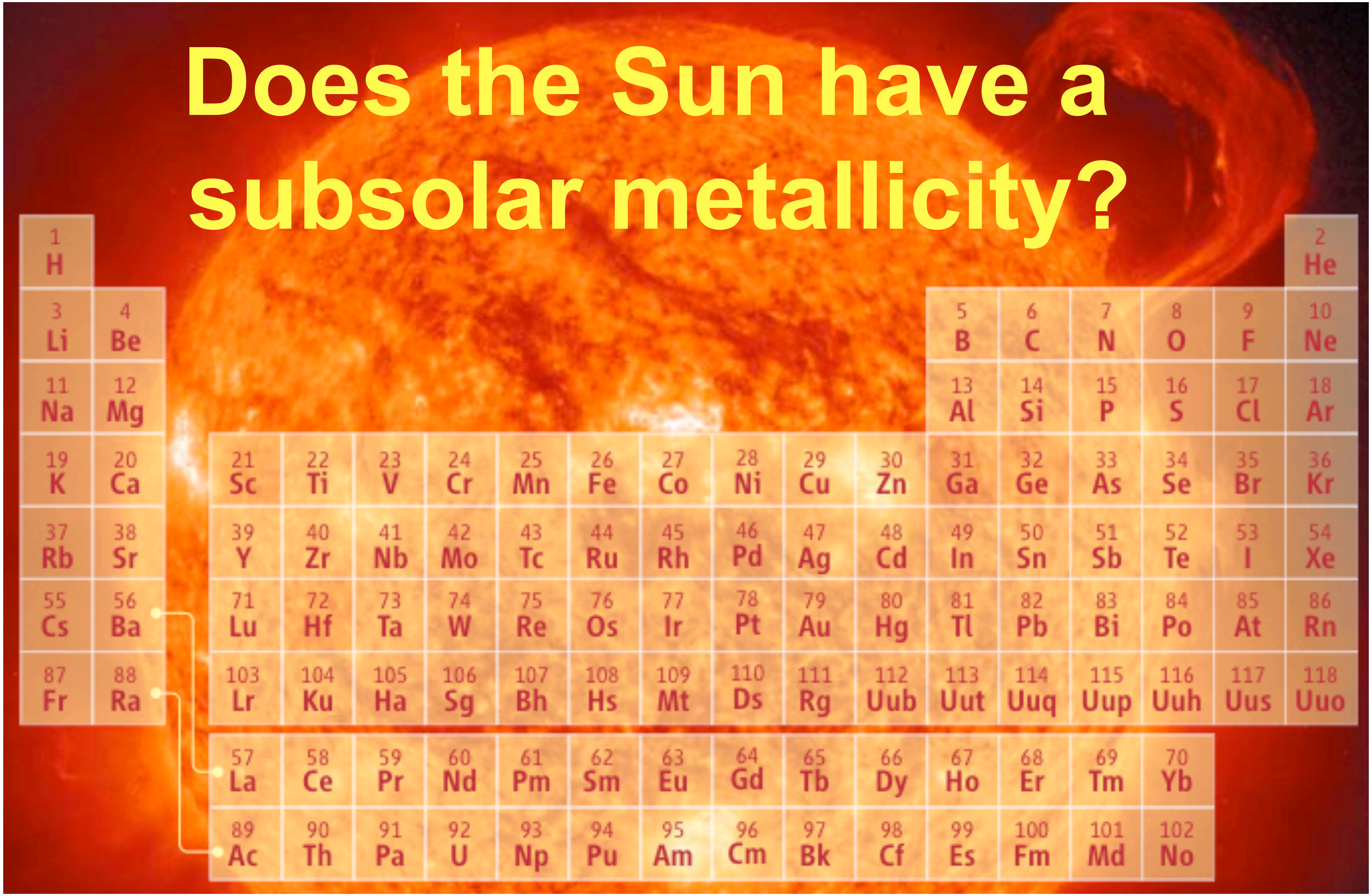
Does the Sun have a subsolar metallicity?



Max Planck Institute
for Astrophysics

Martin Asplund

Main partners in crime

Solar modelling:

Mats Carlsson (Oslo)
Remo Collet (MPA)
Wolfgang Hayek (MPA)
Åke Nordlund (Copenhagen)
Regner Trampedach (Boulder)

Solar abundances:

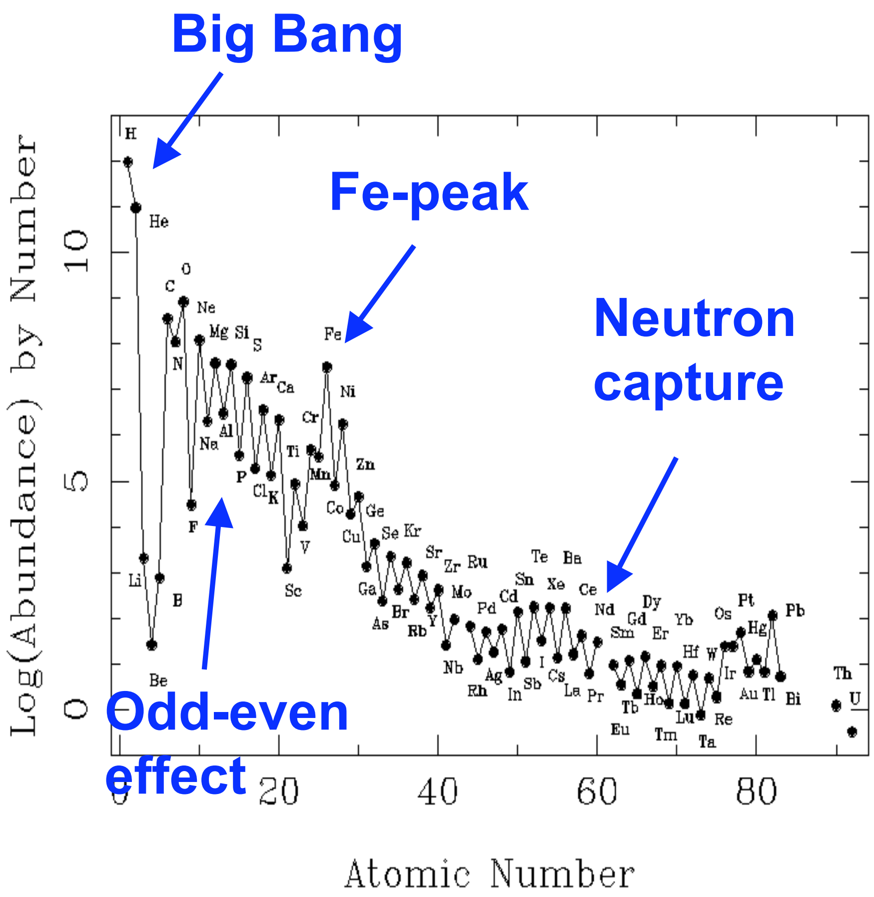
Nicolas Grevesse (Liege)
Jorge Melendez (Porto)
Tiago Pereira (ANU)
Ivan Ramirez (MPA)
Jacques Sauval (Brussels)
Patrick Scott (Stockholm)

