Light elements in the light of 3D and non-LTE

Martin Asplund

Remo Collet
Ana Garcia Perez
Wolfgang Hayek
Karin Lind
Tiago Pereira
Regner Trampedach

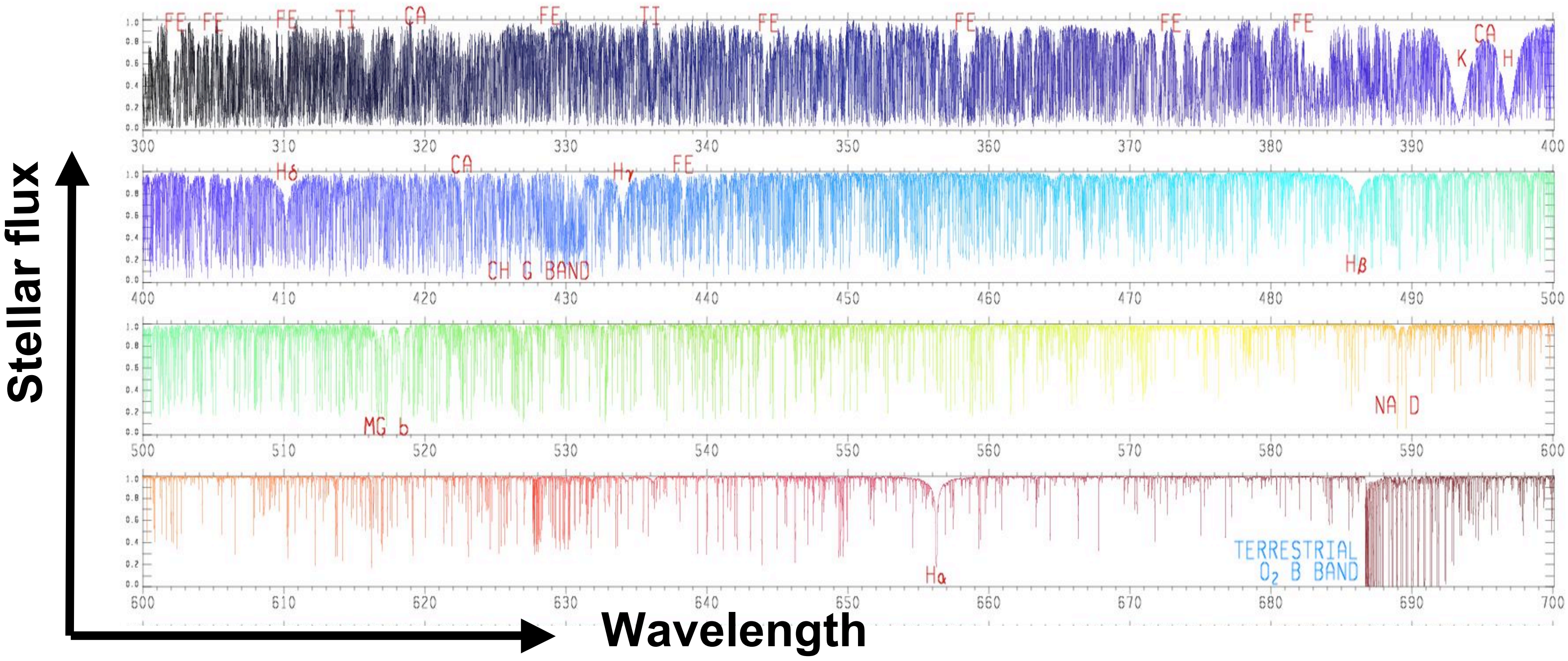
MAX-PLANCK-GESELLSCHAFT

Max Planck Institute
for Astrophysics

Elemental fingerprints

The chemical composition is encoded in stellar spectra but detailed modelling is required:

- Stellar atmospheres ⇒ Convection/3D
- Radiative transfer ⇒ Non-LTE



LTE vs non-LTE

LTE: Boltzmann + Saha distribution

$$\frac{N_i}{N} = \frac{g_i}{u(T)} e^{-\chi_i/kT}$$

$$\frac{N_{i+1}}{N_i} N_e = \frac{U_{i+1}}{U_i} \left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-\chi_{ion}/kT}$$

"Depends only on local conditions"

Non-LTE: Rate equations + radiative transfer equation

$$\frac{dn_i(r)}{dt} = \sum_{j=i}^{N} n_j(r) P_{ji}(r) - n_i(r) \sum_{j=i}^{N} P_{ij}(r) = 0$$

$$P_{ij} = A_{ij} + B_{ij}\bar{J} + C_{ij}$$

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu$$

"Everything depends on everything everywhere"

Non-LTE input atomic data

Radiative transitions:

- Bound-bound
- Photo-ionization

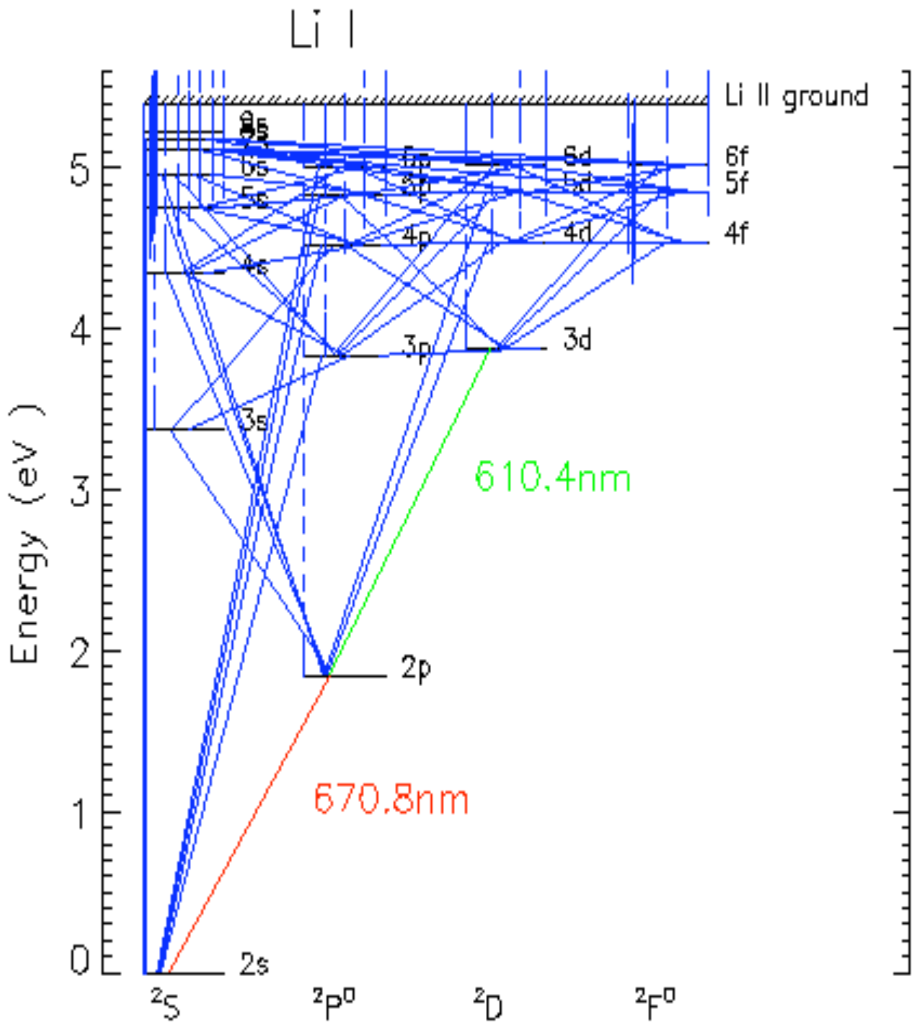
Data available (Opacity Project, Iron Project etc)

Collisional transitions:

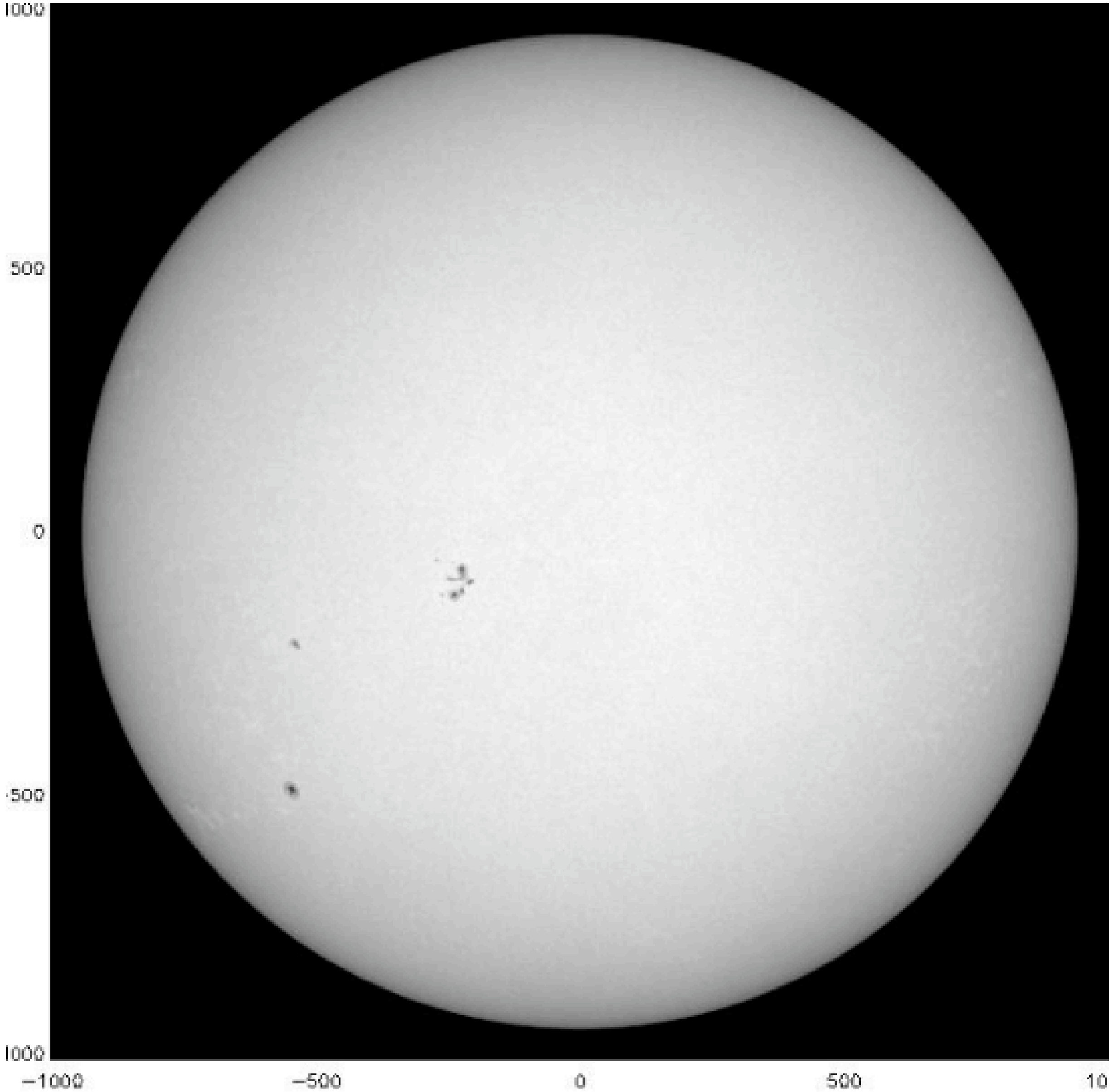
- Electrons
- Hydrogen
- Charge transfer

Data available for Li (Barklem et al. 2003)

Uncertain classical recipes for Be+B (e.g. Drawin 1968)

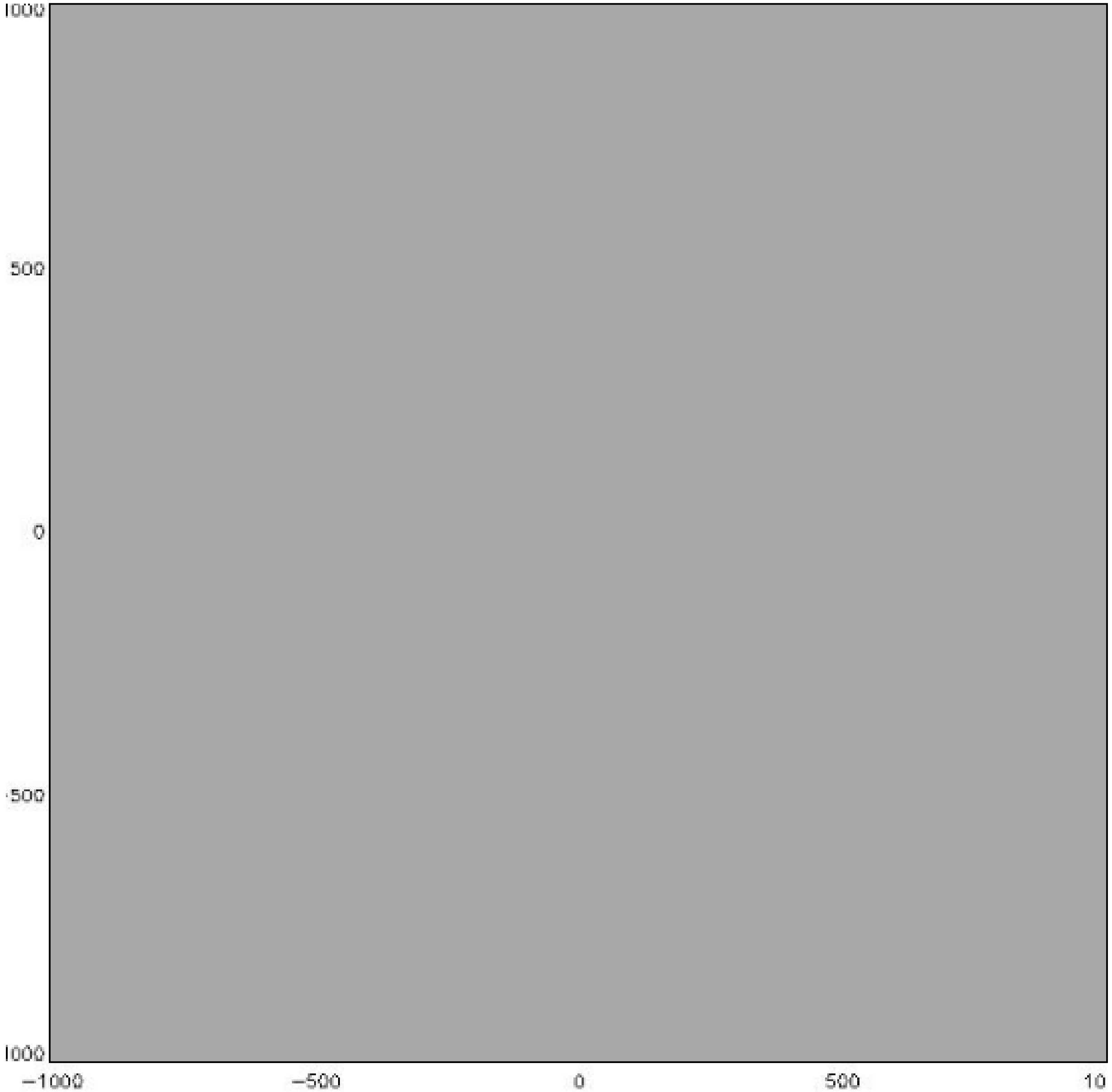


Solar atmosphere



Mats Carlsson (Oslo)

