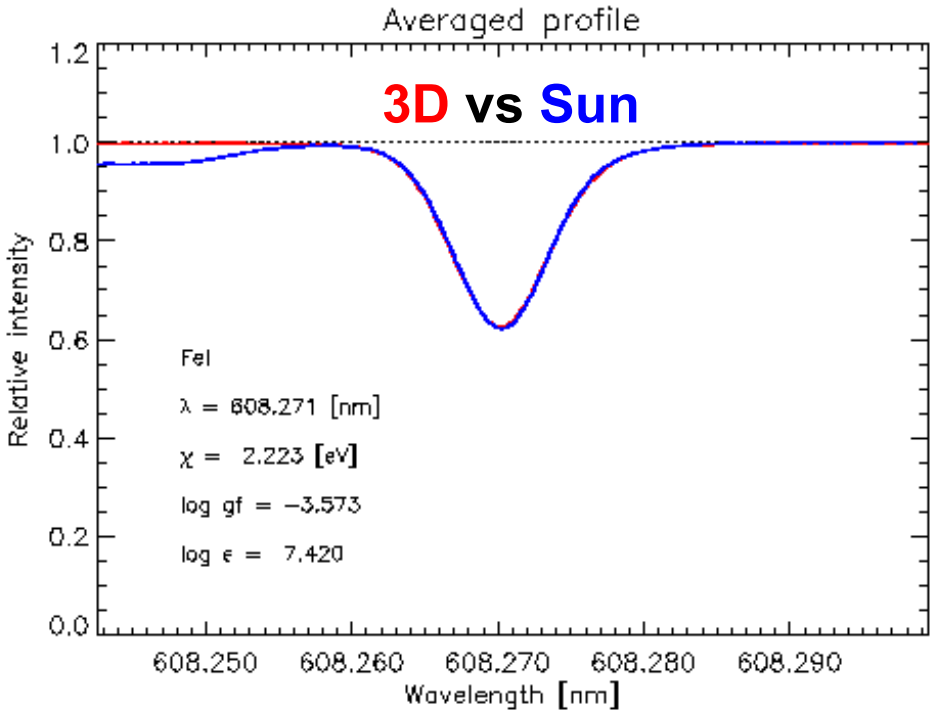
Center-to-limb variation: 3D model has right T(tau)



Spectral line formation

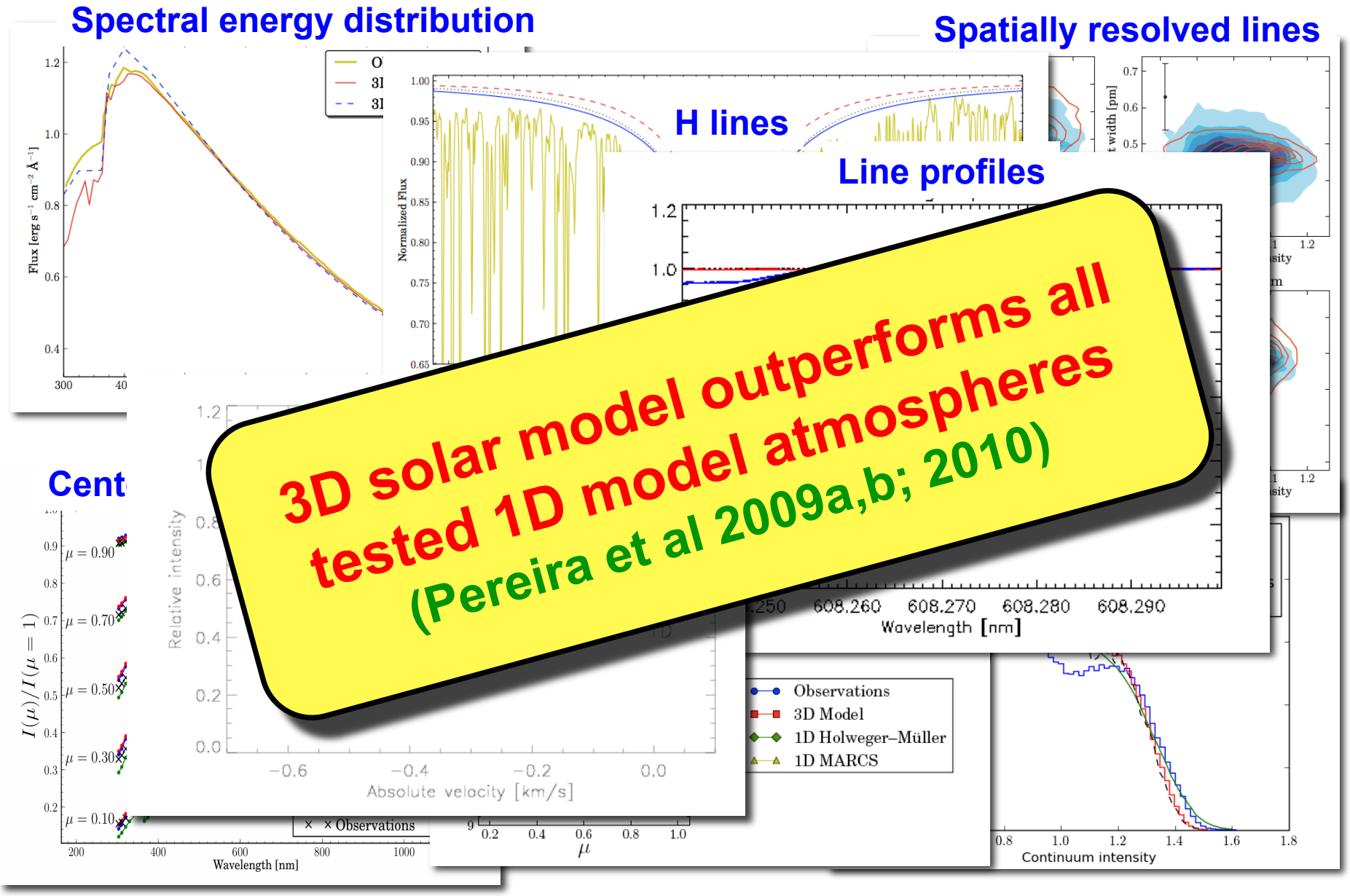


Line profiles vary tremendously across the solar surface



3D model describes observations very well without free parameters

More observational tests



Solar abundances revisited

- Asplund et al., 2009, ARAA, 47, 481
- Realistic 3D model for the solar atmosphere
- Detailed spectrum formation calculations
- Improved atomic and molecular input data
- Careful selection of lines

Element	Anders & Grevesse (1989)	Asplund et al. (2009)	Difference
Carbon	8.56+/-0.06	8.43+/-0.05	-26%
Nitrogen	8.05+/-0.04	7.83+/-0.05	-40%
Oxygen	8.93+/-0.03	8.69+/-0.05	-42%

Note: logarithmic scale with H defined to have 12.00

Oxygen

Oxygen diagnostics

- Discordant results in 1D: log O~8.6-8.9
- Excellent agreement in 3D: log O=8.70±0.05
- Asplund et al. (2009, 2012)