Solar abundances

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

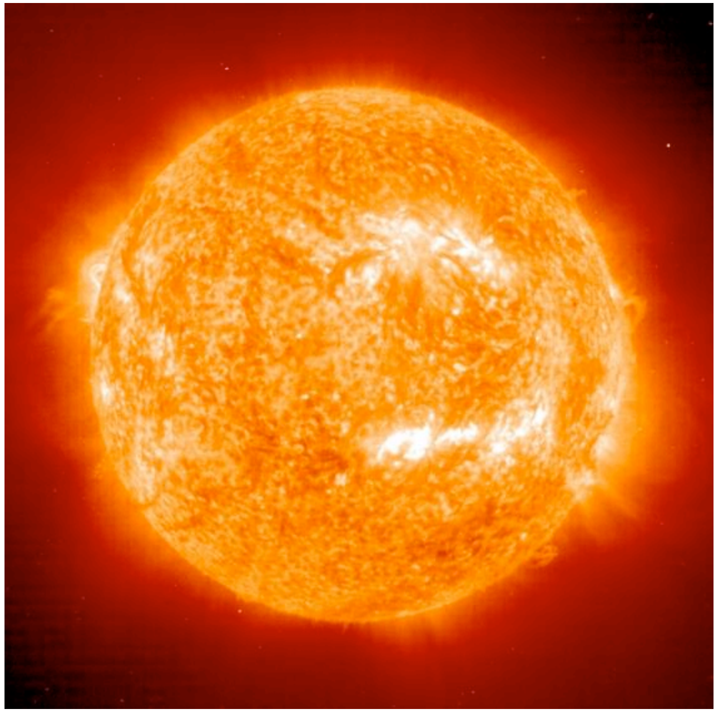
Some compilations:

Russell (1929)
Unsöld (1948)
Suess & Urey (1956)
Goldsmith et al. (1960)
Anders & Grevesse (1989)
Grevesse & Sauval (1998)
Lodders (2003)
Asplund et al. (2005, 2009)

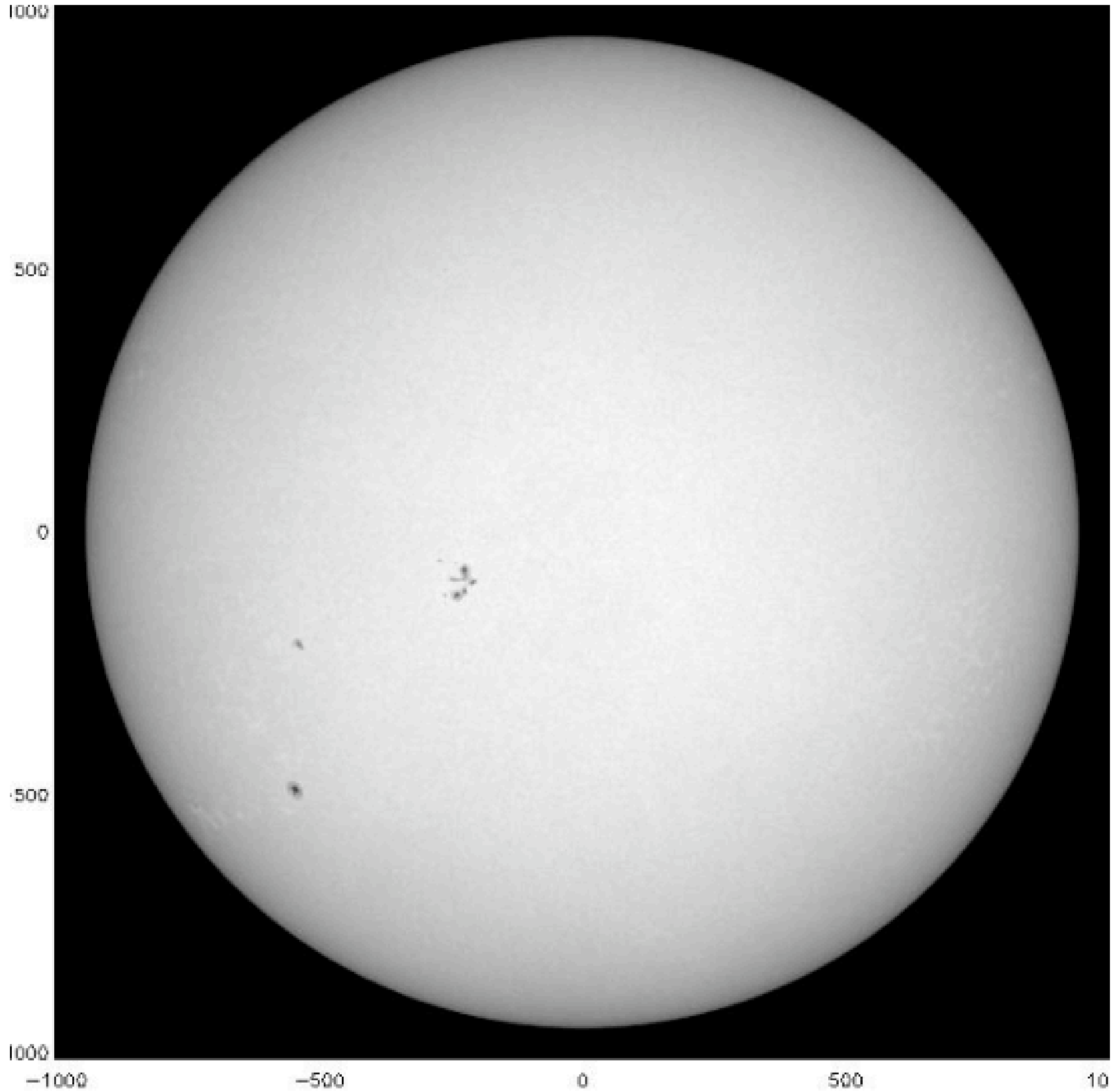


Solar system abundances

Meteorites	Solar atmosphere
Mass spectroscopy	Solar spectroscopy
Very high accuracy	Modelling-dependent
Element depletion	Very little depletion



Solar atmosphere



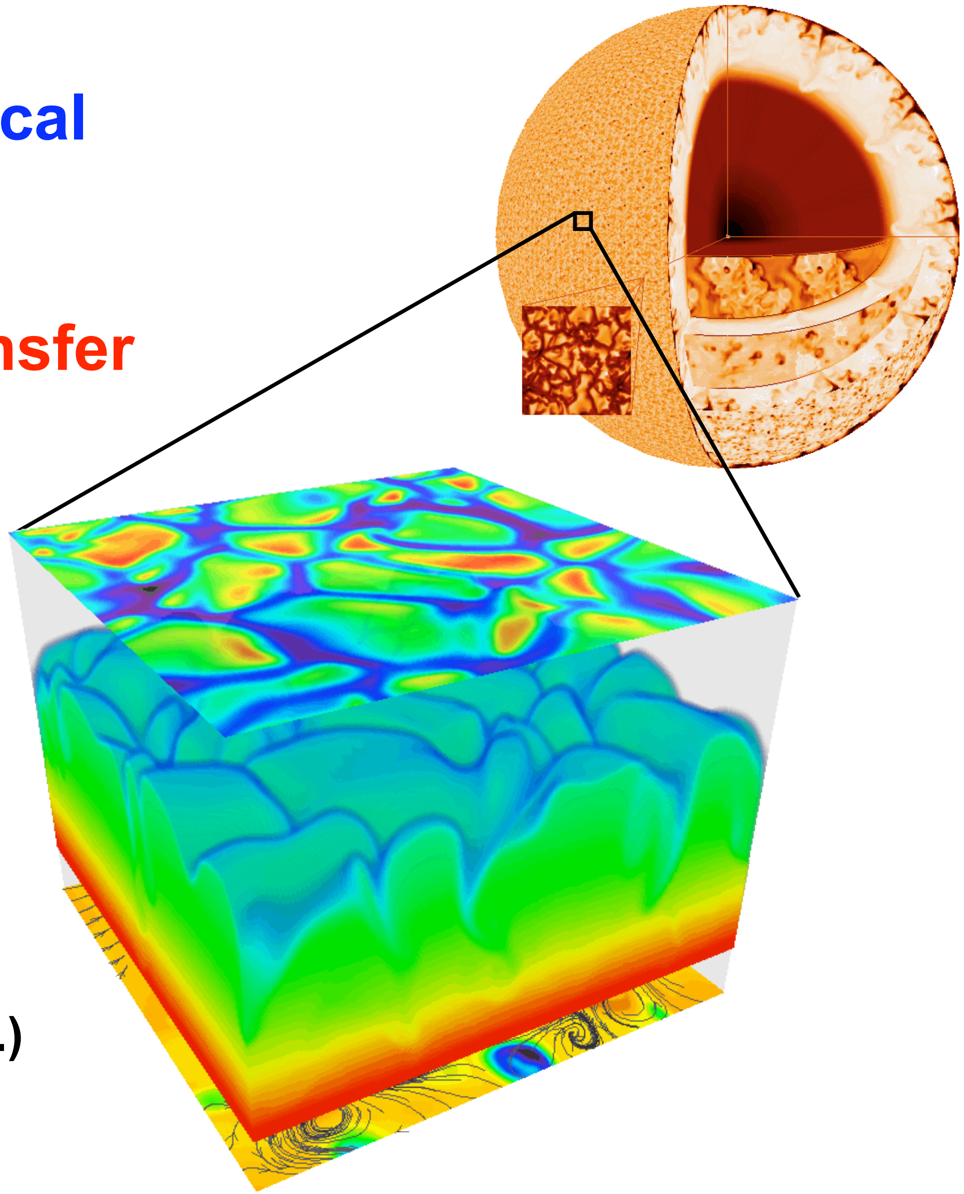
Mats Carlsson (Oslo)