Solar atmosphere

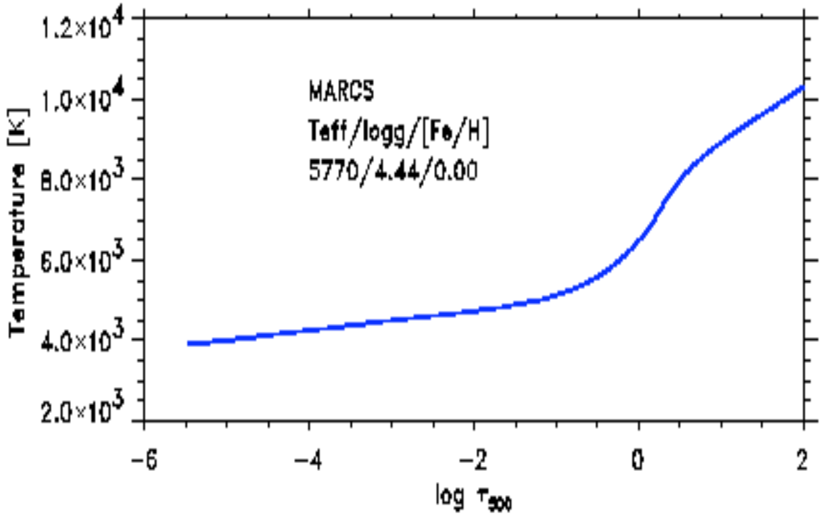


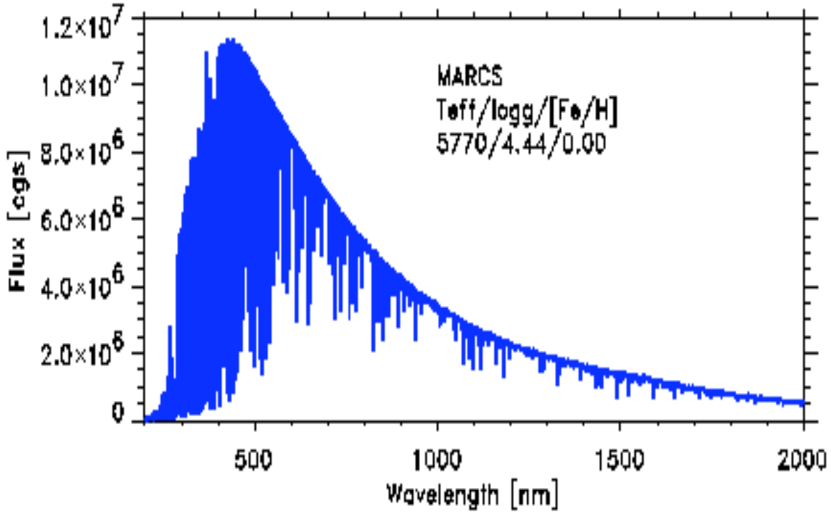
Mats Carlsson (Oslo)

1D stellar atmosphere models

Model atmospheres:

- Time-independent
- 1-dimensional
- Hydrostatic
- Mixing length theory
- LTE
- Detailed radiative transfer
- MARCS, Kurucz etc



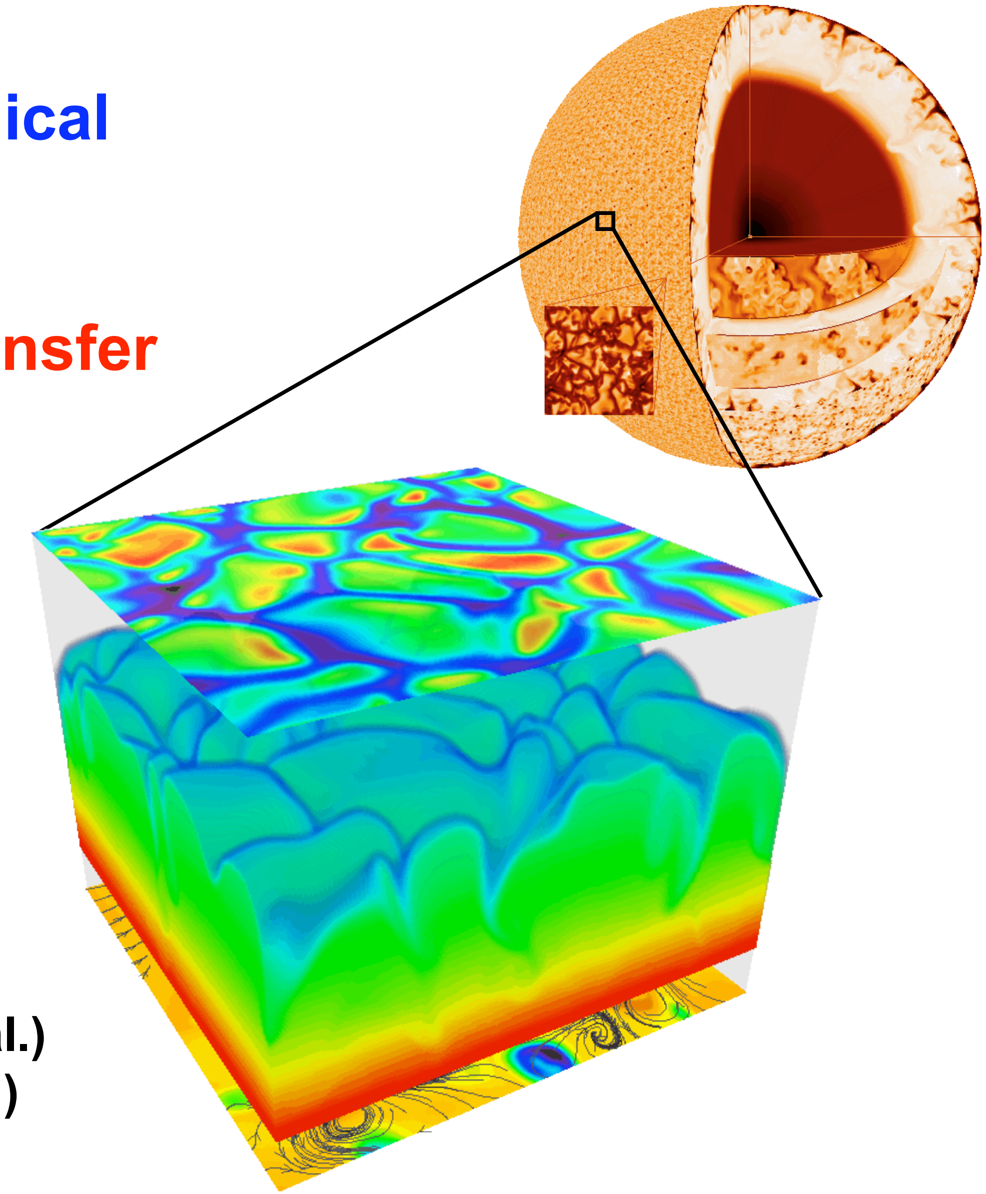


3D stellar atmosphere models

Ingredients:

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

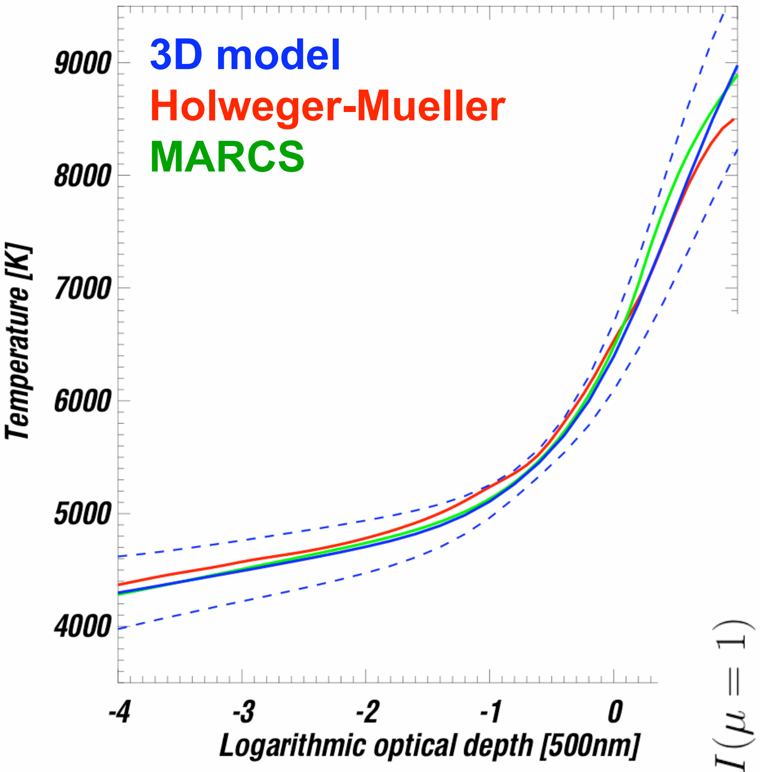
Essentially parameter free



For the aficionados:

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

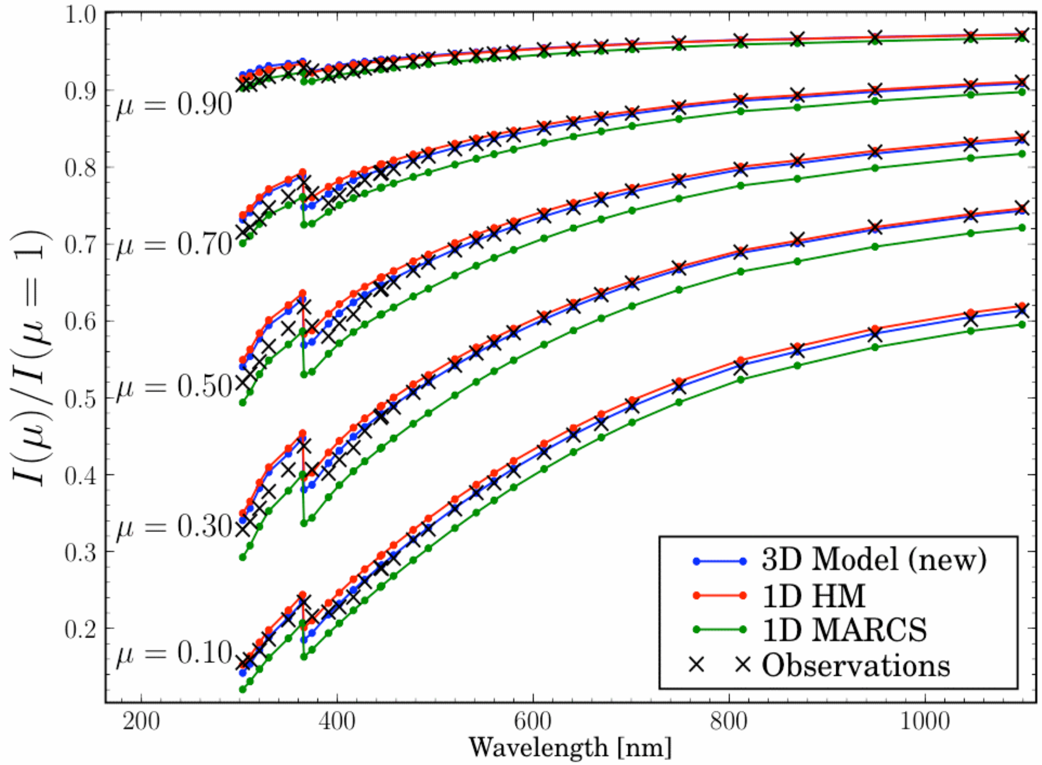
Temperature structure



Atmospheric temperature structure is critical

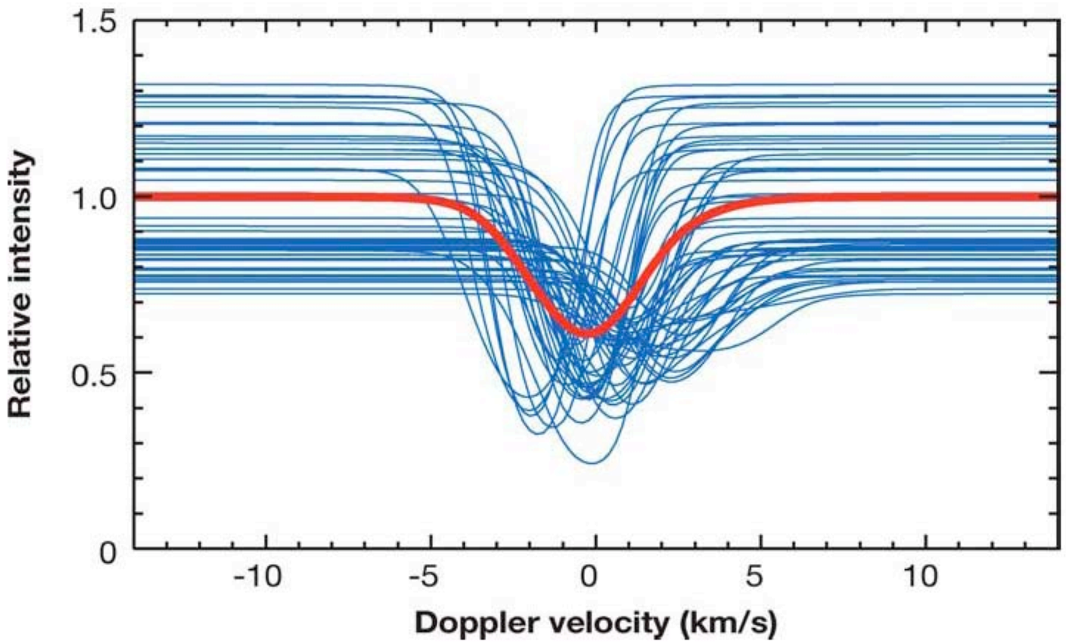
Our 3D model performs remarkably well

Pereira et al. 2009

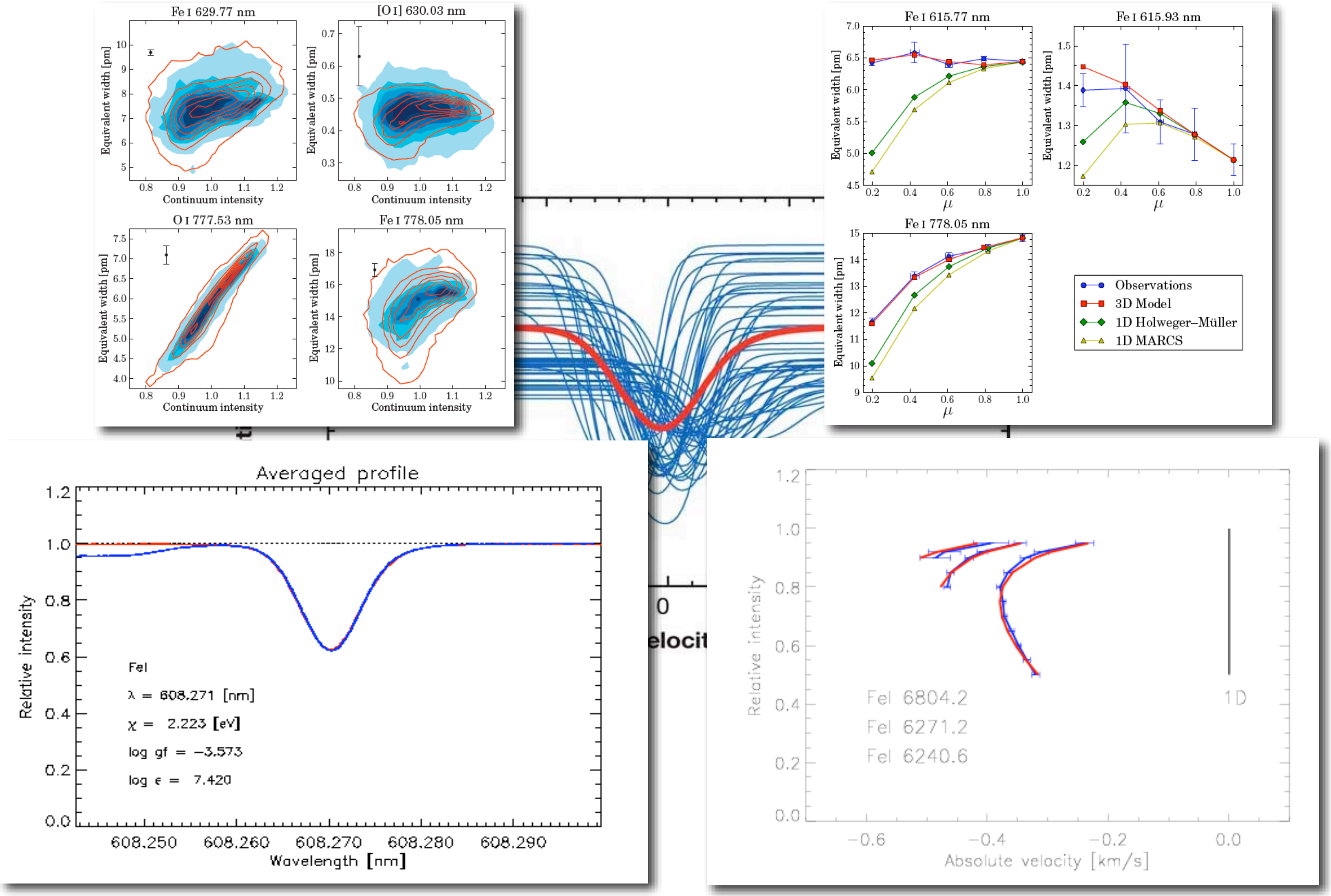


Similar good agreement with CO5BOLD 3D solar model (Caffau et al. 2008)

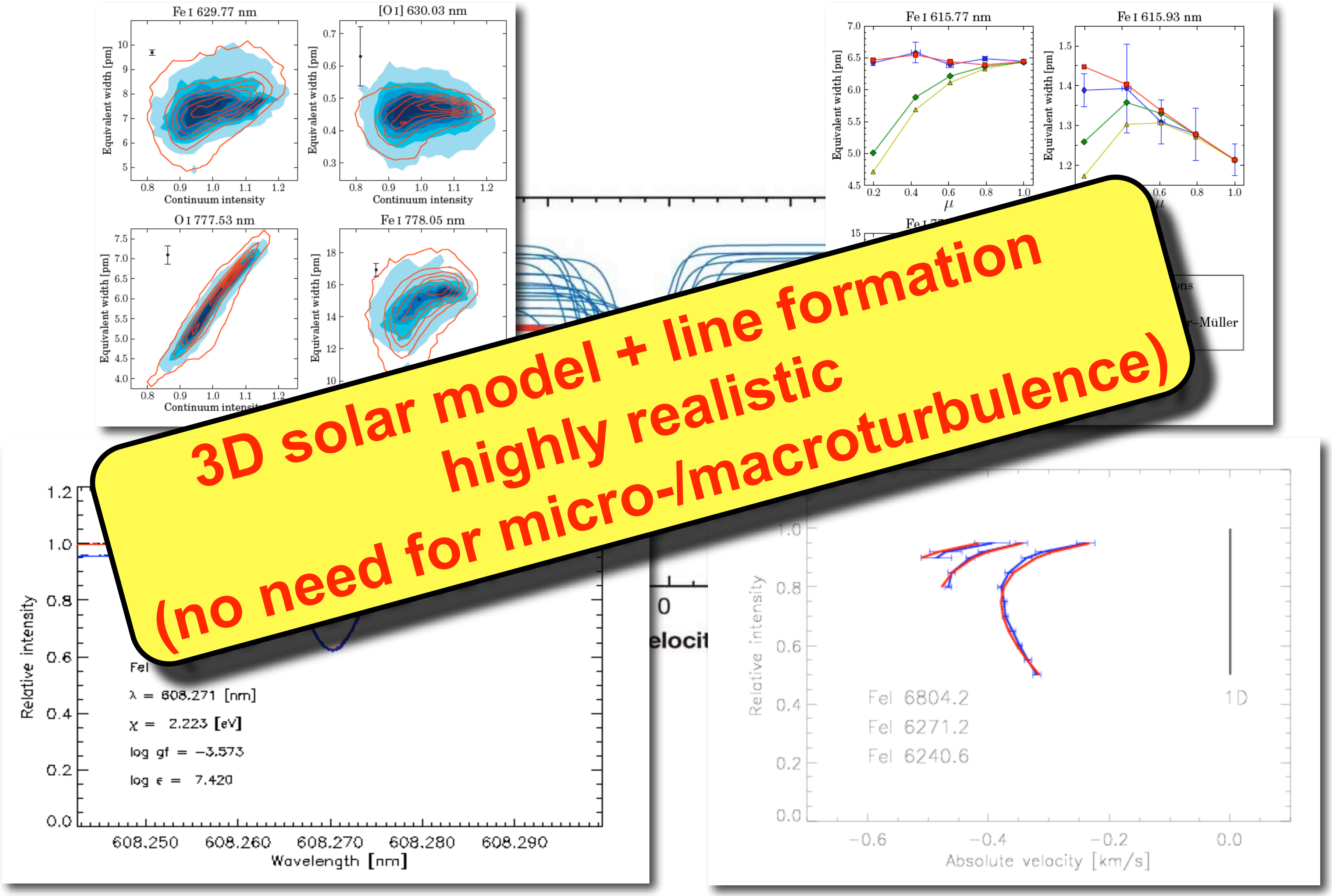
3D line formation



3D line formation



3D line formation



3D solar model + line formation highly realistic (no need for micro-/macroturbulence)

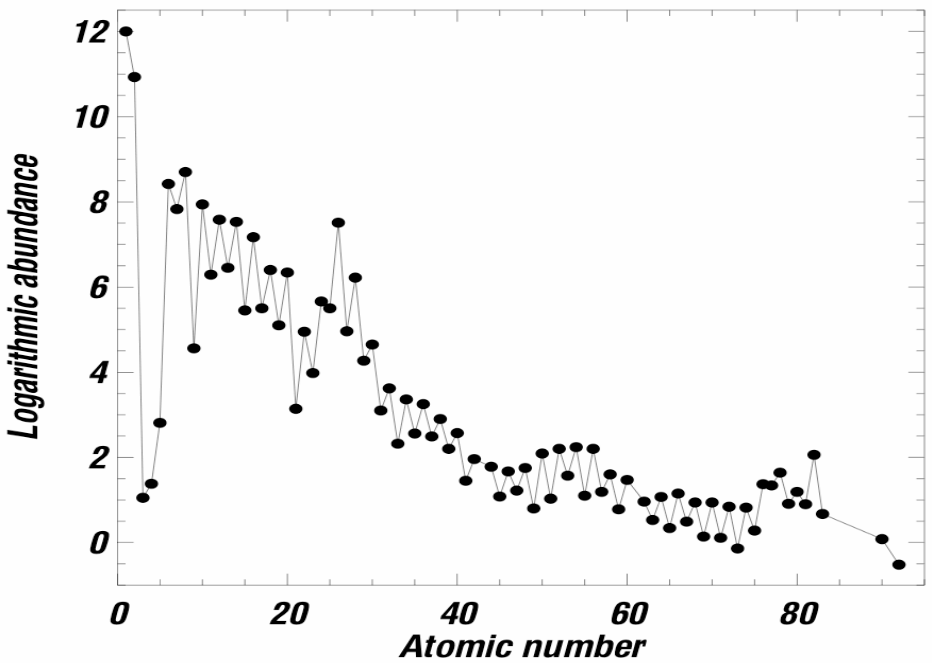
Complete solar inventory

Asplund et al. (2009, ARAA):

3D-based analysis of all elements

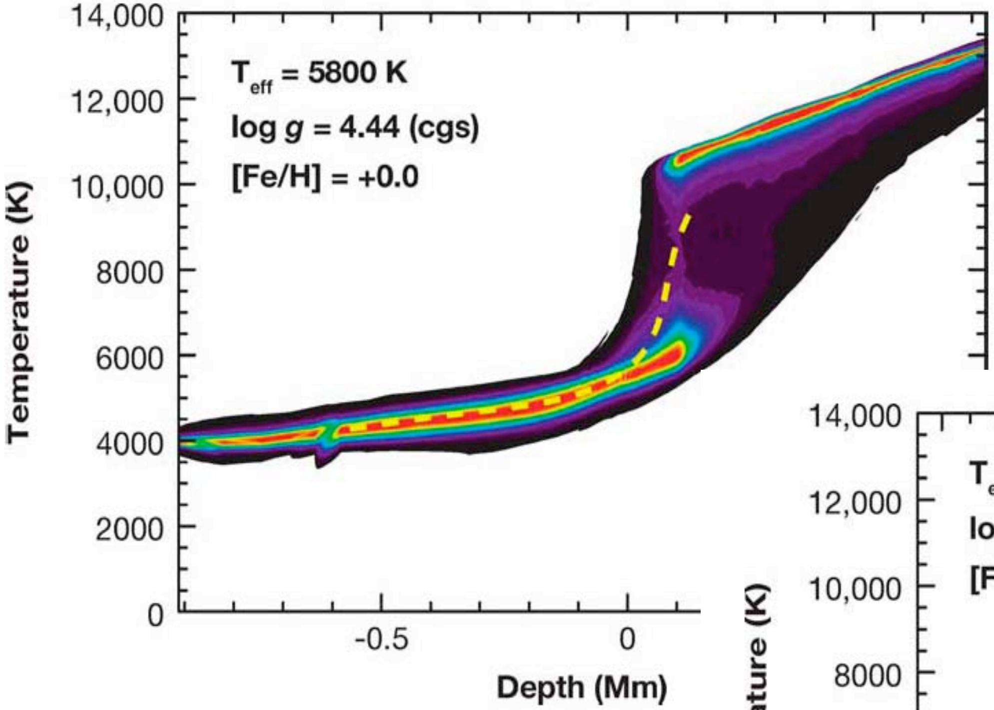
- **>2200 atomic + molecular lines**
- **3D non-LTE for some elements**

⇒ 3D stellar analysis doable!