Lines	MARCS	Holweger-Mueller	3D
[O I]	8.69+/-0.05	8.73+/-0.05	8.70+/-0.05
O I	8.62+/-0.05	8.69+/-0.05	8.69+/-0.05
OH, dv=0	8.78+/-0.03	8.83+/-0.03	8.71+/-0.03
OH, dv=1	8.75+/-0.03	8.86+/-0.03	8.71+/-0.02

Two often-used 1D model atmospheres

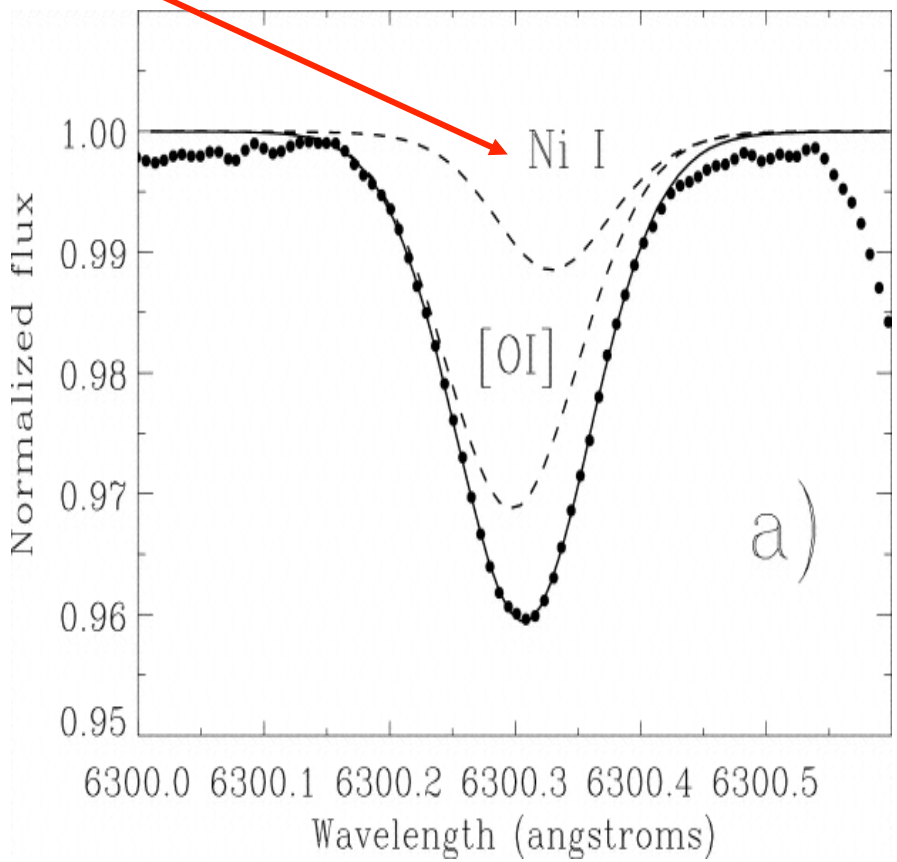
[O I]: blends

Allende Prieto et al. 2001:
Blend with Ni: -0.19 dex

Johansson et al. 2003:
gf-value of Ni I blend measured experimentally

Scott et al. 2009, 2012:
New solar Ni abundance

Asplund et al. 2009, 2012:
log O = 8.70±0.05
(Mean of three [OI] lines)



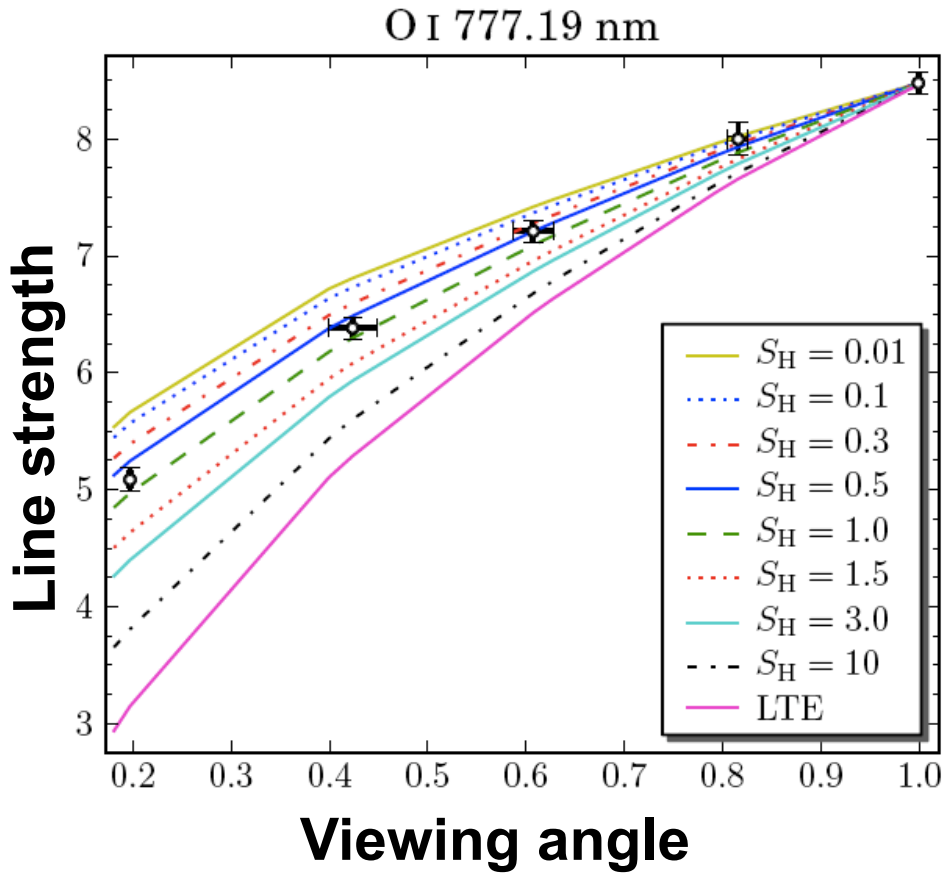
O I: non-LTE effects

High-excitation O I lines are sensitive to non-LTE effects

Non-LTE - LTE ≈ -0.2 dex

Pereira et al. 2009:
Use observed center-to-limb variations to determine poorly known H collisions