3D solar atmosphere models

Ingredients:

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

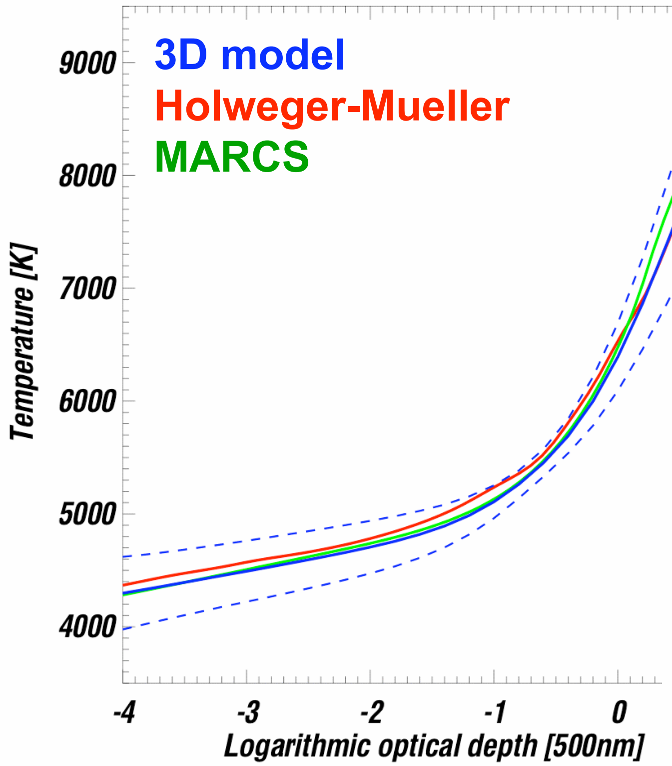
Essentially parameter free



For the aficionados:

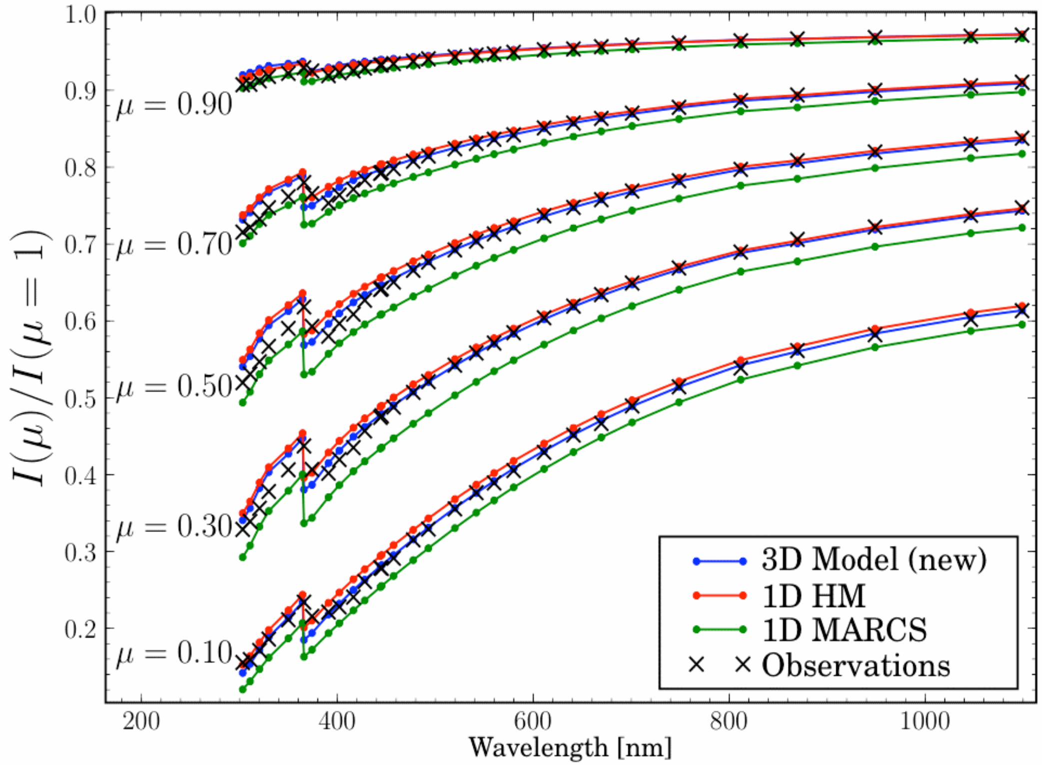
Stagger-code (Nordlund et al.)
MHD equation-of-state (Mihalas et al.)
MARCS opacities (Gustafsson et al.)
Opacity binning (Nordlund)