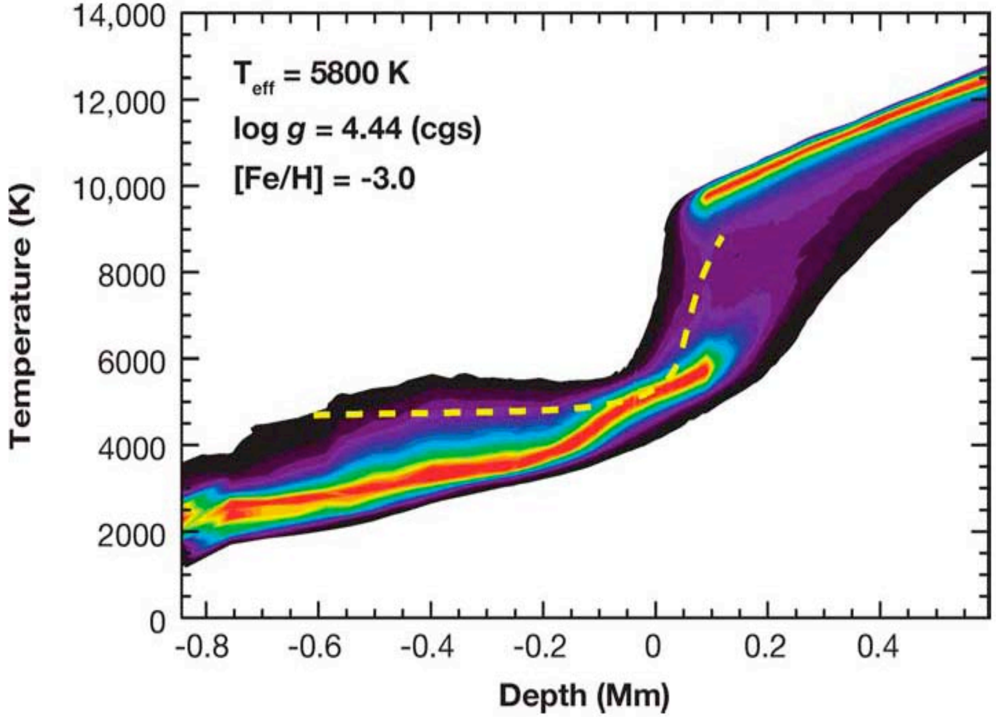


	Elem.	Photosphere	Meteorites		Elem.	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.09	1.76 ± 0.03
2	He	[10.93 ± 0.01]	1.29	45	Rh	0.91 ± 0.08	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.07	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.11	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 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]	-1.08	53	I		1.55 ± 0.08
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	[2.24 ± 0.06]	-1.93
12	Mg	7.60 ± 0.04	7.53 ± 0.01	55	Cs		1.08 ± 0.02
13	Al	6.45 ± 0.04	6.43 ± 0.01	56	Ba	2.18 ± 0.09	2.18 ± 0.03
14	Si	7.51 ± 0.04	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]	-0.46	62	Sm	0.96 ± 0.04	0.94 ± 0.02
19	K	5.03 ± 0.09	5.08 ± 0.02	63	Eu	0.51 ± 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	0.24 ± 0.08	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	0.93 ± 0.05	0.92 ± 0.02
25	Mn	5.43 ± 0.05	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	0.84 ± 0.04	0.71 ± 0.02
29	Cu	4.19 ± 0.05	4.25 ± 0.04	73	Ta		-0.12 ± 0.04
30	Zn	4.56 ± 0.04	4.63 ± 0.04	74	W	0.87 ± 0.11	0.65 ± 0.04
31	Ga	3.04 ± 0.10	3.08 ± 0.02	75	Re		0.26 ± 0.04
32	Ge	3.65 ± 0.09	3.58 ± 0.04	76	Os	1.29 ± 0.06	1.35 ± 0.03
33	As		2.30 ± 0.04	77	Ir	1.35 ± 0.10	1.32 ± 0.02
34	Se		3.34 ± 0.03	78	Pt		1.62 ± 0.03
35	Br		2.54 ± 0.06	79	Au	0.93 ± 0.11	0.80 ± 0.04
36	Kr	[3.25 ± 0.06]	-2.23	80	Hg		1.17 ± 0.08
37	Rb	2.52 ± 0.08	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	1.76 ± 0.08	2.04 ± 0.03
39	Y	2.21 ± 0.05	2.17 ± 0.04	83	Bi		0.65 ± 0.04
40	Zr	2.58 ± 0.05	2.53 ± 0.04	90	Th	0.02 ± 0.09	0.06 ± 0.03
41	Nb	1.46 ± 0.04	1.41 ± 0.04	92	U		-0.50 ± 0.03
42	Mo	1.88 ± 0.08	1.94 ± 0.04				

3D models of metal-poor dwarfs

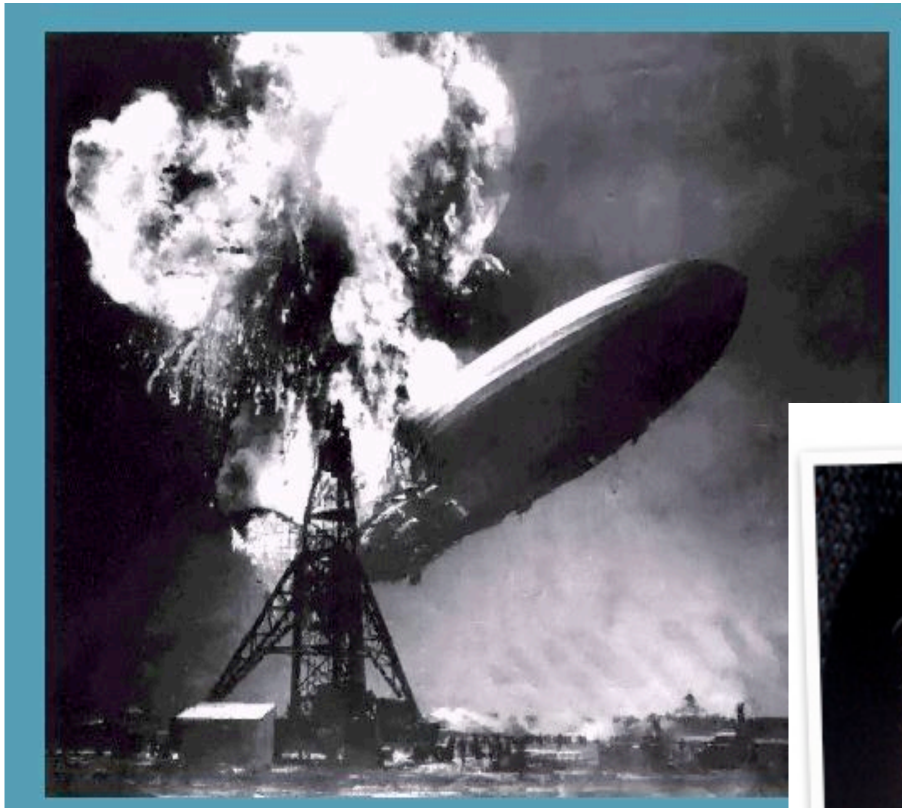


Asplund et al. 1999:
Very different atmospheric temperature structure in 3D than in 1D models at low [Fe/H]

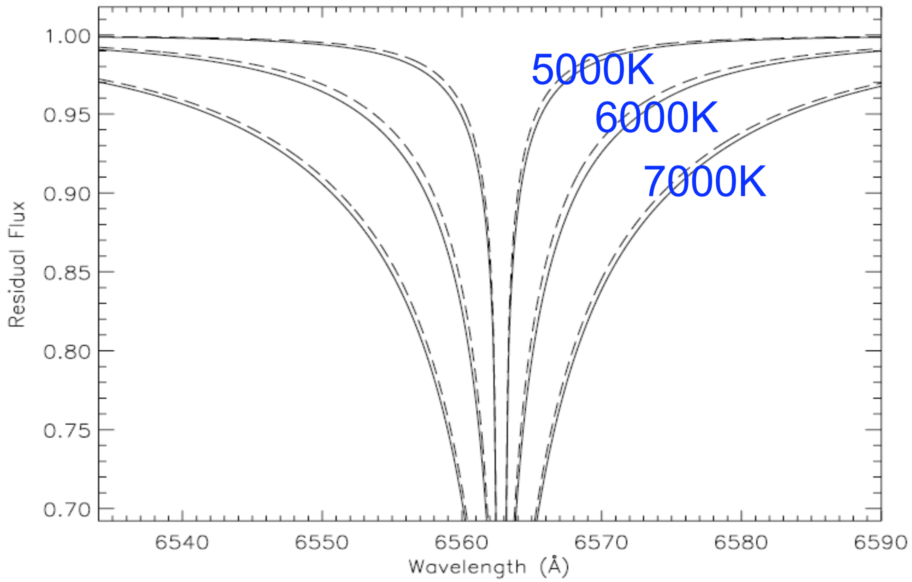


Confirmed by 3D models from CO^5BOLD group (Ludwig et al.)