Asplund et al. 2009:
log O=8.69±0.05

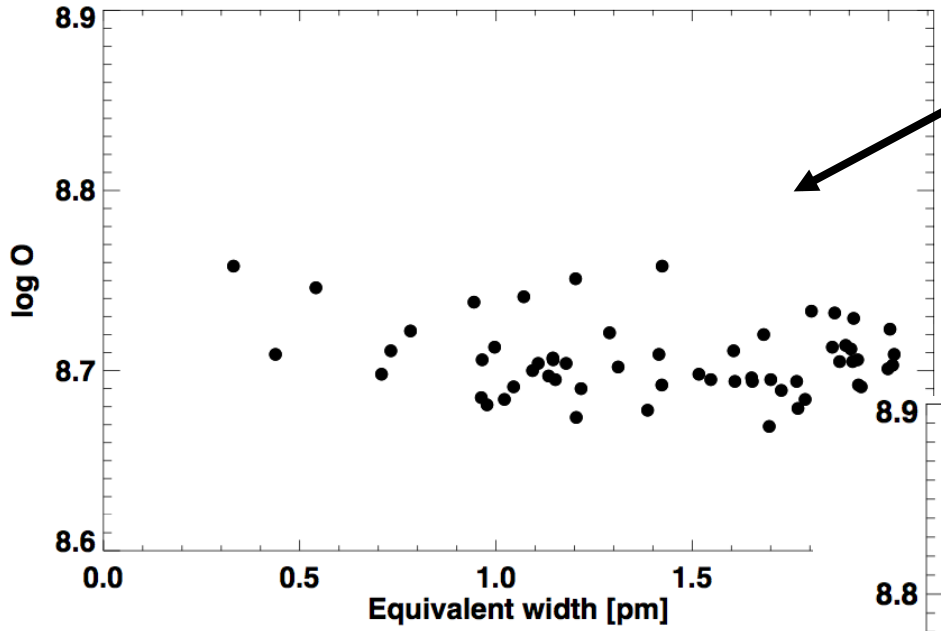


Note: S_H only makes sense for a given model atom and atmosphere

OH lines: 3D effects

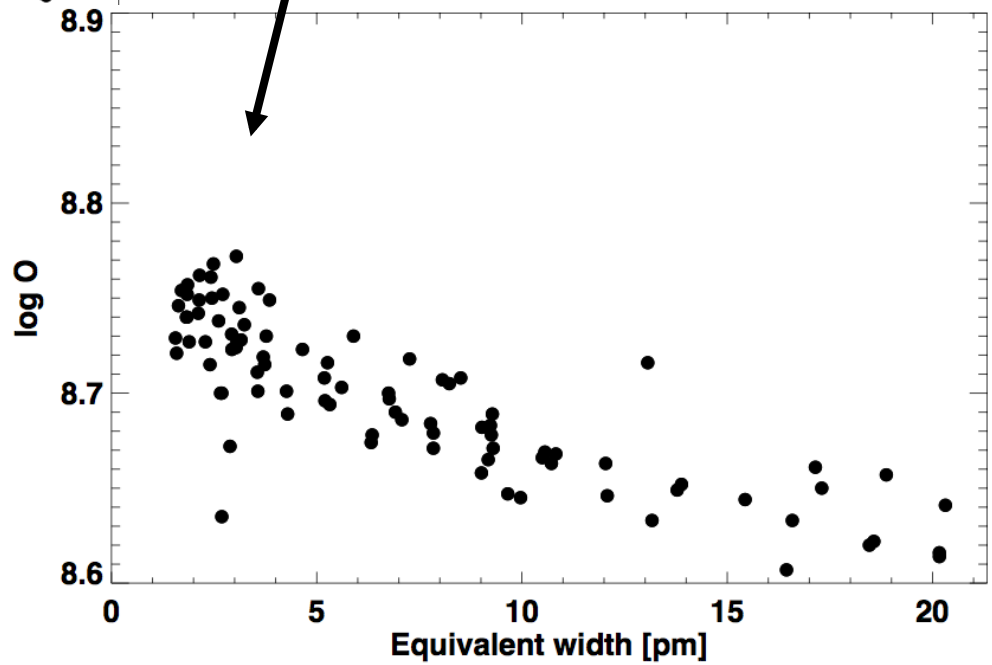
Molecular lines are very temperature sensitive

3D model: different mean T(τ) and T inhomogenities



Vibration-rotation lines:
log O=8.71±0.02

Pure rotation lines:
log O=8.71±0.03



Asplund et al. 2009, 2012

Independent studies

3D-based solar analysis by CO5BOLD collaboration

Caffau, Ludwig, Steffen, Freytag et al.

Element	Caffau et al. (2008, 2009a,b)	Asplund et al. (2012)
Carbon	8.54+/-0.13	8.43+/-0.05
Nitrogen	7.86+/-0.12	7.83+/-0.05
Oxygen	8.76+/-0.07	8.70+/-0.05

Very good agreement when same input data are used

- **Selection of lines**
- **Equivalent widths**
- **Non-LTE corrections**

(Caffau et al. do not consider molecular lines)

Independent studies

3D-based solar analysis by CO5BOLD collaboration

Caffau, Ludwig, Steffen, Freytag et al.

Element	Caffau et al. (2008, 2009a,b)	Asplund et al. (2012)
Carbon	8.54+/-0.13	[illegible]-0.05
Nitrogen	[illegible]	[illegible].05
Oxygen	[illegible]	[illegible]0+/-0.05

H.G. Ludwig's talk

Very good a[illegible]nt when same input data are used

- **Selection of lines**
- **Equivalent widths**
- **Non-LTE corrections**

(Caffau et al. do not consider molecular lines)

Complete solar inventory

Asplund et al. (2009, ARAA):

3D-based analysis of all elements

Statistical and systematic errors included in total uncertainties

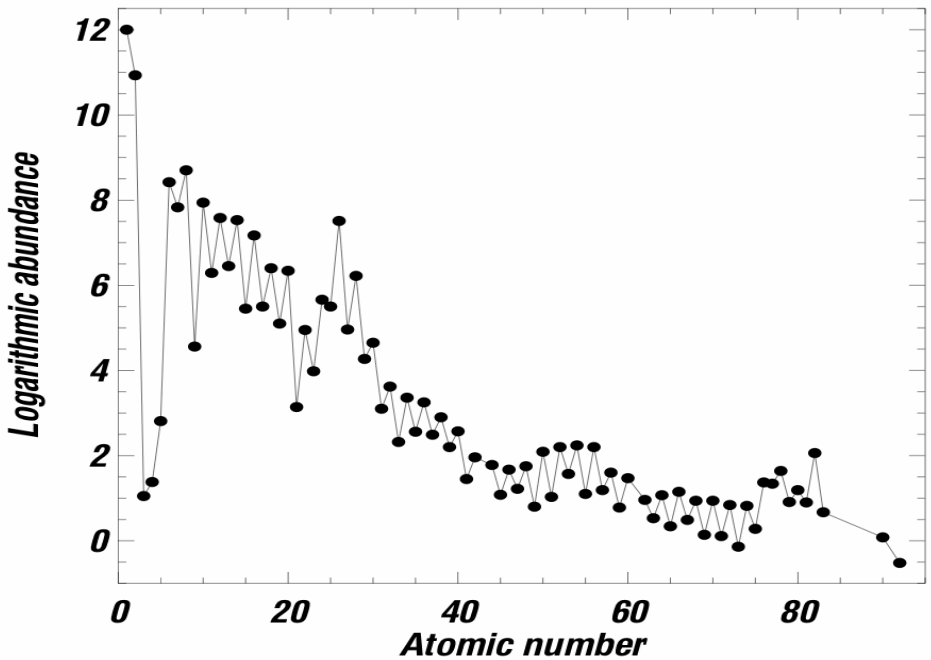


Table 1 Element abundances in the present-day solar photosphere. Also given are the corresponding values for CI carbonaceous chondrites (Lodders, Palme & Gail 2009). Indirect photospheric estimates have been used for the noble gases (Section 3.9)