Temperature structure

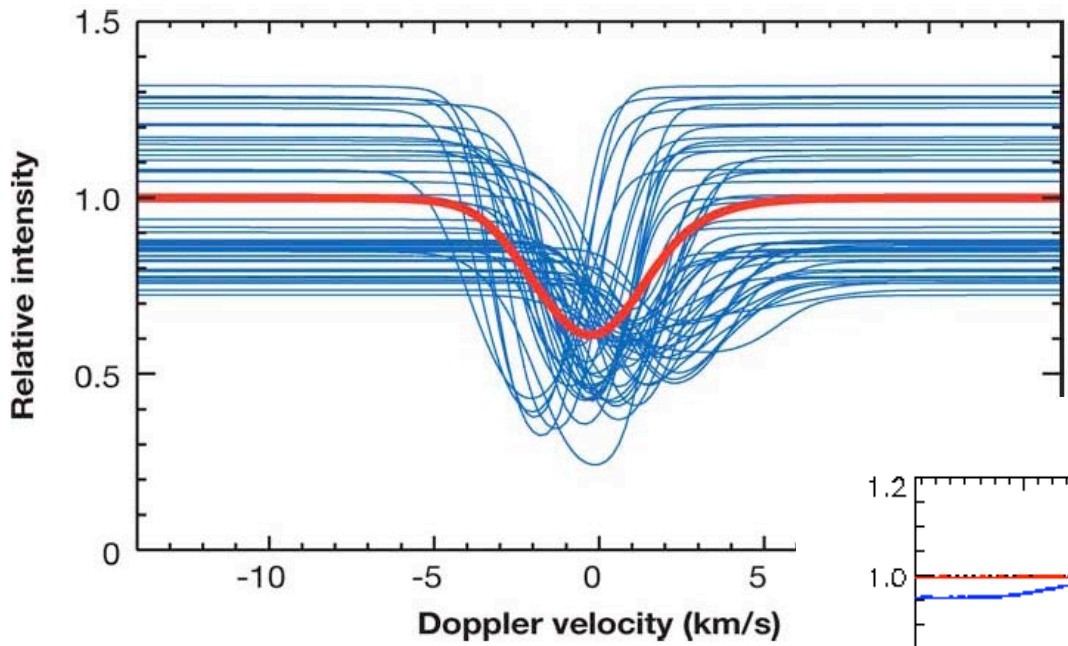


Atmospheric temperature structure is critical

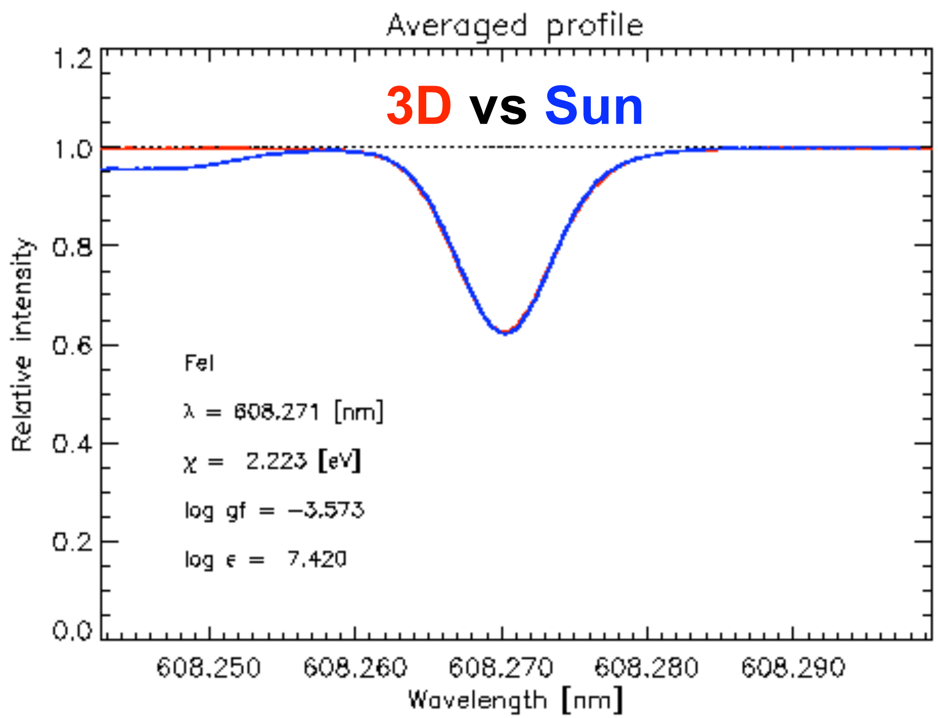
Our 3D model performs remarkably well



Spectral line formation

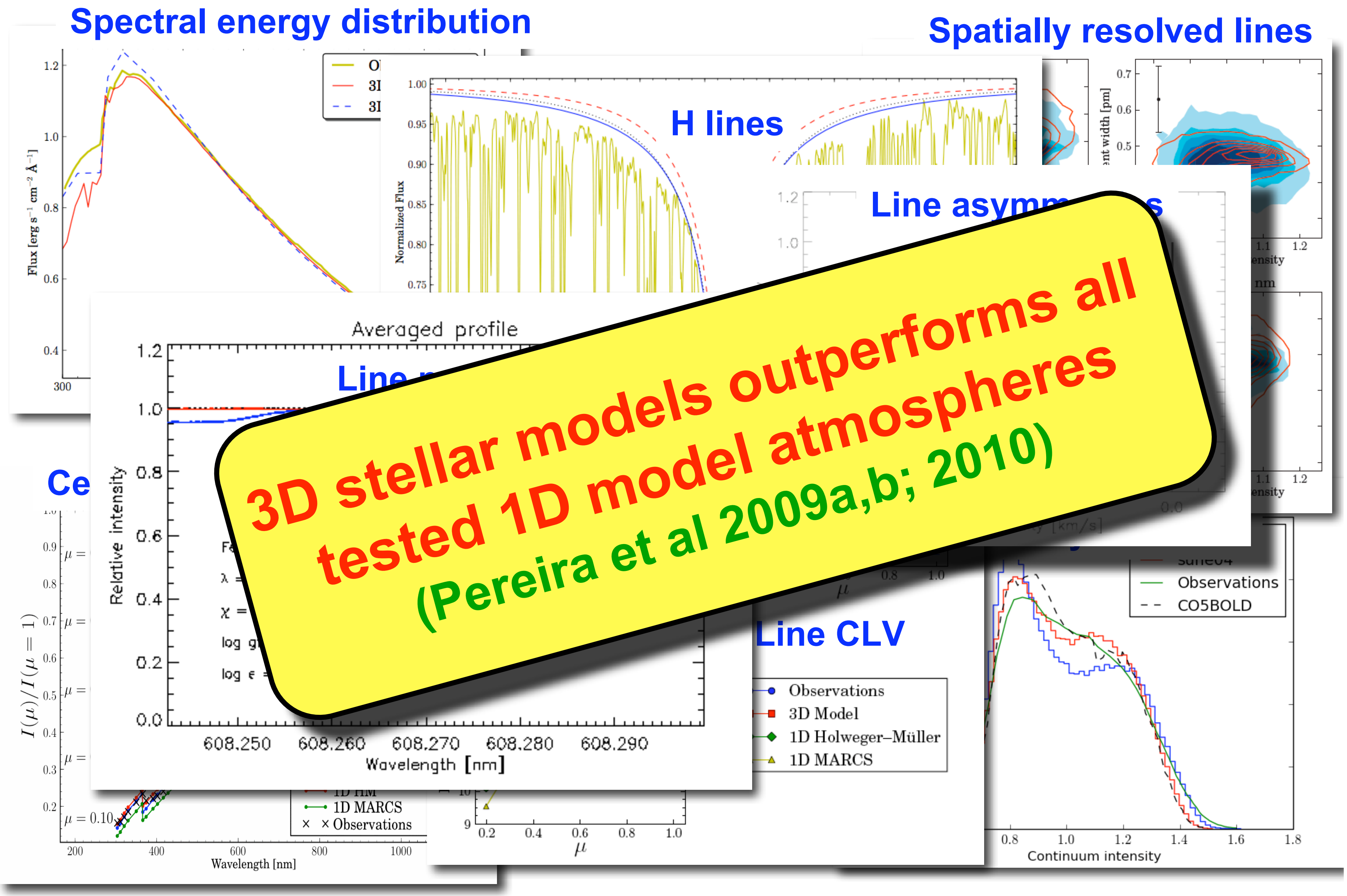


Line profiles vary tremendously across the solar surface



3D model describes observations very well without free parameters

More observational tests



3D stellar models outperforms all tested 1D model atmospheres (Pereira et al 2009a,b; 2010)

Solar abundances revisited

- Asplund, Grevesse, Sauval, Scott, 2009, ARAA, 47, 481 + series of A&A papers
- Realistic 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=8.69±0.05
- **Asplund et al. (2009)**

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	8.69+/-0.03
OH, dv=1	8.75+/-0.03	8.86+/-0.03	8.69+/-0.03