Hydrogen



Hydrogen lines and T_{eff}



H lines as thermometer

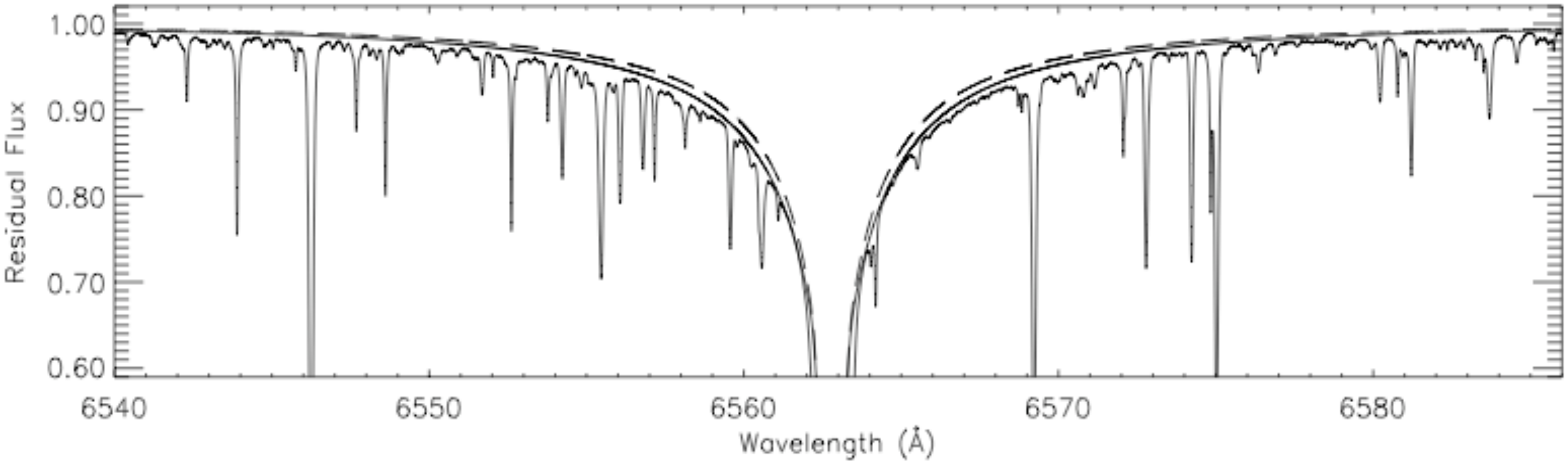
+ precise

+ pressure broadening

- non-LTE

- convection

Barklem et al. 2000: Importance of self-broadening

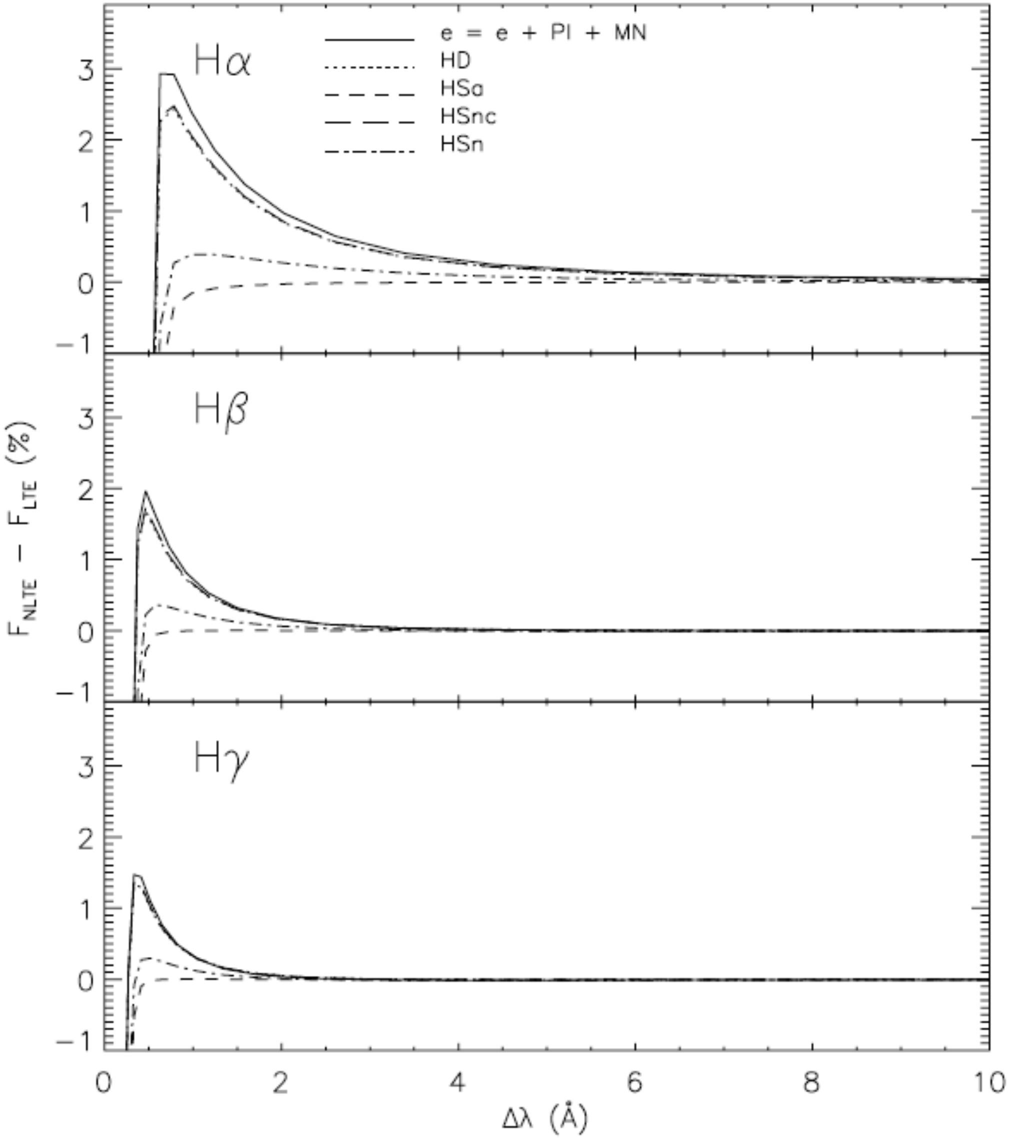


Hydrogen non-LTE

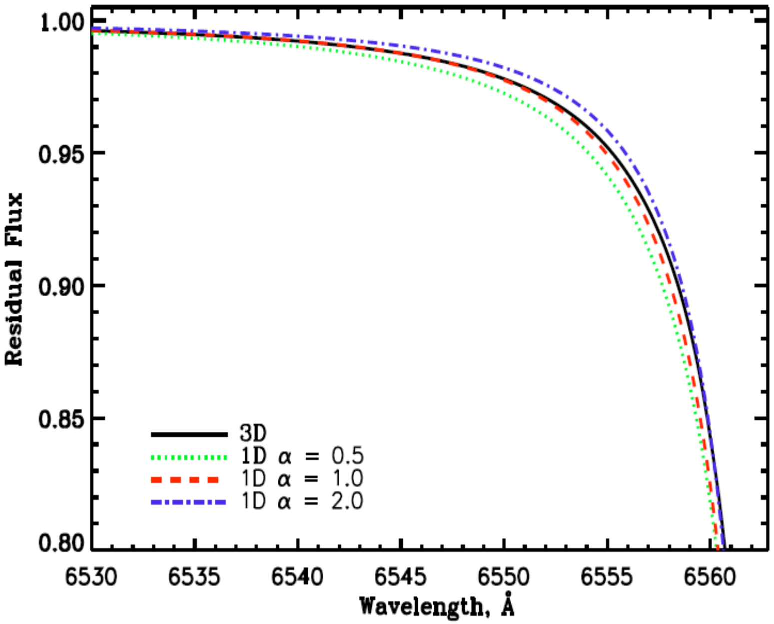
LTE normally assumed valid but is it true?

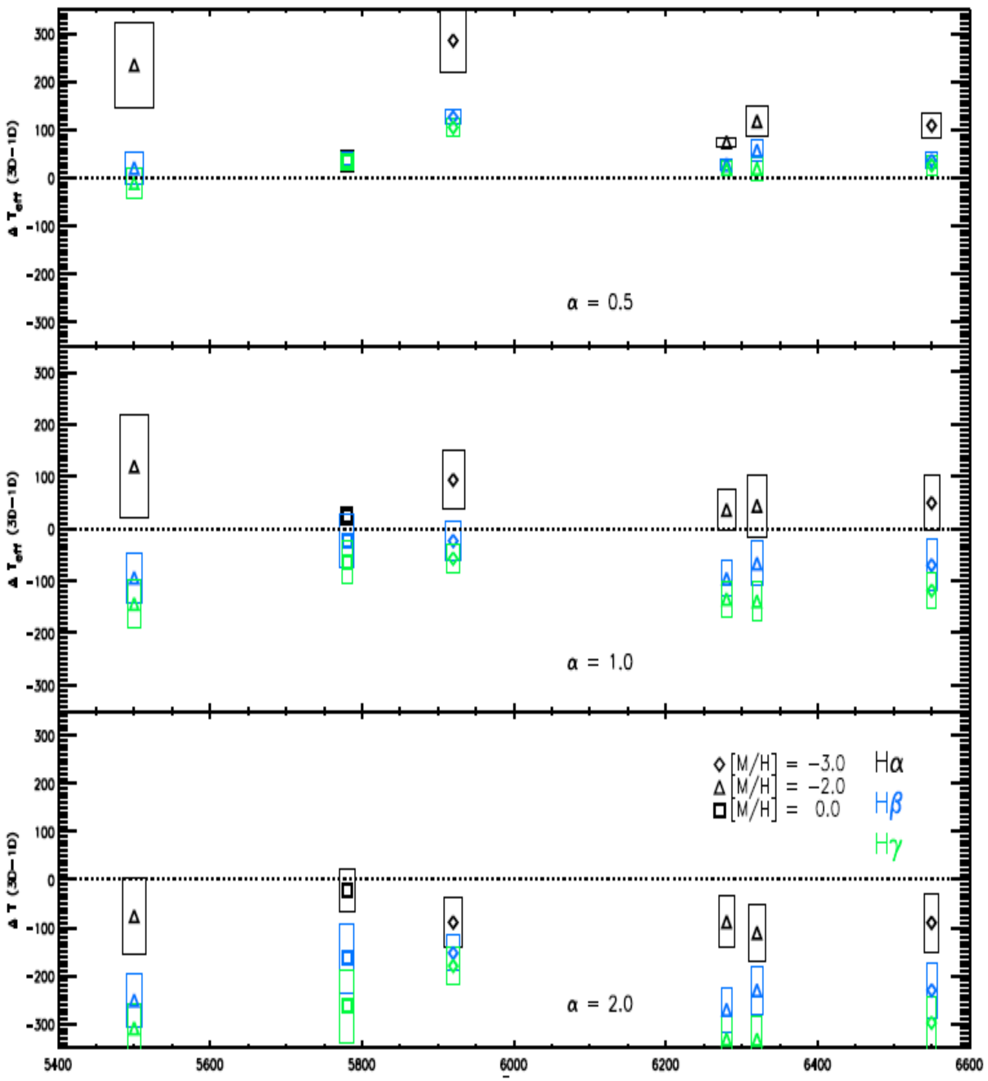
Barklem 2007:
Departures from LTE in 1D makes H line wings weaker
⇒ Lower T_{eff} by ~100K?

Unclear whether LTE or non-LTE due to uncertain inelastic H+H collisions



Convection sensitivity





Ludwig et al. 2009:

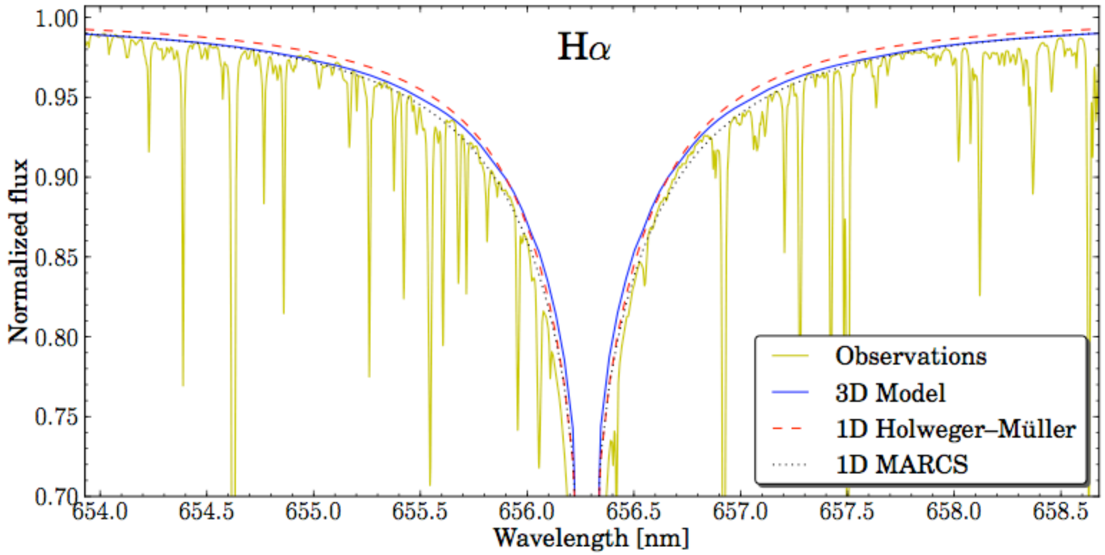
"3D correction" of T_{eff} depends on MLT flavour of 1D model

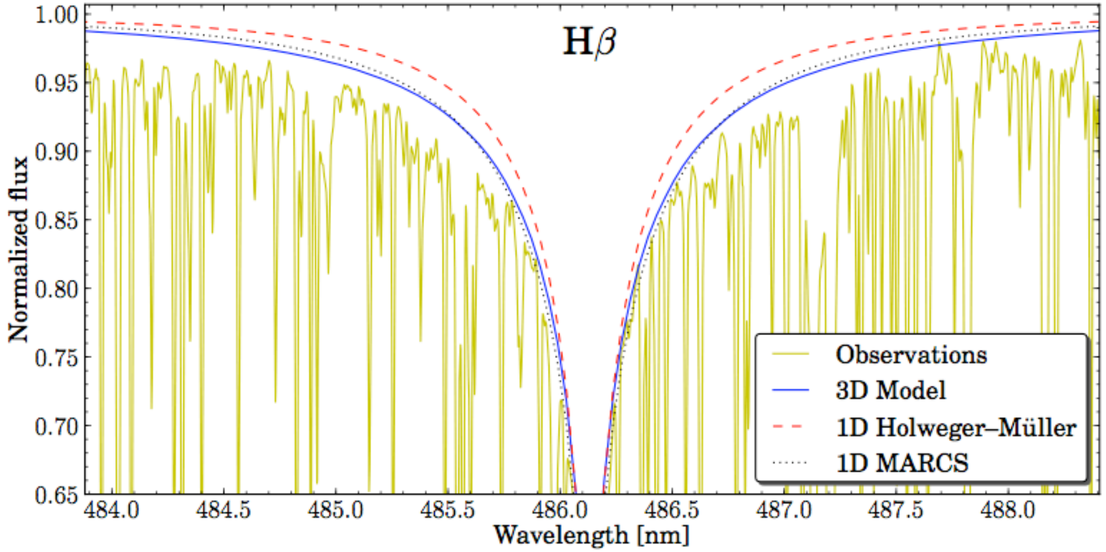
ΔTeff as large as ±300K!

3D non-LTE for solar H lines

Pereira et al. 2009:
Full 3D non-LTE line formation of H lines
⇒ Good agreement with observed profiles

Caution: collisional data uncertain

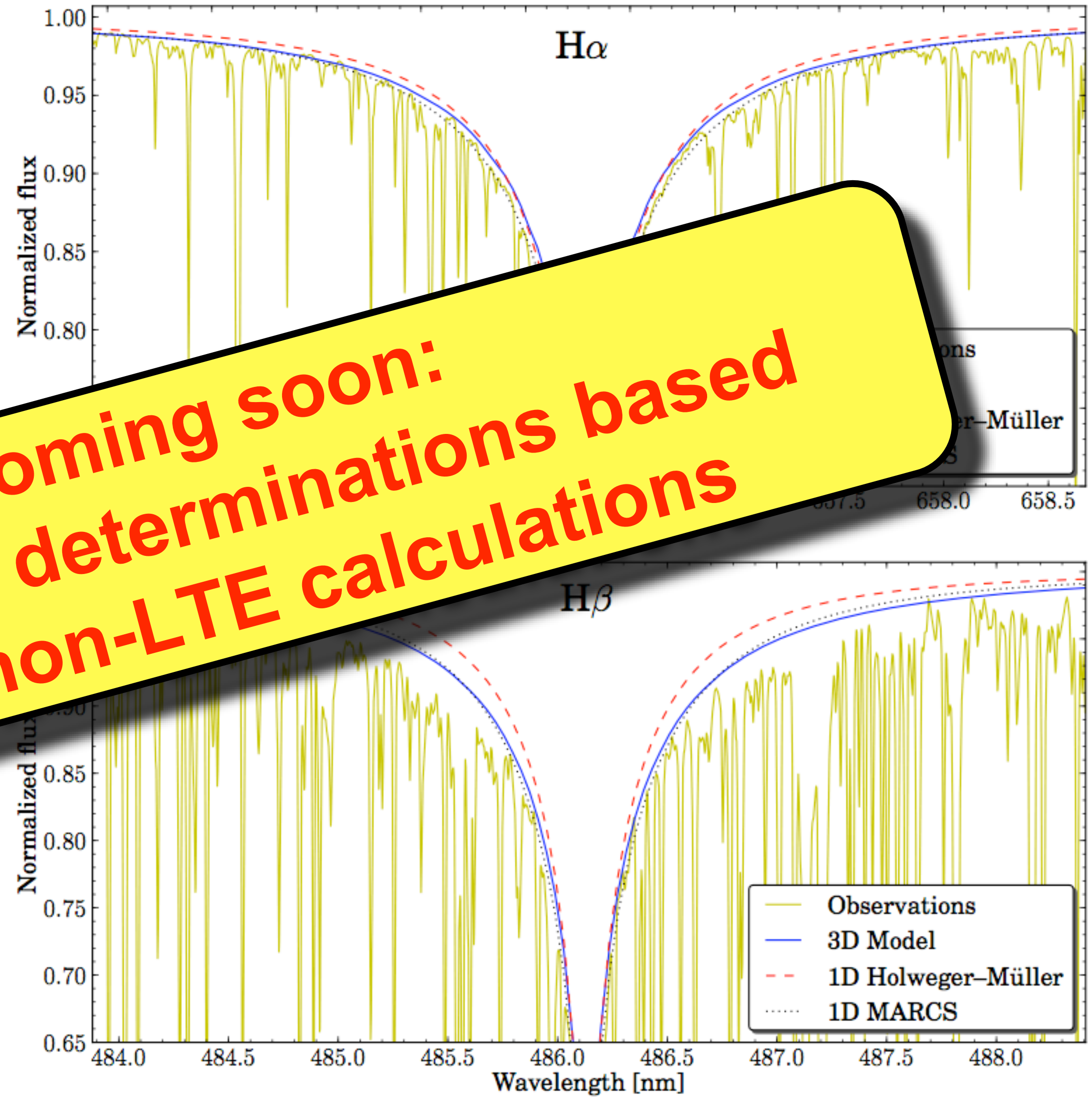




3D non-LTE for solar H lines

Pereira et al. 2009:
Full 3D non-LTE line formation of H lines
⇒ Good agreement with observed pr[...]