Z	Element	Photosphere	Meteorites	Z	Element	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	[10.93 ± 0.01]	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06
9	F	4.56 ± 0.30	4.42 ± 0.06	52	Te		2.18 ± 0.03
10	Ne	[7.93 ± 0.10]	−1.12	53	I		1.55 ± 0.08
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	[2.24 ± 0.06]	−1.95
12	Mg	7.60 ± 0.04	7.53 ± 0.01	55	Cs		1.08 ± 0.02
13	Al	6.45 ± 0.03	6.43 ± 0.01	56	Ba	2.18 ± 0.09	2.18 ± 0.03
14	Si	7.51 ± 0.03	7.51 ± 0.01	57	La	1.10 ± 0.04	1.17 ± 0.02
15	P	5.41 ± 0.03	5.43 ± 0.04	58	Ce	1.58 ± 0.04	1.58 ± 0.02
16	S	7.12 ± 0.03	7.15 ± 0.02	59	Pr	0.72 ± 0.04	0.76 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.42 ± 0.04	1.45 ± 0.02
18	Ar	[6.40 ± 0.13]	−0.50	62	Sm	0.96 ± 0.04	0.94 ± 0.02
19	K	5.03 ± 0.09	5.08 ± 0.02	63	Eu	0.52 ± 0.04	0.51 ± 0.02
20	Ca	6.34 ± 0.04	6.29 ± 0.02	64	Gd	1.07 ± 0.04	1.05 ± 0.02
21	Sc	3.15 ± 0.04	3.05 ± 0.02	65	Tb	0.30 ± 0.10	0.32 ± 0.03
22	Ti	4.95 ± 0.05	4.91 ± 0.03	66	Dy	1.10 ± 0.04	1.13 ± 0.02
23	V	3.93 ± 0.08	3.96 ± 0.02	67	Ho	0.48 ± 0.11	0.47 ± 0.03
24	Cr	5.64 ± 0.04	5.64 ± 0.01	68	Er	0.92 ± 0.05	0.92 ± 0.02
25	Mn	5.43 ± 0.04	5.48 ± 0.01	69	Tm	0.10 ± 0.04	0.12 ± 0.03
26	Fe	7.50 ± 0.04	7.45 ± 0.01	70	Yb	0.84 ± 0.11	0.92 ± 0.02
27	Co	4.99 ± 0.07	4.87 ± 0.01	71	Lu	0.10 ± 0.09	0.09 ± 0.02
28	Ni	6.22 ± 0.04	6.20 ± 0.01	72	Hf	0.85 ± 0.04	0.71 ± 0.02
29	Cu	4.19 ± 0.04	4.25 ± 0.04	73	Ta		−0.12 ± 0.04
30	Zn	4.56 ± 0.05	4.63 ± 0.04	74	W	0.85 ± 0.12	0.65 ± 0.04
31	Ga	3.04 ± 0.09	3.08 ± 0.02	75	Re		0.26 ± 0.04
32	Ge	3.65 ± 0.10	3.58 ± 0.04	76	Os	1.40 ± 0.08	1.35 ± 0.03
33	As		2.30 ± 0.04	77	Ir	1.38 ± 0.07	1.32 ± 0.02
34	Se		3.34 ± 0.03	78	Pt		1.62 ± 0.03
35	Br		2.54 ± 0.06	79	Au	0.92 ± 0.10	0.80 ± 0.04
36	Kr	[3.25 ± 0.06]	−2.27	80	Hg		1.17 ± 0.08
37	Rb	2.52 ± 0.10	2.36 ± 0.03	81	Tl	0.90 ± 0.20	0.77 ± 0.03
38	Sr	2.87 ± 0.07	2.88 ± 0.03	82	Pb	1.75 ± 0.10	2.04 ± 0.03
39	Y	2.21 ± 0.05	2.17 ± 0.04	83	Bi		0.65 ± 0.04
40	Zr	2.58 ± 0.04	2.53 ± 0.04	90	Th	0.02 ± 0.10	0.06 ± 0.03
41	Nb	1.46 ± 0.04	1.41 ± 0.04	92	U		−0.54 ± 0.03
42	Mo	1.88 ± 0.08	1.94 ± 0.04				

(Some) Implications

- **Significantly lower solar metal mass fraction Z**
  - Z=0.0213 (Anders & Grevesse 1989)
  - Z=0.0143 (Asplund et al. 2009)
- **Alters cosmic yardstick**
  - [X/H], [X/Fe] etc
- **Makes Sun normal compared with surroundings**
  - Young stars in solar neighborhood
  - Local interstellar medium

Solar neighborhood

Asplund et al. (2009):

Proto-Sun agrees with present-day ISM and OB stars

Table 5 Comparison of the protosolar abundances with those in nearby B stars and HII regions[a]

Elem.	Sun[b]	Sun[c]	B stars[d]	HII[e]	GCE[f]
He	10.98 ± 0.01	10.98 ± 0.01	10.98 ± 0.02	10.96 ± 0.01	0.01
C	8.56 ± 0.06	8.47 ± 0.05	8.35 ± 0.03	8.66 ± 0.06	0.06
N	7.96 ± 0.06	7.87 ± 0.05	7.76 ± 0.05	7.85 ± 0.06	0.08
O	8.87 ± 0.06	8.73 ± 0.05	8.76 ± 0.03	8.80 ± 0.04	0.04
Ne	8.12 ± 0.06	7.97 ± 0.10	8.08 ± 0.03	8.00 ± 0.08	0.04
Mg	7.62 ± 0.05	7.64 ± 0.04	7.56 ± 0.05		0.04
Si	7.59 ± 0.05	7.55 ± 0.04	7.50 ± 0.02		0.08
S	7.37 ± 0.11	7.16 ± 0.03	7.21 ± 0.13	7.30 ± 0.04	0.09
Ar	6.44 ± 0.06	6.44 ± 0.13	6.66 ± 0.06	6.62 ± 0.06	
Fe	7.55 ± 0.05	7.54 ± 0.04	7.44 ± 0.04		0.14

Solar surface + diffusion (0.04 dex) (Asplund et al. 2009)

Galactic chemical evolution over 4.5Gyr (Chiappini et al. 2003)

Solar neighborhood

Asplund et al. (2009):

Proto-Sun agrees with present-day ISM and OB stars

Table 5 Comparison of the protosolar abundances with those in nearby B stars and HII regions[a]

Elem.	Sun[b]	Sun[c]	B stars[d]	HII[e]	GCE[f]
He	10.98 ± 0.01	10.98 ± 0.01	10.98 ± 0.0[illegible]	[illegible]96 ± 0.01	0.01
C	8.56 ± 0.06	8.47 ± 0.05	[illegible]	[illegible]6 ± 0.06	0.06
N	7.96 ± 0.06	7.87 [illegible]	[illegible]	[illegible] ± 0.06	0.08
O	8.87 ± 0.06	[illegible]	[illegible]	[illegible]0 ± 0.04	0.04
Ne	8.12 [illegible]	[illegible]	[illegible]	8.00 ± 0.08	0.04
Mg	7.62 ± [illegible]	[illegible]	7.56 ± 0.05		0.04
Si	7.59 ± [illegible]	[illegible] ± 0.04	7.50 ± 0.02		0.08
S	7.37 ± [illegible]	7.16 ± 0.03	7.21 ± 0.13	7.30 ± 0.04	0.09
Ar	6.44 ± 0.06	6.44 ± 0.13	6.66 ± 0.06	6.62 ± 0.06	
Fe	7.55 ± 0.05	7.54 ± 0.04	7.44 ± 0.04		0.14