Two often-used 1D model atmospheres

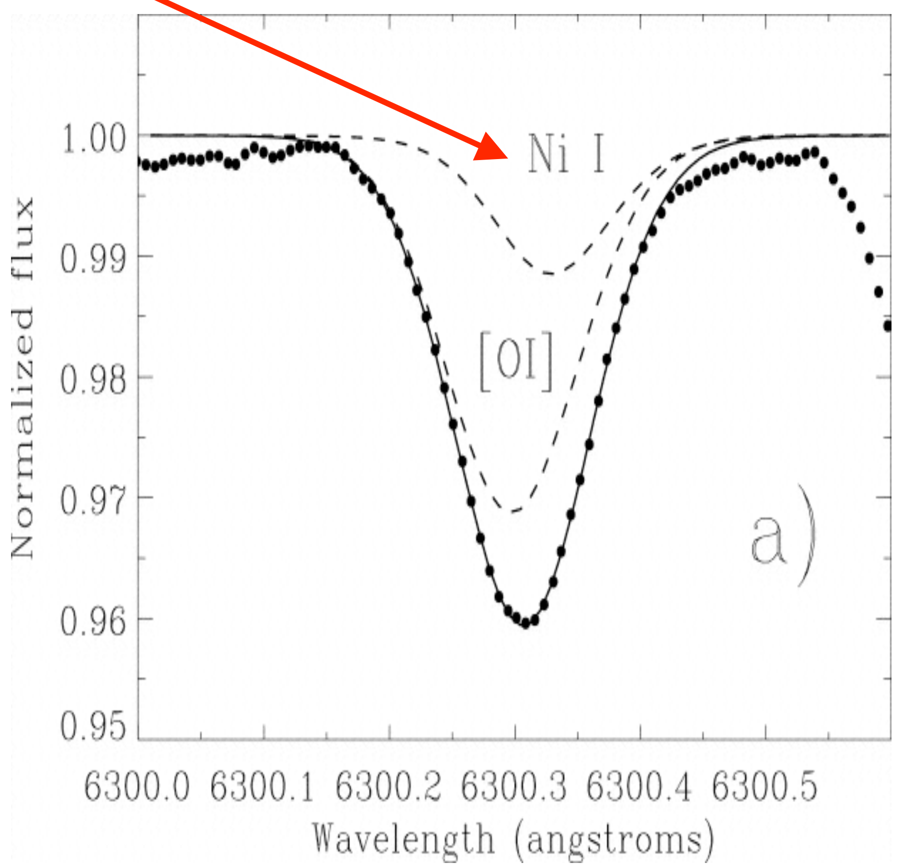
[O I]: blends

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:
New solar Ni abundance

Asplund et al. 2009,
Pereira et al. 2009:
log O = 8.69±0.05



(Similar results for other [OI] lines)