Caut[...]
data



Helium

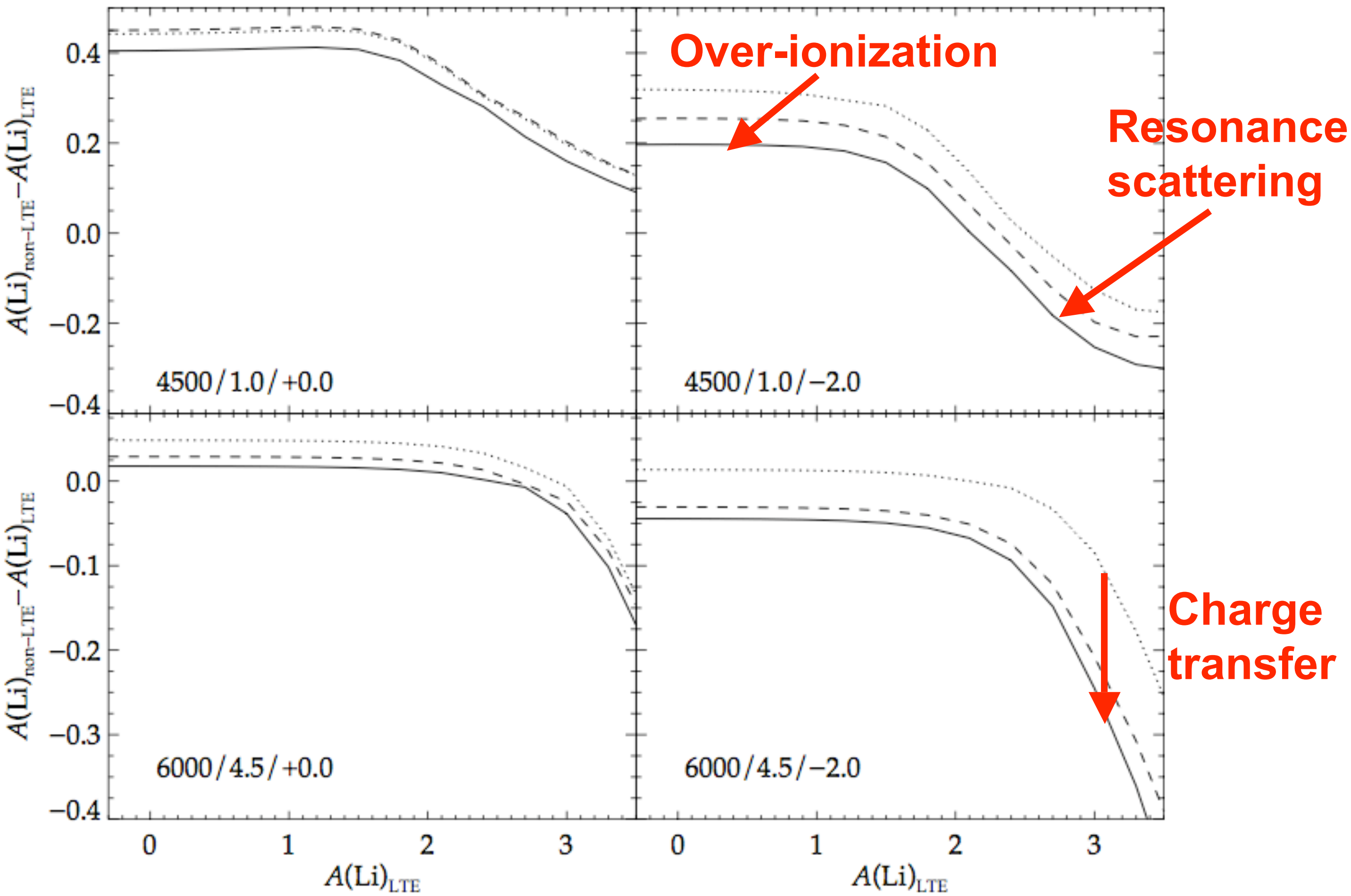
Lithium


リチウムバッテリー
LITHIUM BATTERY
CR2032
3V
HL


SOLVAY
4492
Copyright © 2003 Theodore W. Gray

1D non-LTE line formation

Lind et al. 2009:
Non-LTE abundance corrections for wide range of stellar parameters with collisional data from Barklem et al. (2003)



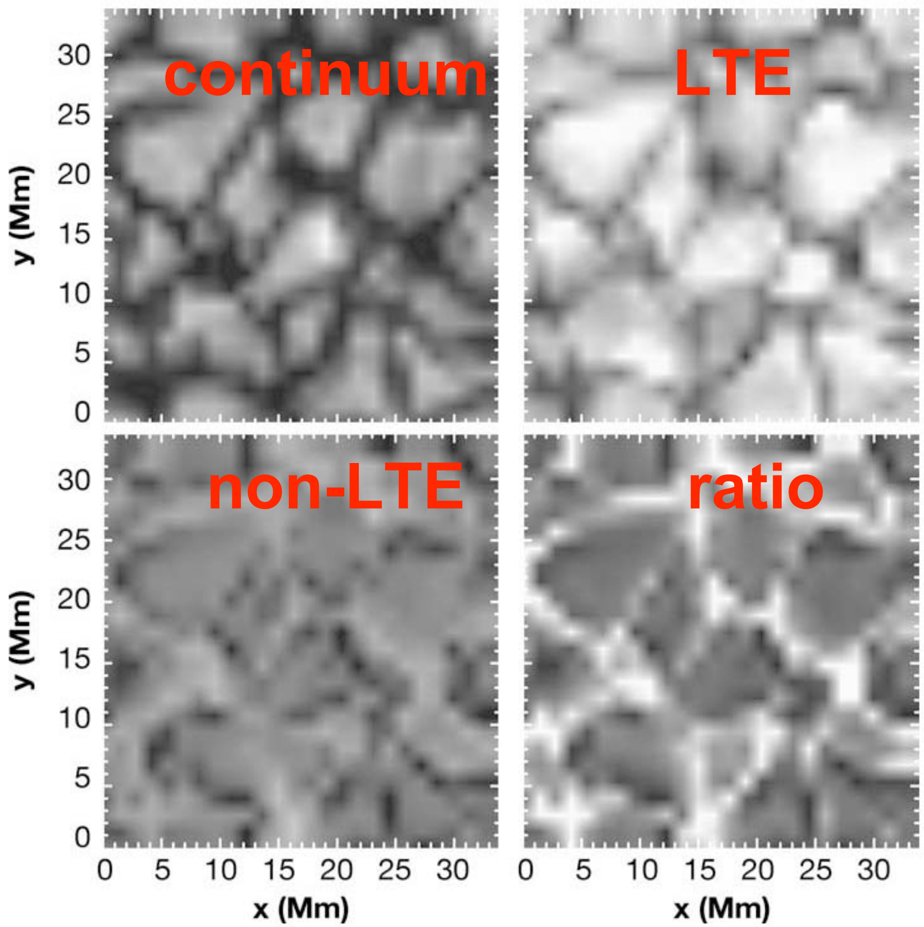
3D non-LTE line formation

Asplund et al. (1999):
Low atmospheric T(τ) at low [Fe/H] makes Li line very strong in LTE

Asplund et al. (2003):
3D non-LTE for Li reveals over-ionization

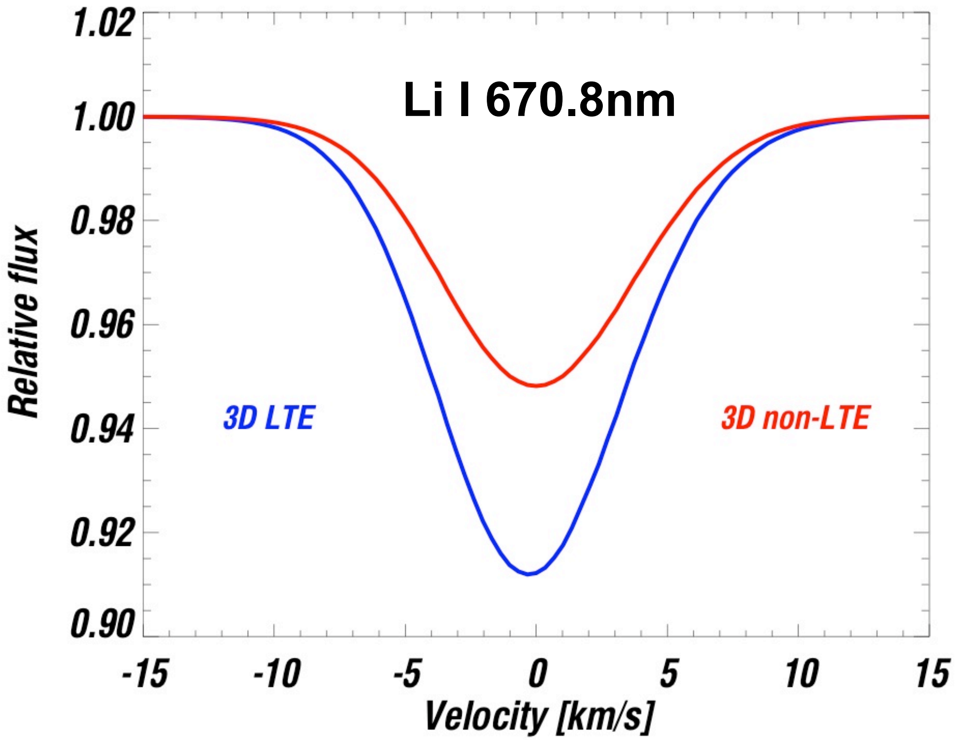
↓

Li line much weaker in 3D non-LTE than 3D LTE



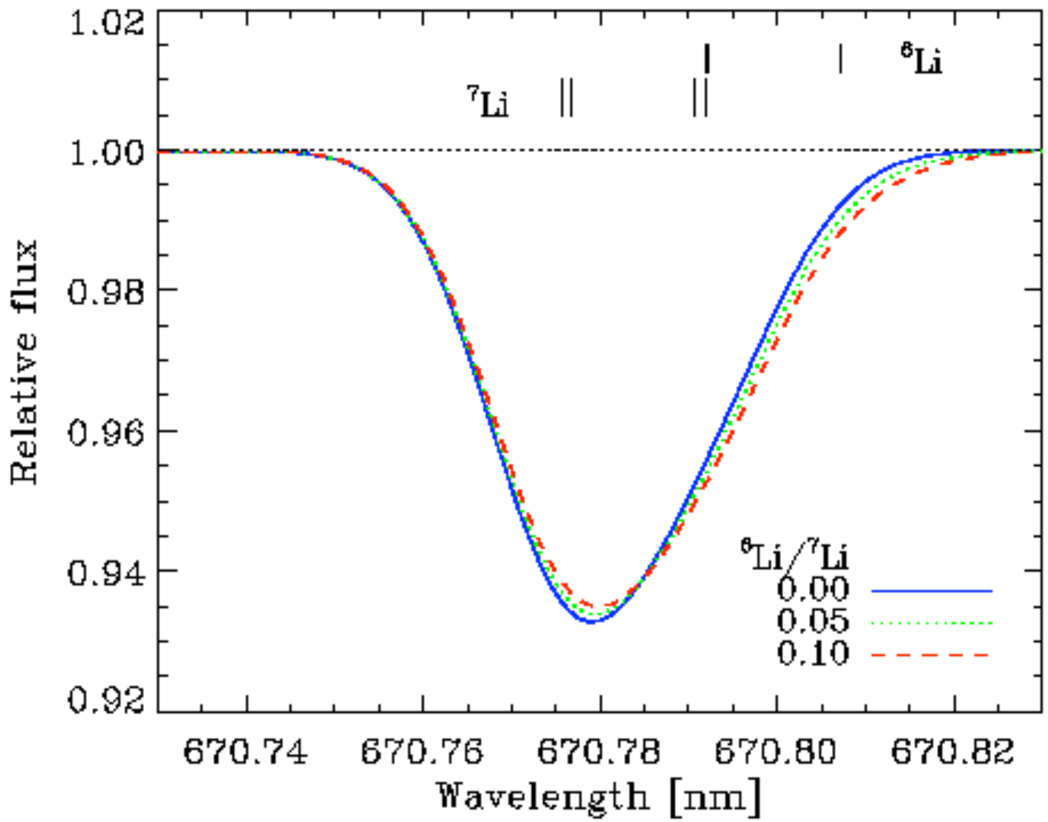
Li abundances

Asplund et al. (2003), Barklem et al (2003):
Li abundance in 3D non-LTE the same as 1D non-LTE to within ±0.1 dex
Sbordone et al. (2009, submitted + poster):
3D non-LTE calculations for grid of metal-poor dwarfs