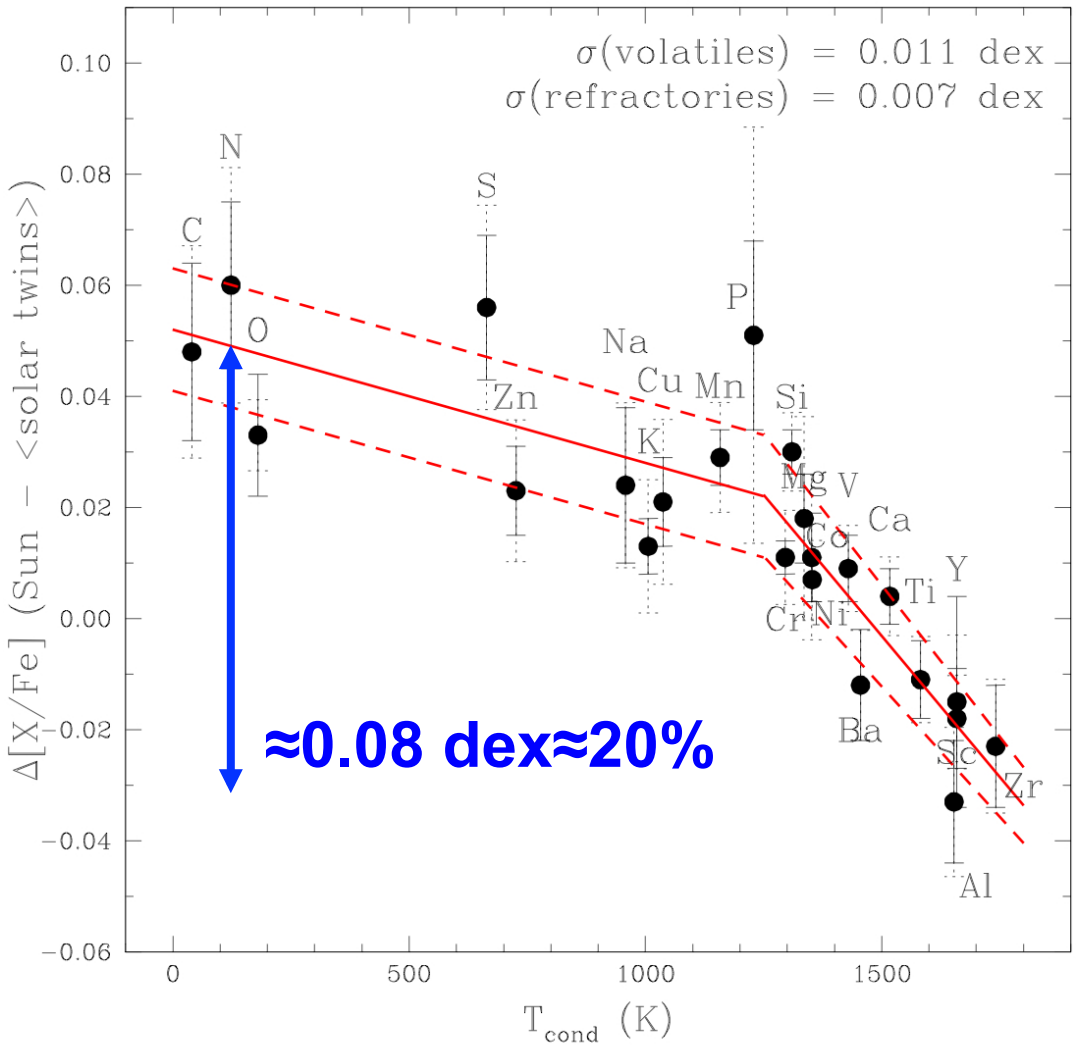
Talk by F. Nieva

Solar surface + diffusion (0.04 dex) (Asplund et al. 2009)

Galactic chemical evolution over 4.5Gyr (Chiappini et al. 2003)

Caution: Sun vs solar twins

Melendez et al. 2009



Precision stellar spectroscopy: ≤0.01 dex in [X/Fe]