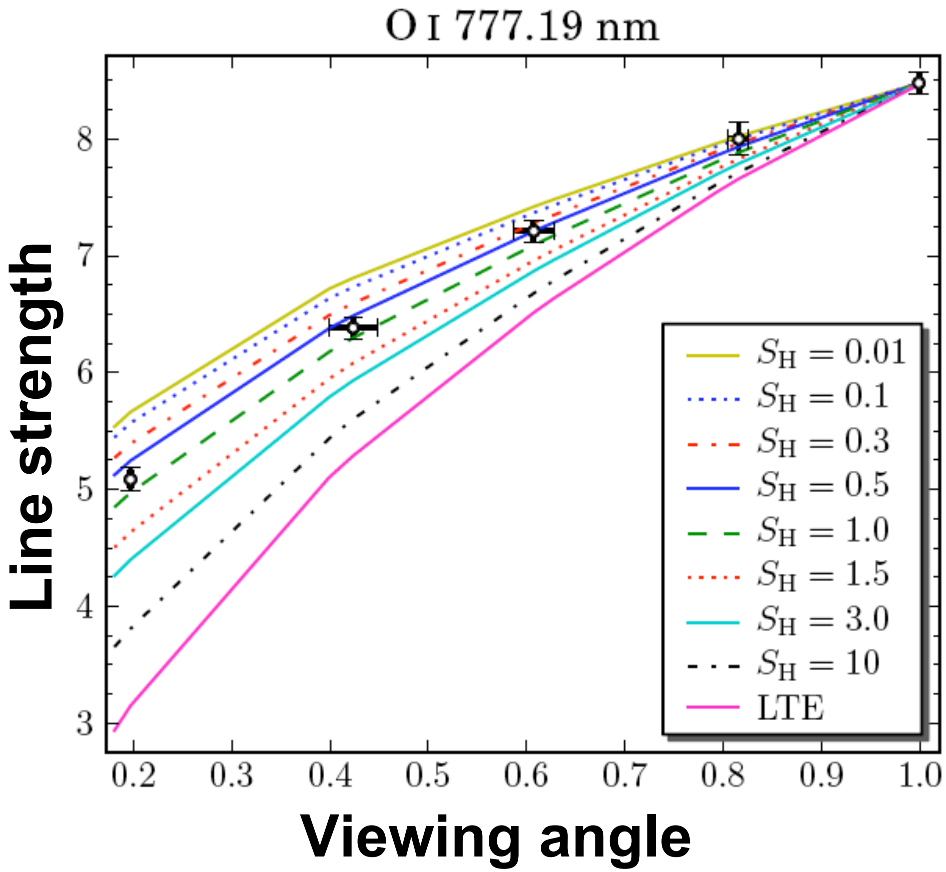
O I: non-LTE effects

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

Non-LTE - LTE ≈ -0.2 dex

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

Asplund et al. 2009a:
log O=8.69±0.05

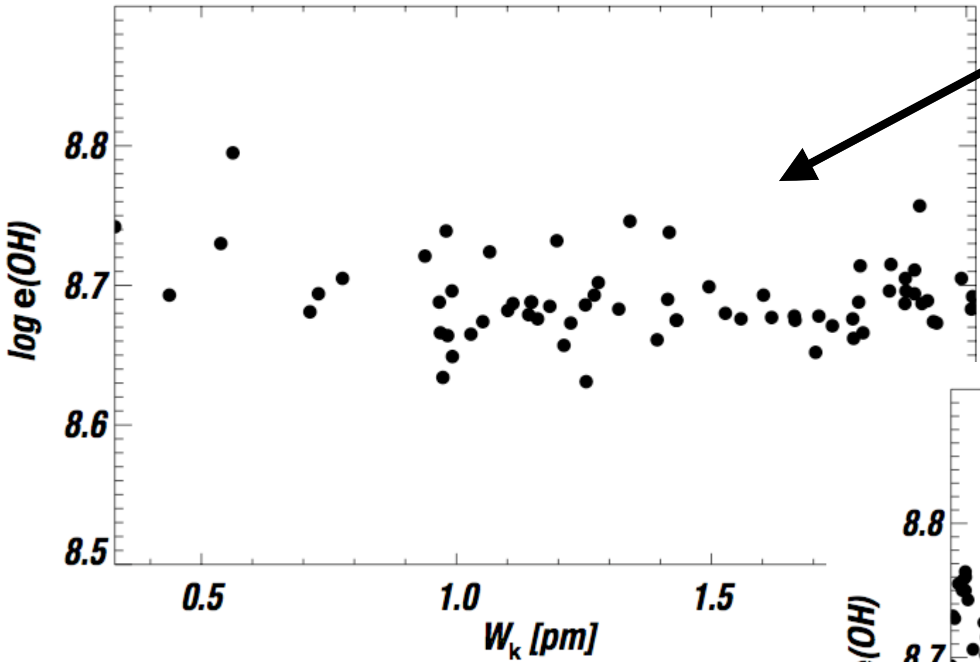


Note: S_H only makes sense for a given model atom and atmosphere

OH lines: 3D effects

Molecular lines are very temperature sensitive

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

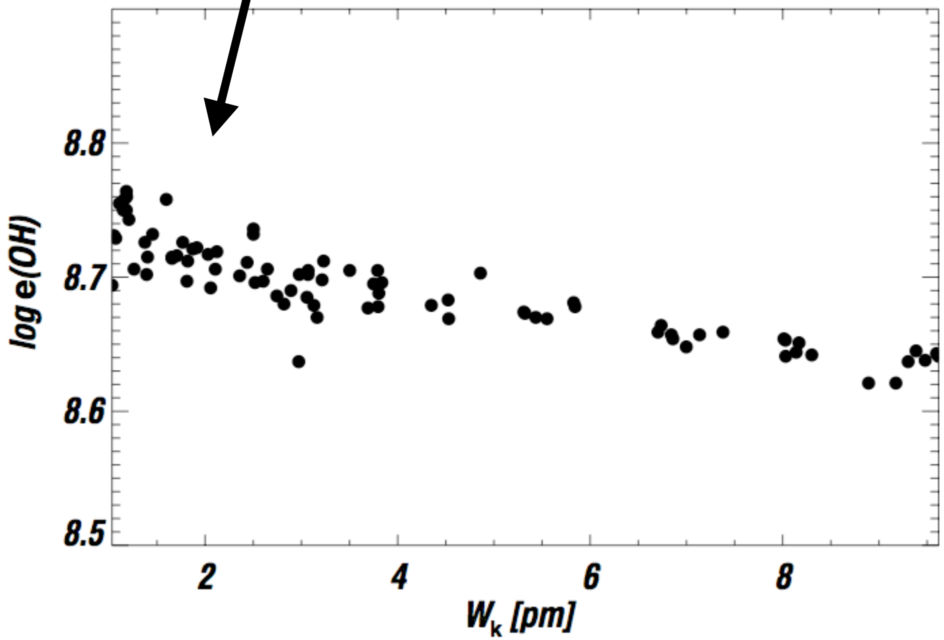


Vibration-rotation lines:

log O=8.69±0.03

Pure rotation lines:

log O=8.69±0.03



Asplund et al. 2009a

Carbon diagnostics

- Discordant results in 1D: log C~8.4-8.7
- Excellent agreement in 3D: log C=8.43±0.05
- C/O=0.55±0.07
- Asplund et al. (2009)

Lines	MARCS	Holweger-Mueller	3D
[C I]	8.38	8.41	8.41
C I	8.39+/-0.04	8.45+/-0.04	8.42+/-0.05
CH, dv=1	8.44+/-0.04	8.53+/-0.04	8.44+/-0.04
CH, A-X	8.43+/-0.03	8.51+/-0.03	8.43+/-0.03
C_2, Swan	8.46+/-0.03	8.51+/-0.03	8.46+/-0.03
CO, dv=1	8.55+/-0.02	8.60+/-0.01	8.44+/-0.01
CO, dv=2	8.58+/-0.02	8.69+/-0.02	8.44+/-0.01

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. (2009a)
Carbon	8.50+/-0.11	8.43+/-0.05
Nitrogen	7.86+/-0.12	7.83+/-0.05
Oxygen	8.76+/-0.07	8.69+/-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)

Solar Fe abundance

3D model:

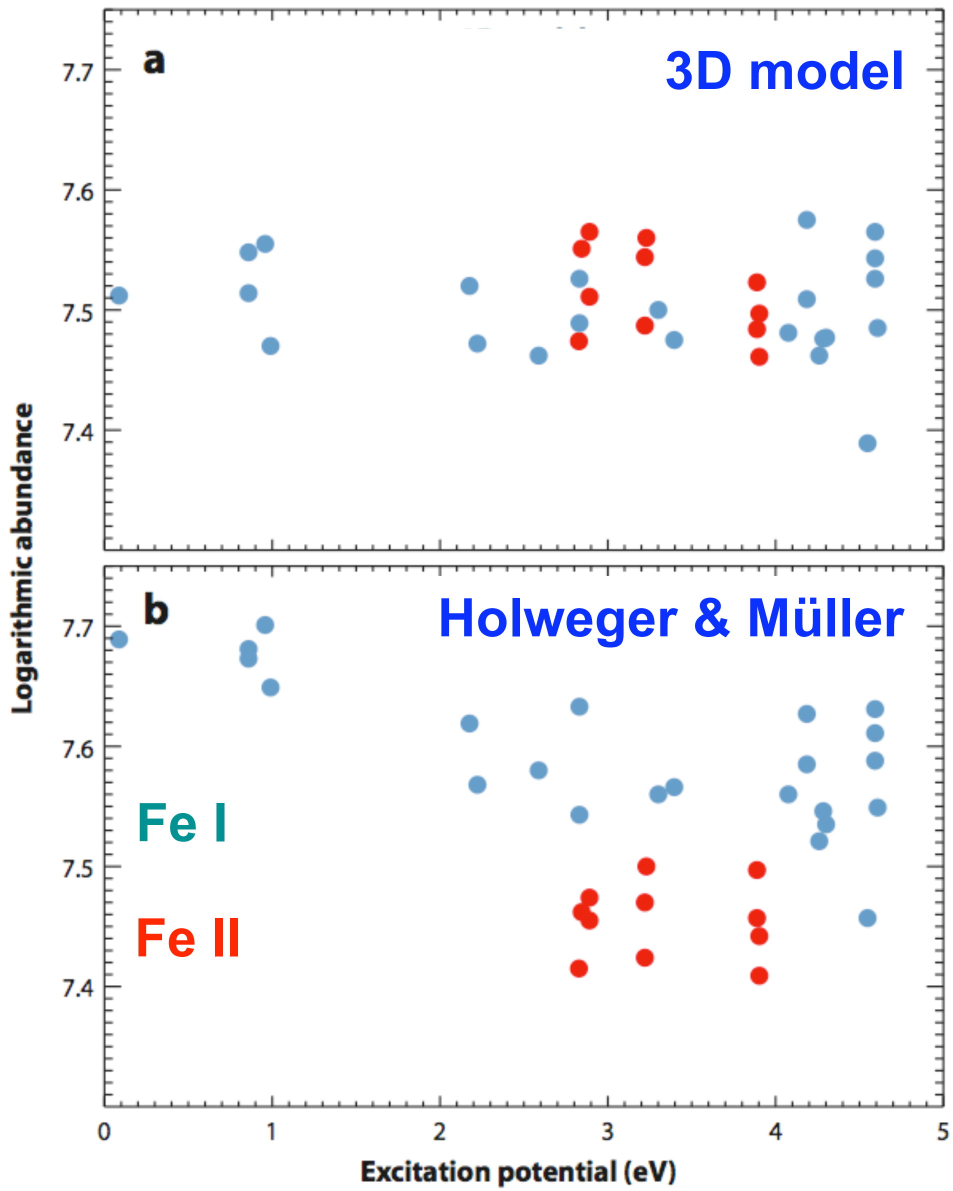
log Fe I =7.51±0.05

log Fe II=7.50±0.04

Holweger & Müller:

Fe I trend with χ_{ex}

Fe I and Fe II offset



Complete solar inventory

Asplund et al. (2009, ARAA):
3D-based analysis of all elements
Statistical and systematic errors included in total uncertainties