Li isotopes

Isotopic shift in Li I 670.8nm resonance line



Exceptionally high-quality spectra needed

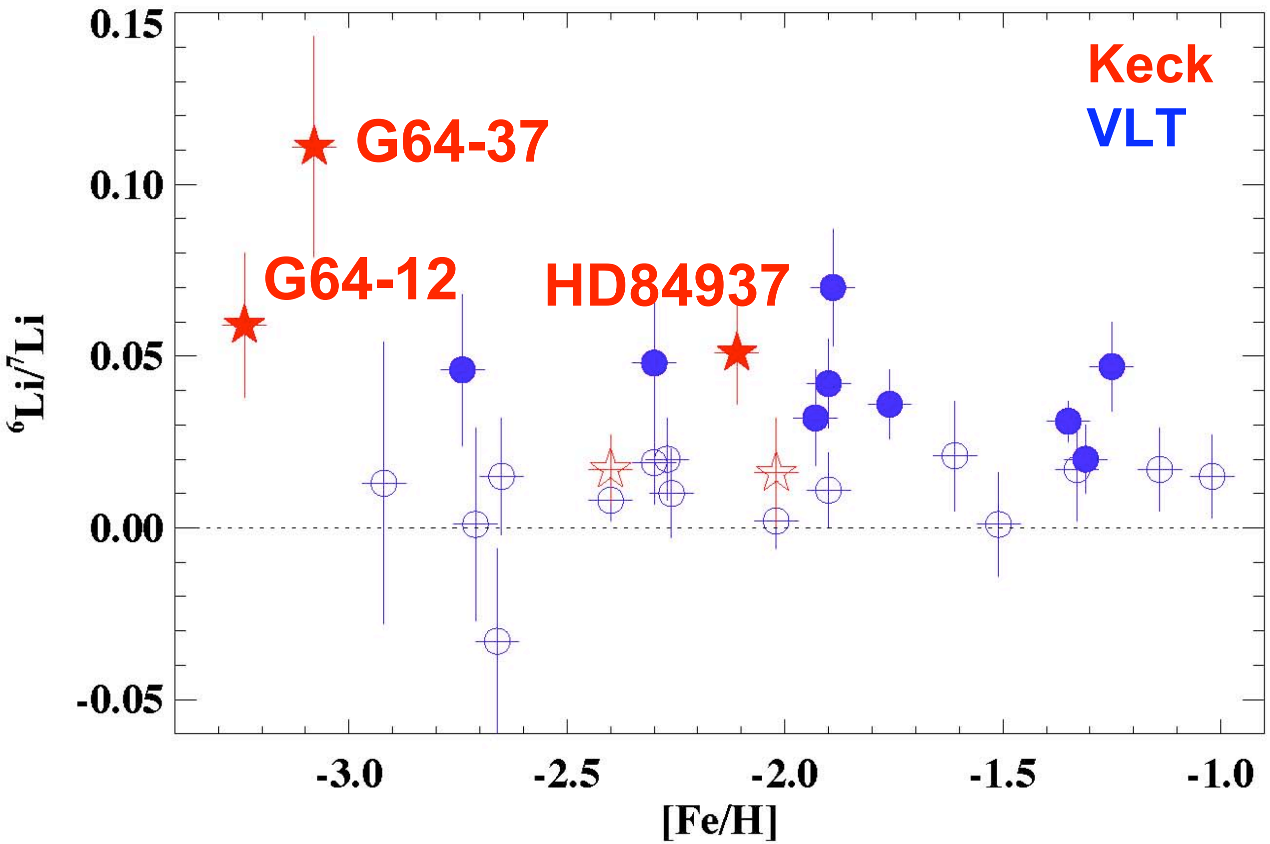
^{6}Li detections

Asplund et al. (2006, 2009):

Twelve >2σ detections but many ~1σ results

⇒ **Most stars have ^{6}Li/^{7}Li ≥ 0.01?**

Or systematic errors?

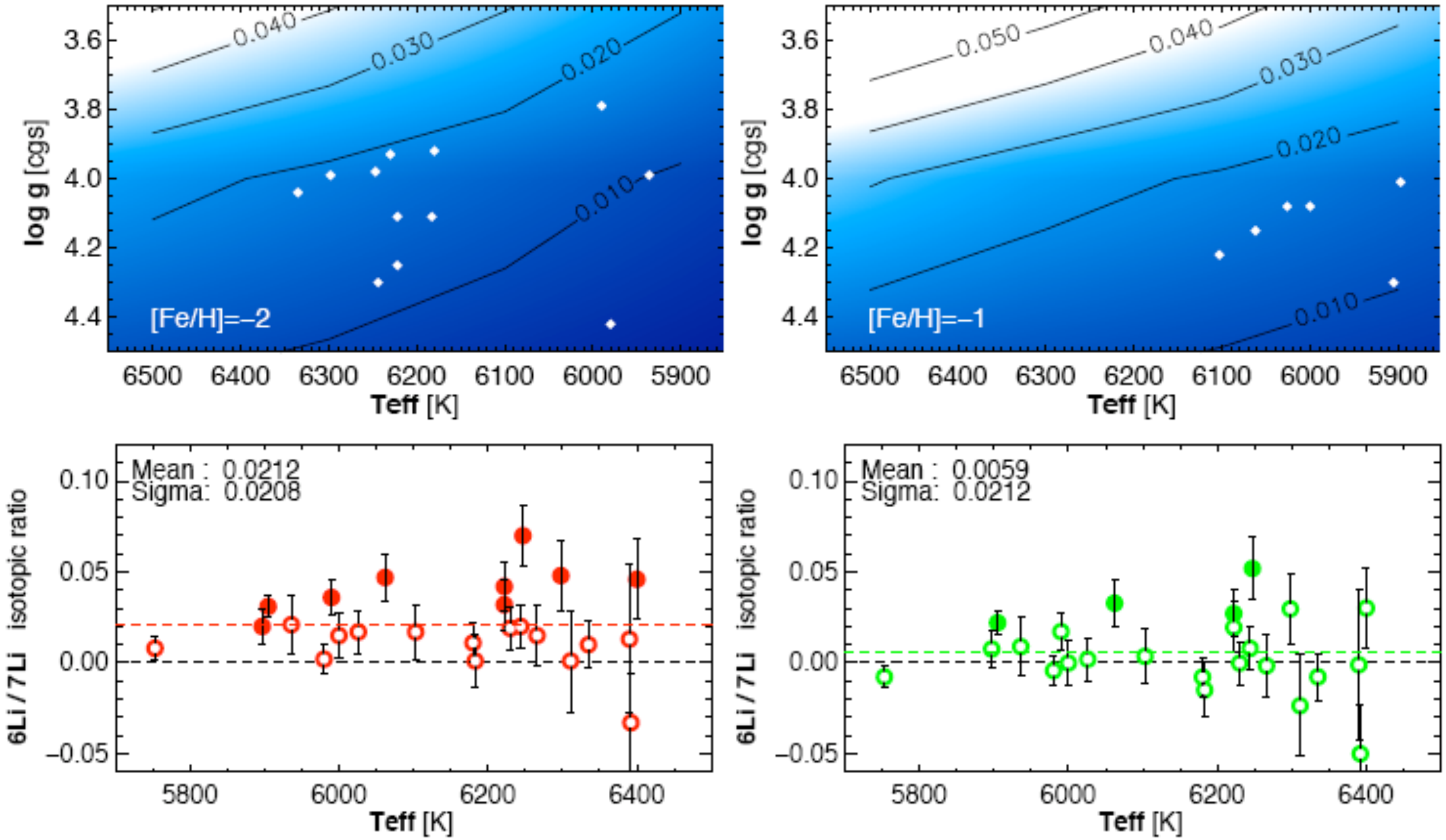


^{6}Li detections spurious?

Cayrel et al. (2007), see also Steffen's talk!

Convective line asymmetries can mimic ^{6}Li

Steffen et al. (2009)



Similarities and differences

Asplund et al.

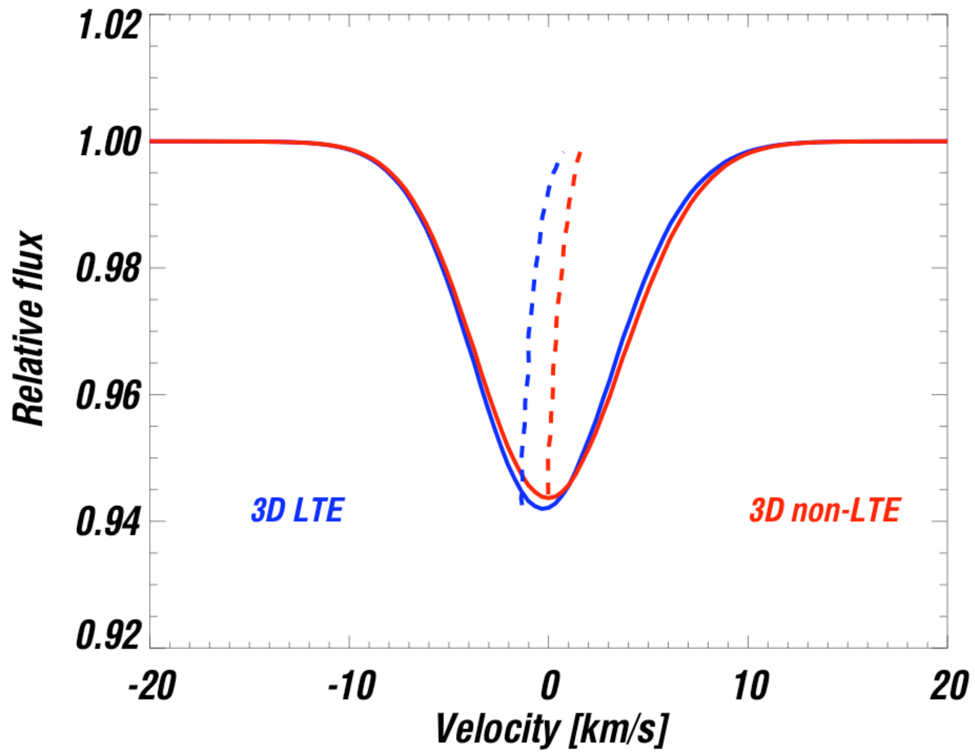
- 3D non-LTE for Li
- Broadening from Fe, Ca etc
- Free: ^{7}Li, ^{6}Li, λ

Steffen, Cayrel et al.

- 3D non-LTE for Li
- Only use Li I 670.8nm
- Free: ^{7}Li, ^{6}Li, λ, FWHM

Similar ^{6}Li/^{7}Li results in 1D, 3D LTE and 3D non-LTE for Li

⇒ 3D non-LTE also for Na, Ca, Fe etc lines!



Similarities and differences

Asplund et al.
- 3D non-LTE for Li
- Broadening from Fe, Ca etc
- Free: ^{7}Li, ^{6}Li, λ

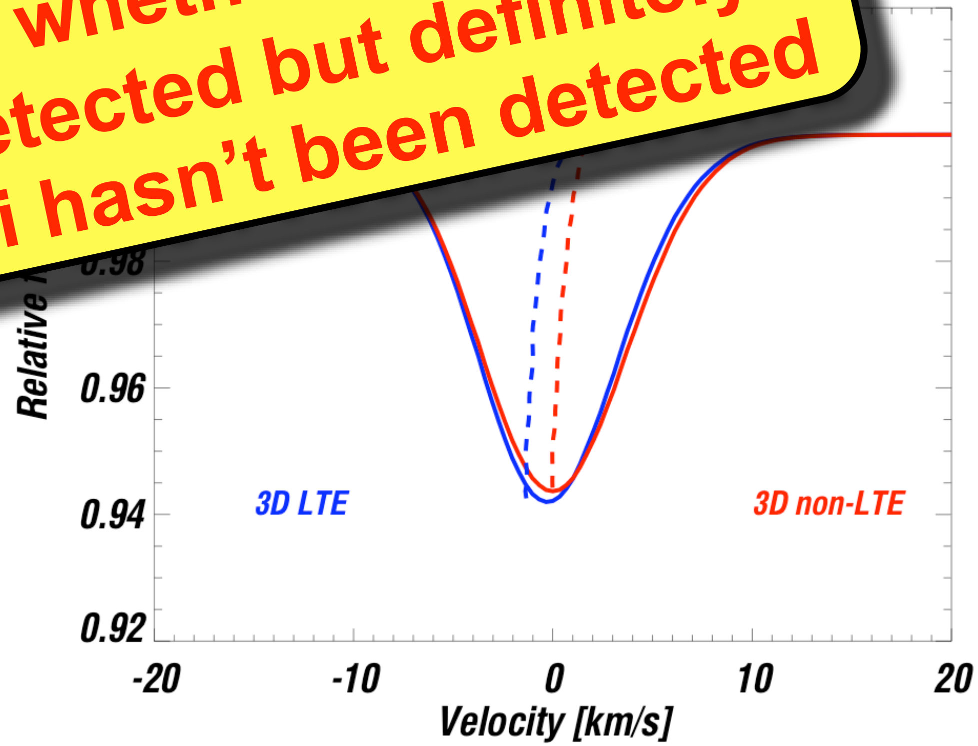
Steffen, Cayrel et al.
- 3D non-LTE for Li
- Only use Li I 670.8nm
- Free: ^{7}Li, ^{6}Li, λ, FWHM

To early to say whether ^{6}Li has definitely been detected but definitely too early to say ^{6}Li hasn't been detected

Simil

L

⇒ non-LTE also for Na, Ca, Fe etc lines!