Sun is unusual but not unique

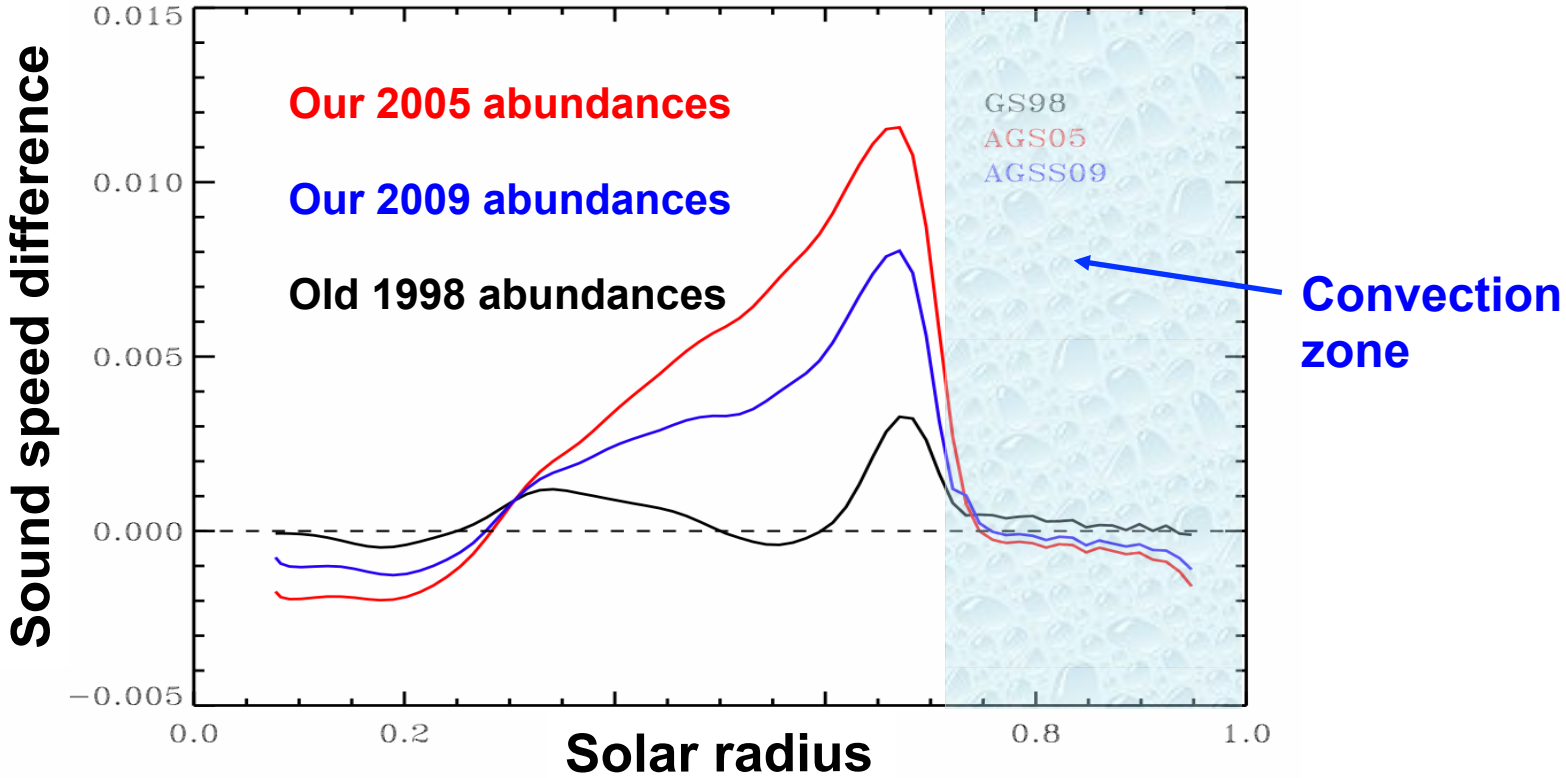
Chemical signature of planet formation

Oxygen unaffected?

(Some) Implications

- Significantly lower solar metal mass fraction Z
  - Z=0.0213 (Anders & Grevesse 1989)
  - Z=0.0143 (Asplund et al. 2009)
- Alters cosmic yardstick
  - [X/H], [X/Fe] etc
- Makes Sun normal compared with surroundings
  - Young stars in solar neighborhood
  - Local interstellar medium
- Changes stellar structure and evolution
  - Wrecks havoc with helioseismology

Trouble in paradise



Solar interior models with new abundances are in conflict with helioseismology

- **Wrong sound speed**
- **Wrong depth of convection zone: R=0.723 vs 0.713±0.001**
- **Wrong surface helium abundance: Y=0.235 vs 0.248±0.004**

Improved 3D solar models

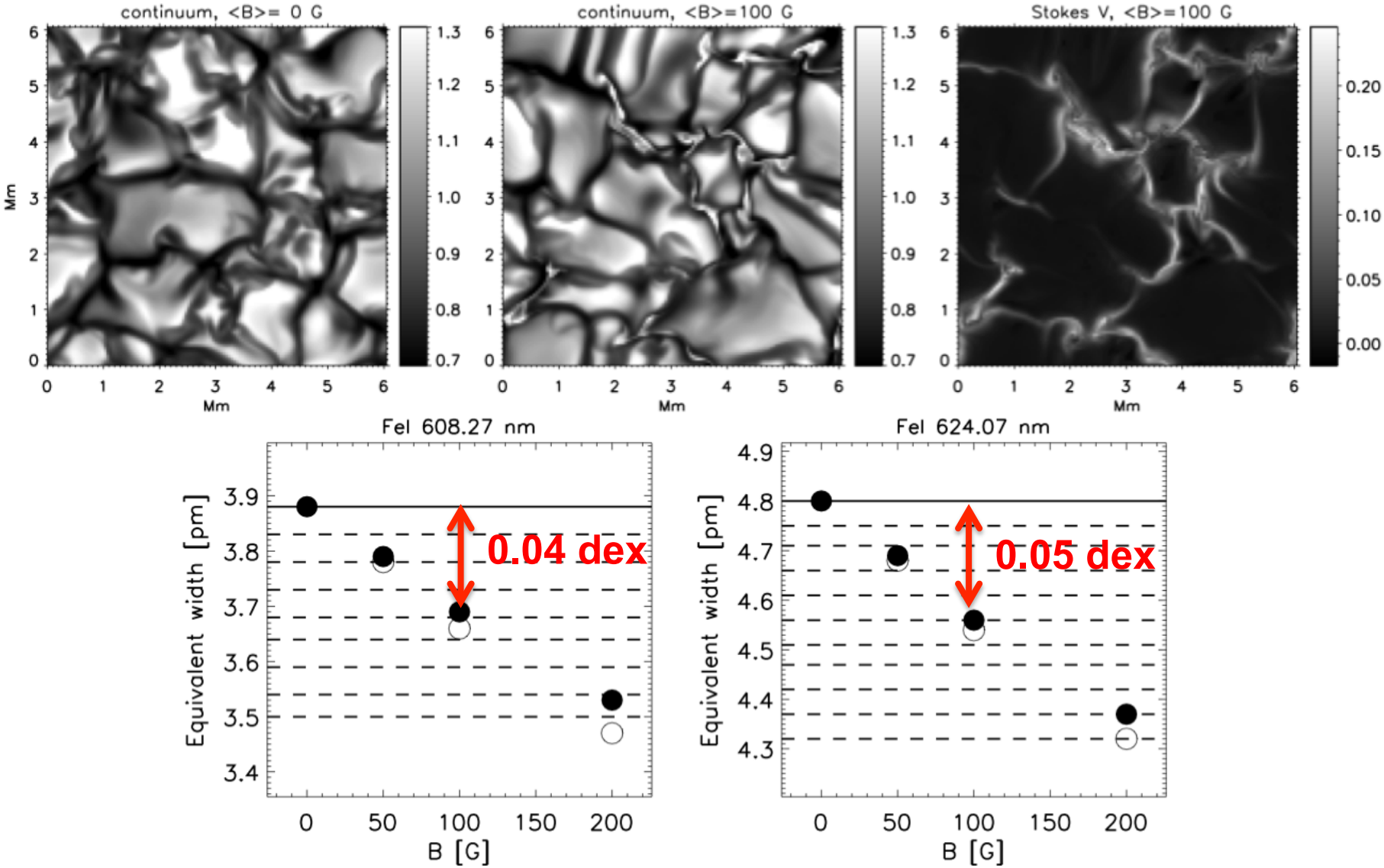
- **Higher numerical resolution**
  - 480^2x240 → 960^2x480
  - Δ(log O) < 0.02 dex