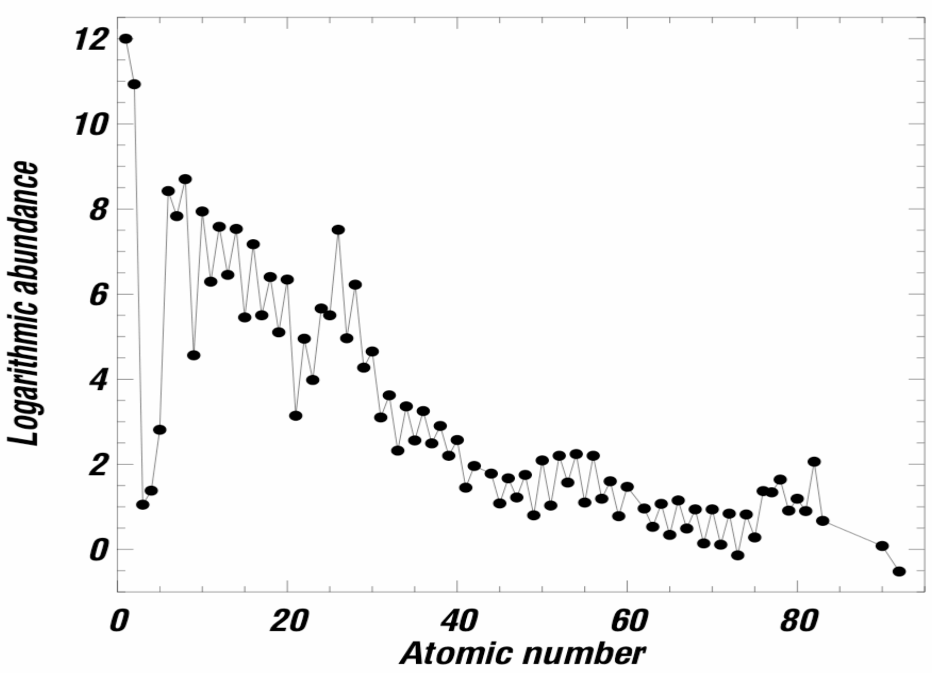


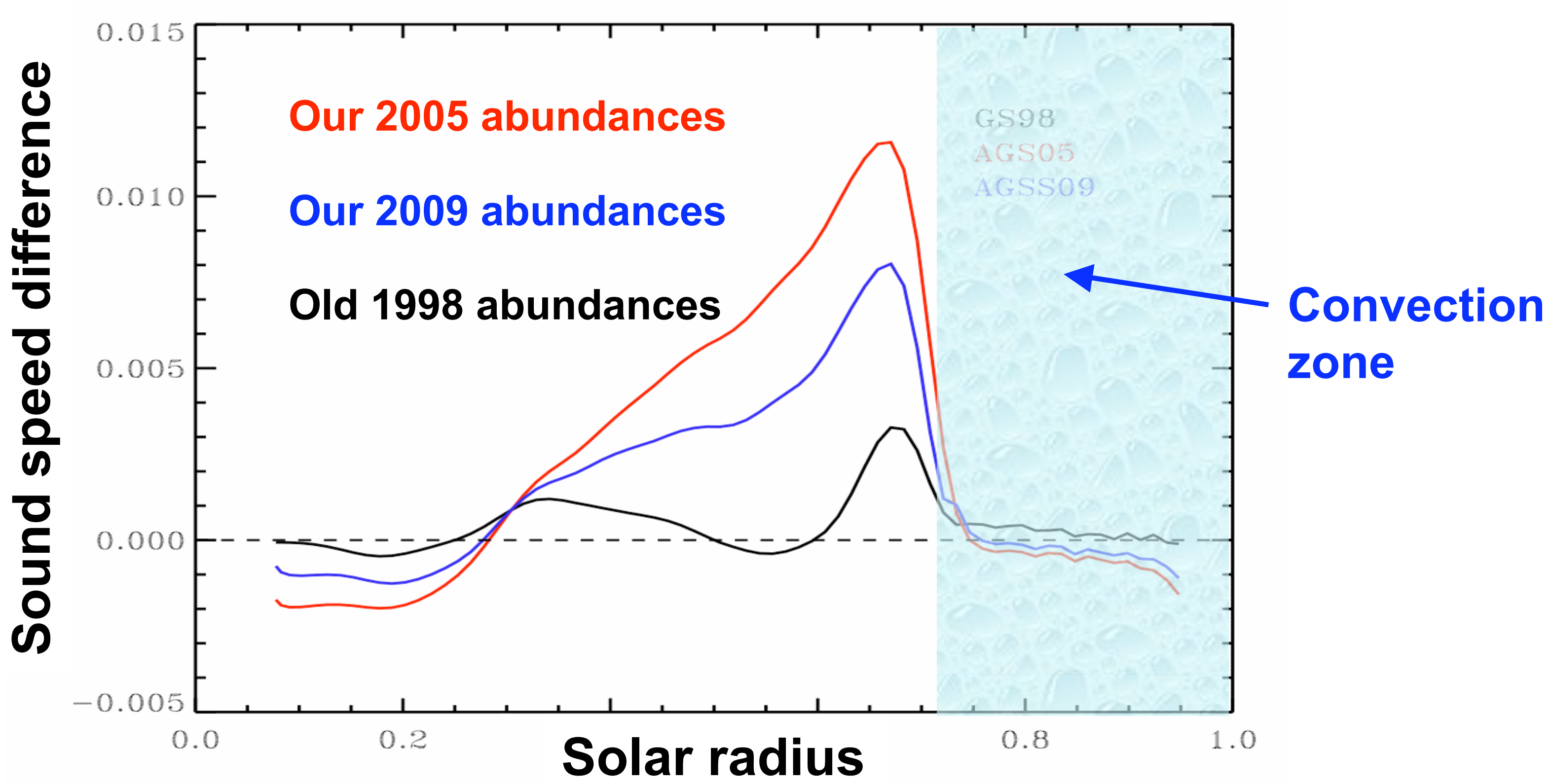
Table 1 Element abundances in the present-day solar photosphere. Also given are the corresponding values for CI carbonaceous chondrites (Lodders, Palme & Gail 2009). Indirect photospheric estimates have been used for the noble gases (Section 3.9)

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
- 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

Possible solutions

- Missing opacity?
  - Possibly?
- Underestimated element diffusion?
  - U
- Acc
  - U
- Inte
  - P
- Unc ance?
  - U
- Err
  - Hopefully not
- Combination of some of the above?
  - Contrived?

Is the Sun unusual?