Beryllium


PING
EYE2
KARSTEN PHOENIX AZ. 85068 U.S.A.
Copyright © 2008 Theodore W. Gray

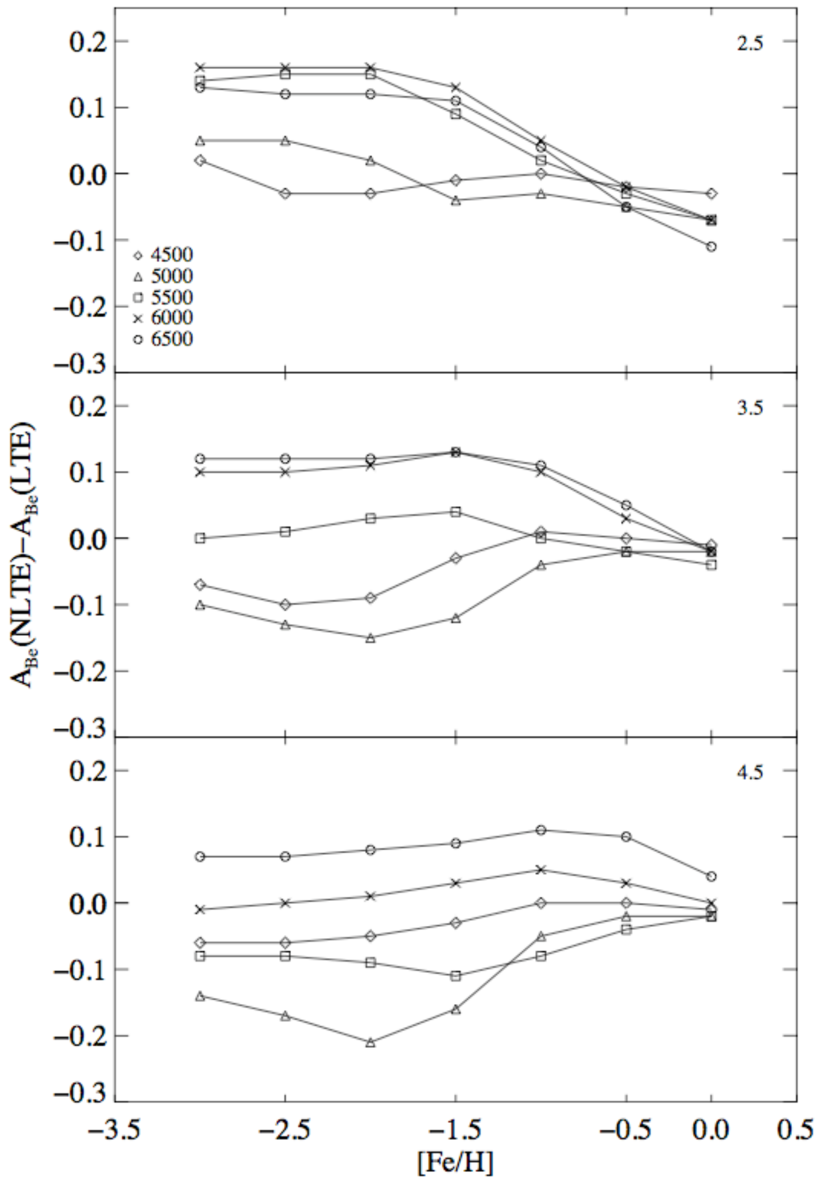

Be
4
9.012
Beryllium

Be non-LTE line formation

Be II 313nm lines relatively insensitive to non-LTE and 3D effects

Garcia Perez et al. 2009:
1D non-LTE calculations for Be II for wide range of stellar parameters

ΔlogBe ≤ ±0.2 dex
(over-ionization and over-excitation)



Boron

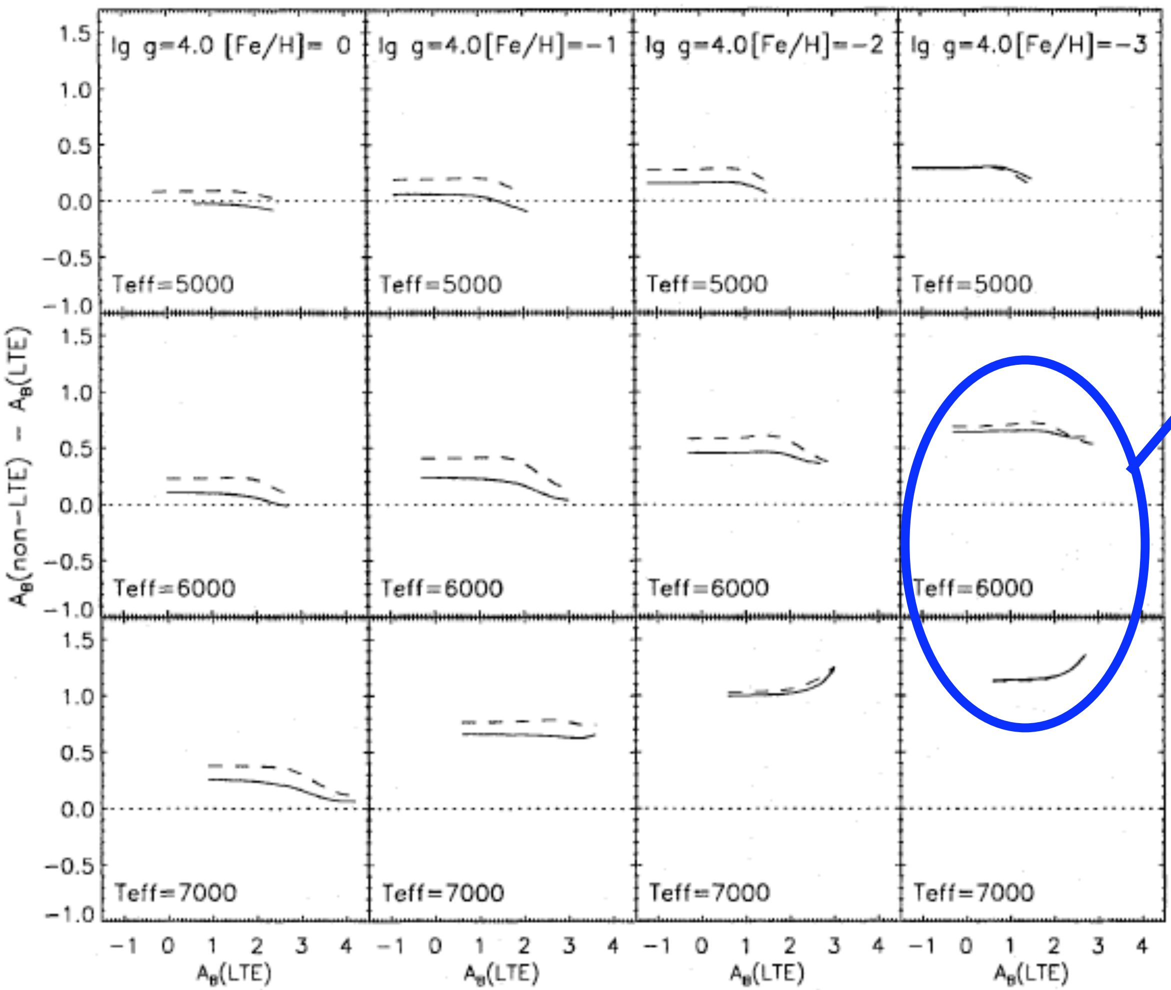

Copyright © 2002 RGB Ltd www.element-collection.com


now
Boron
STRUCTURAL SUPPORT
3 mg
• Supports Bone Strength
• Works with Calcium and Magnesium*
100 Capsules
A Dietary Supplement

B non-LTE line formation

Kiselman & Carlsson 1996:

Very large 1D non-LTE effects on B I 209+250nm lines



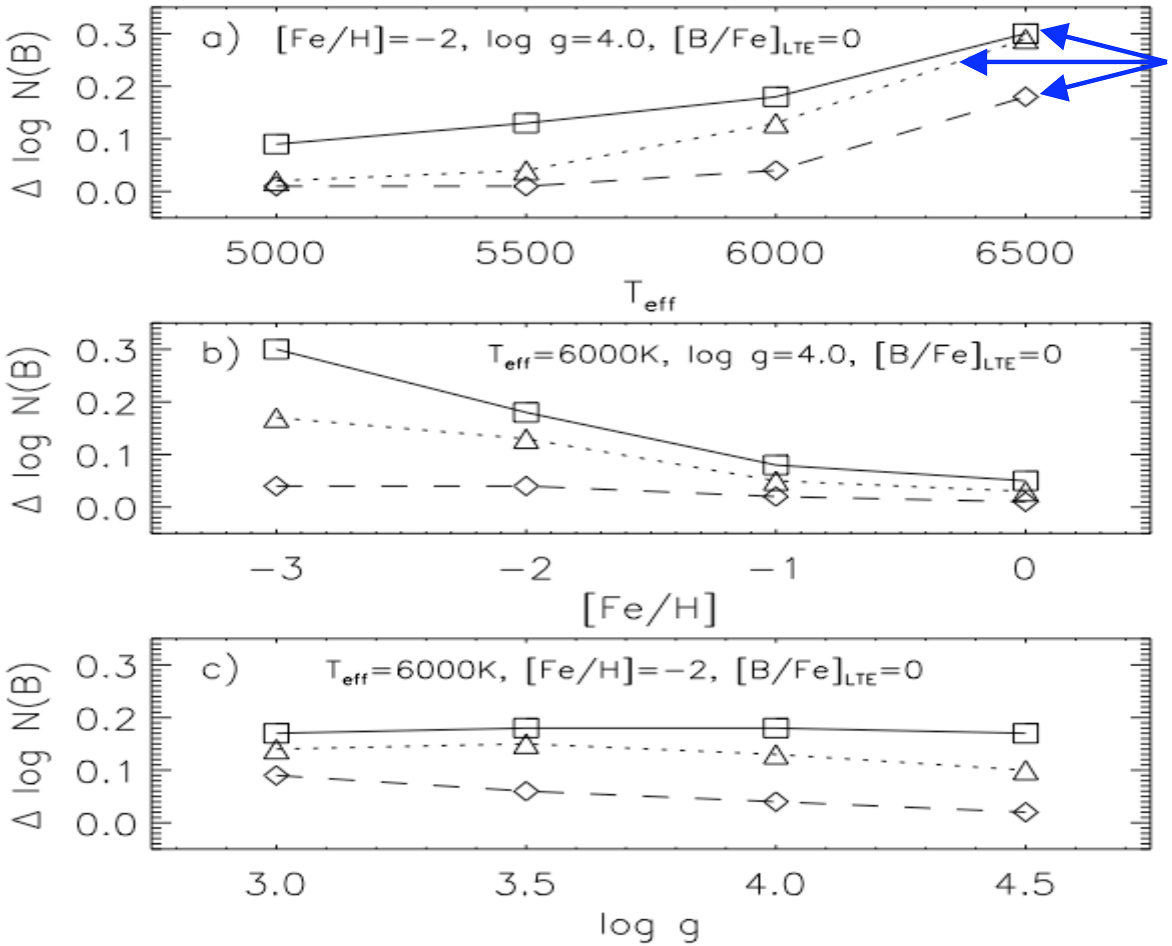
Δlog>0.5 dex for metal-poor turn-off stars!

Over-ionization + photon pumping feeding on *Jν*/*Bν*>1 radiation in UV

B non-LTE revisited

Tan et al. 2009:

New 1D non-LTE calculations with more complete UV line-blocking and H collisions



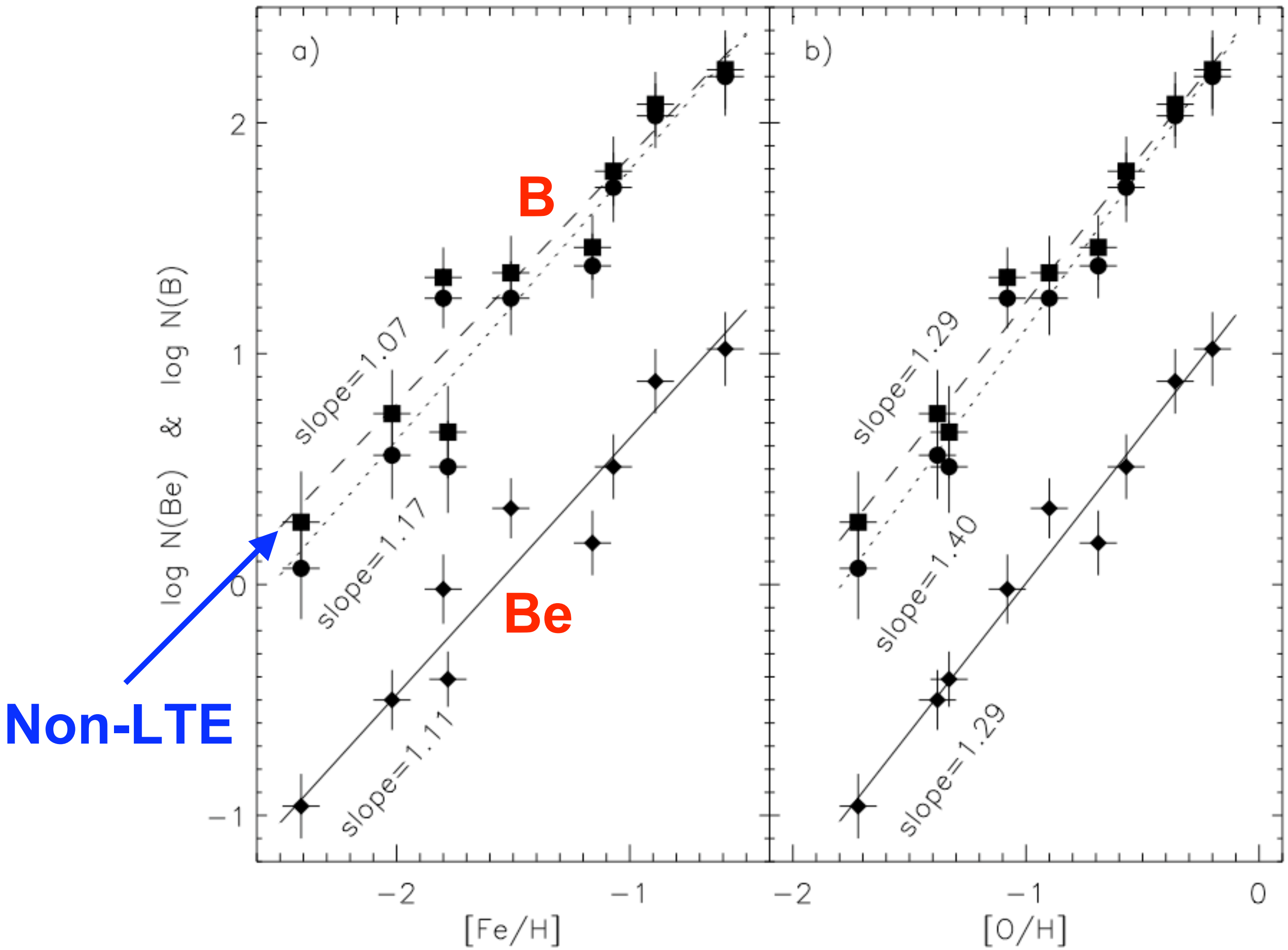
Different S_H scaling factors to H collisions

ΔlogB ≤ 0.3 dex

Caution: 3D will likely aggravate non-LTE effects

Be and B vs metallicity

Tan et al. 2009



Summary

3D and non-LTE are nothing magical or "horrendously complicated" [Lambert]

- Non-LTE and 3D effects more important for T_{eff} ⇑, log g ⇓ and [Fe/H] ⇓
- T_{eff} from H lines sensitive to 3D and non-LTE(?)
- Li abundance: 1D non-LTE ≈ 3D non-LTE
- ^{6}Li/^{7}Li difficult! Use information from other lines
- Non-LTE effects for B smaller than thought