- **Better radiative transfer**
  - 12 → 48 opacity bins
  - Δ(log O) < 0.02 dex

- **Including magnetic fields**
  - 0 Gauss → 50, 100 Gauss

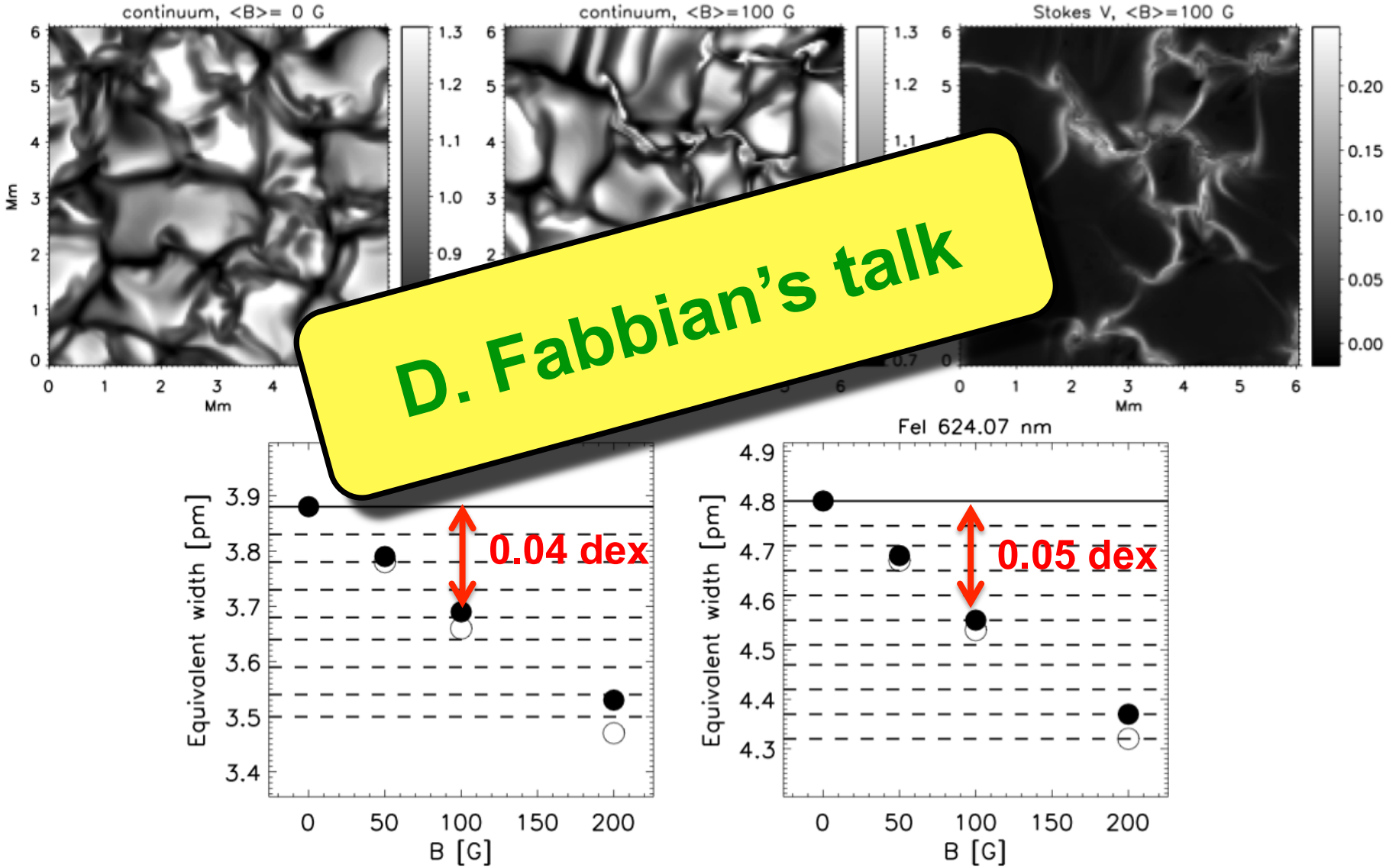
What about magnetic fields?

Fabbian et al. (2010): 3D MHD solar models



What about magnetic fields?

Fabbian et al. (2010): 3D MHD solar models

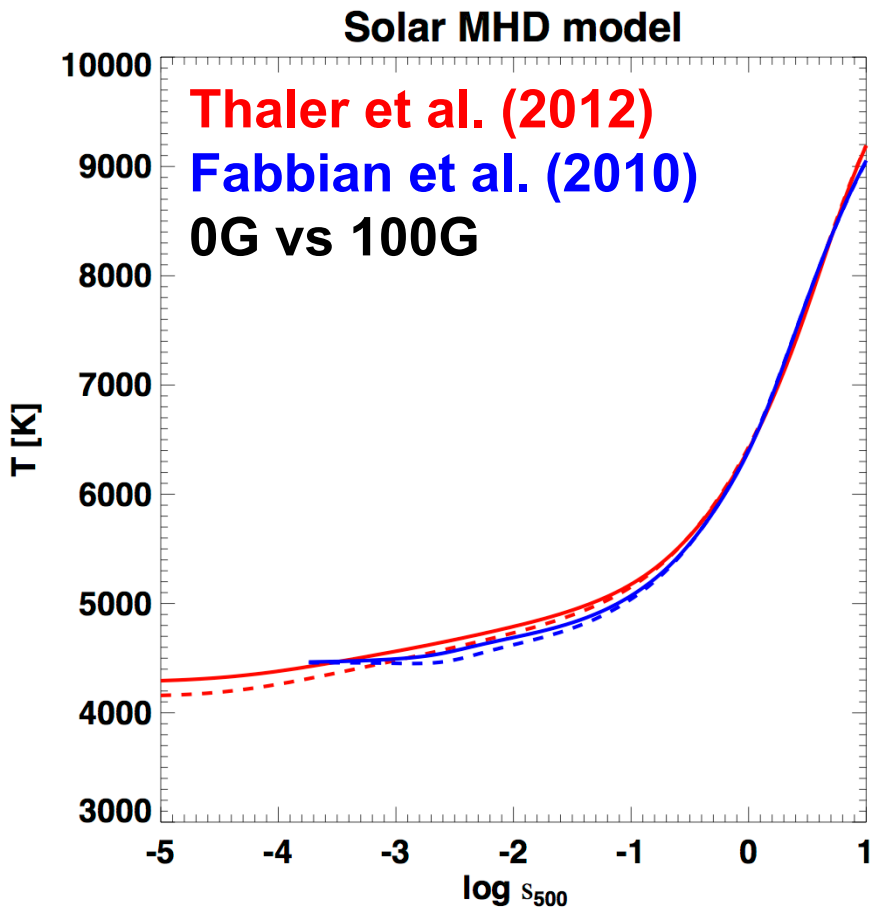


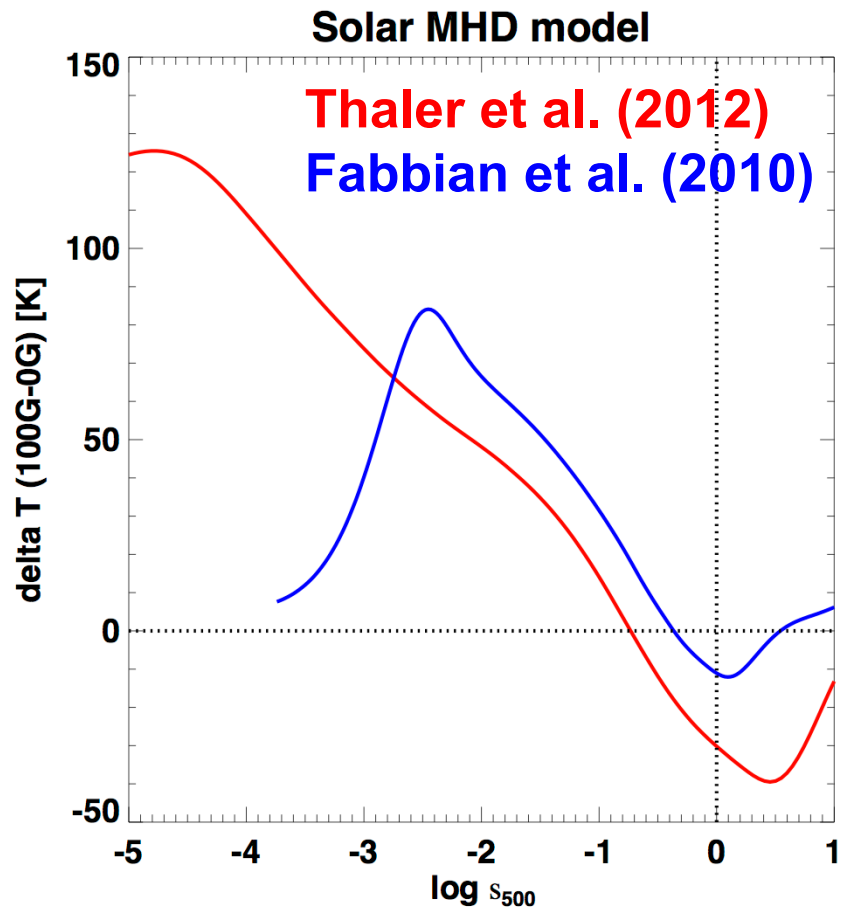
D. Fabbian's talk

MHD temperature structure

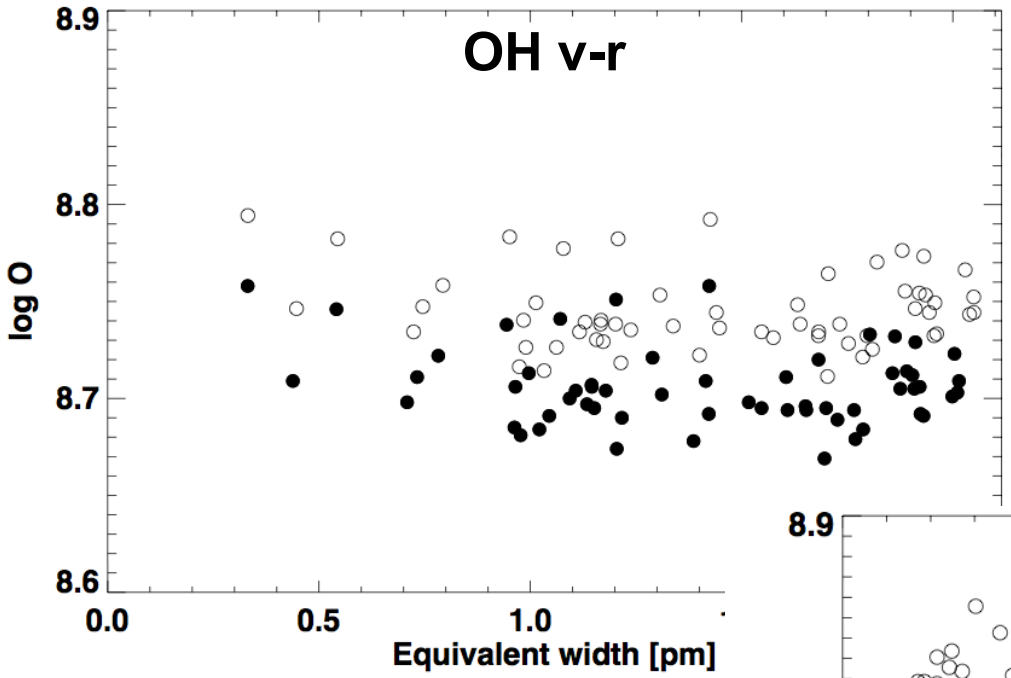
Thaler et al. (2012):

New solar MHD models with improved opacities and radiative transfer





MHD and solar abundances



0G ➔ 100G:

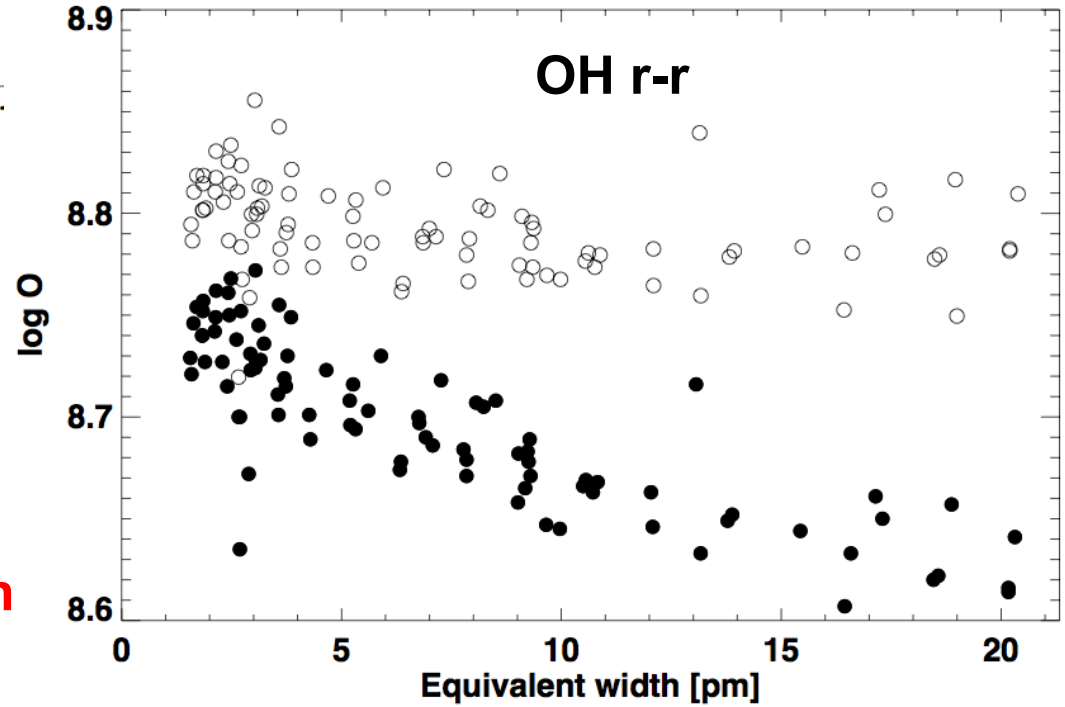
Atoms: Δlogε < 0.02 dex

[OI]: Δlogε ≈ 0.01 dex

OI: Δlogε ≈ 0.01 dex

OH v-r: Δlogε ≈ 0.04 dex

OH r-r: Δlogε ≈ 0.08 dex



+ Remove trends for OH r-r

- Introduce trends for FeI
- Worse continuum CLV
- Worse agreement [OI], OI, OH v-r and OH r-r
- Quiet Sun B-field uncertain

Summary

- New solar abundances for all elements
- Low C, N, O and Ne abundances
- Consistent abundances between all indicators: [OI], OI, OH v-r, OH r-r
- MHD: little impact on [OI], OI (+ other elements) but significant effect on OH
- Solar O abundance still likely “lowish”