Melendez, Asplund, Gustafsson, Yong, 2009, ~~Science~~
~~Nature~~
ApJL

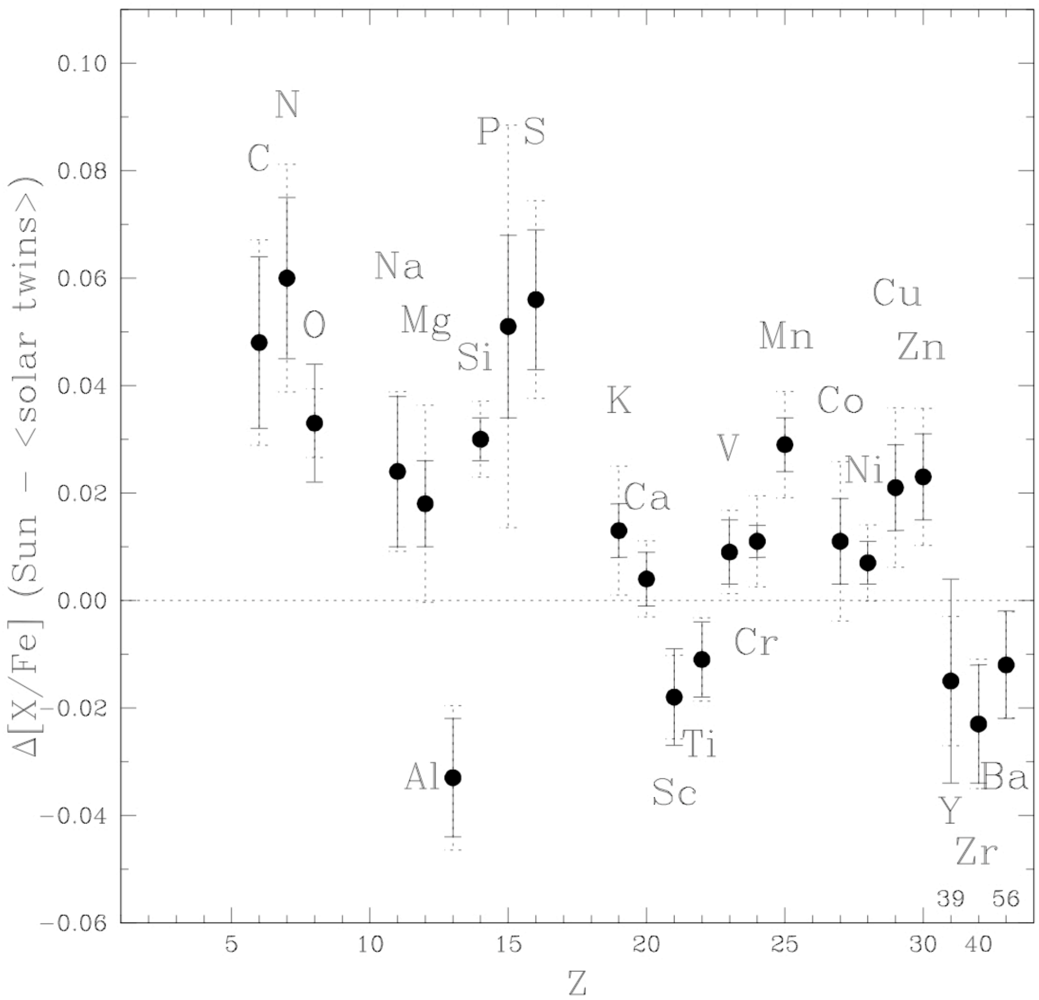
Precision stellar spectroscopy

Melendez et al. 2009:

11 solar twins + Sun observed with Magellan/MIKE:

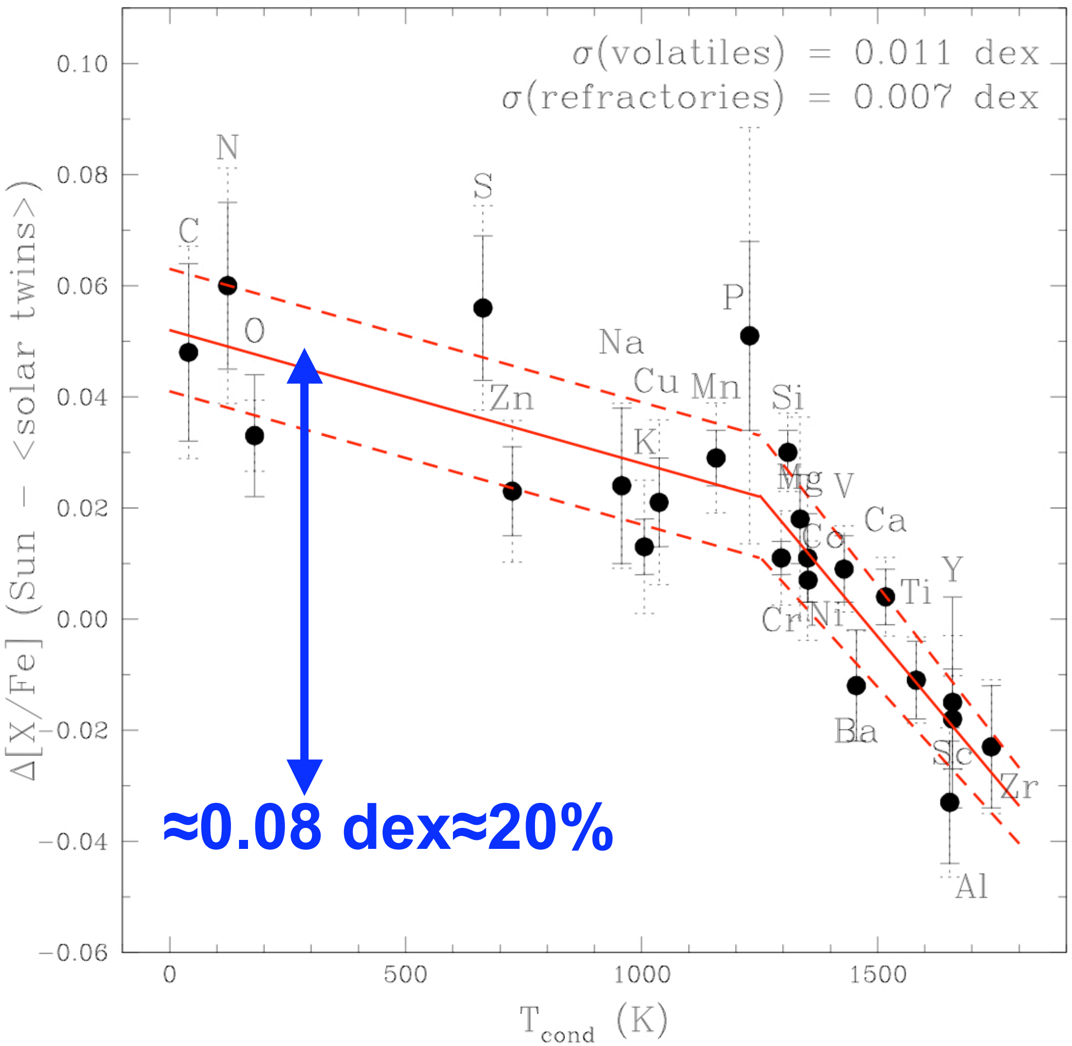
R=65,000
S/N~450

ΔT_{eff}<75K
$\Delta \log g$<0.1
Δ[Fe/H]<0.1



Extremely high precision achieved:
≤0.01 dex in [X/H], [X/Fe]

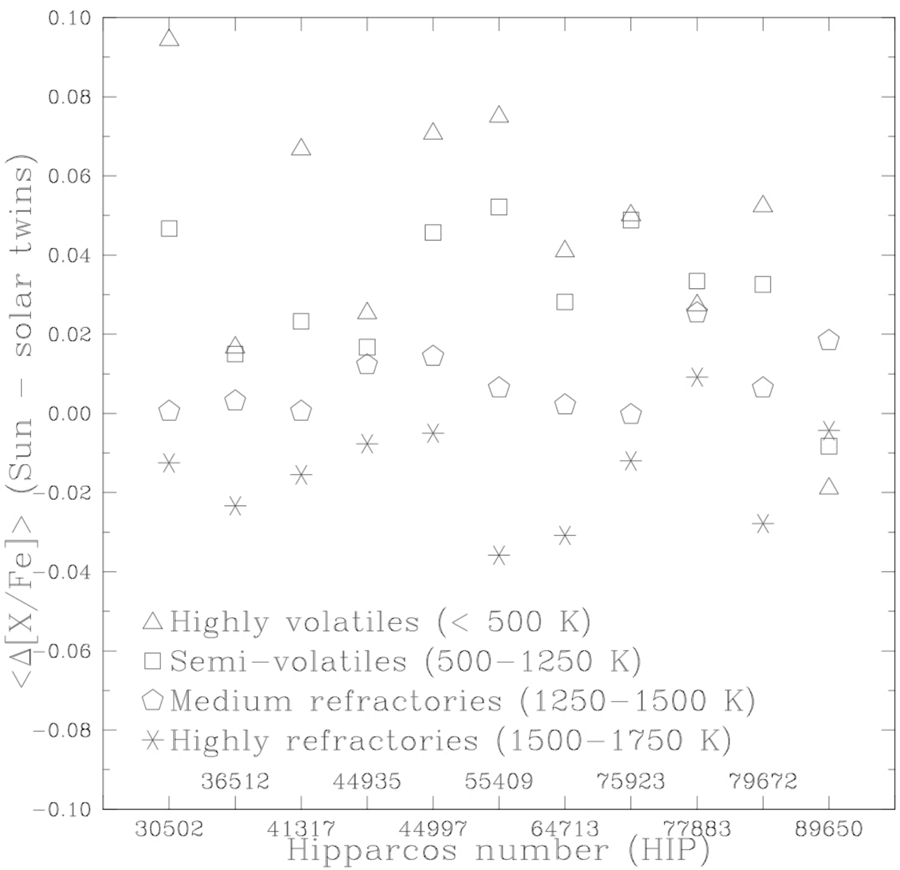
Signatures of planet formation

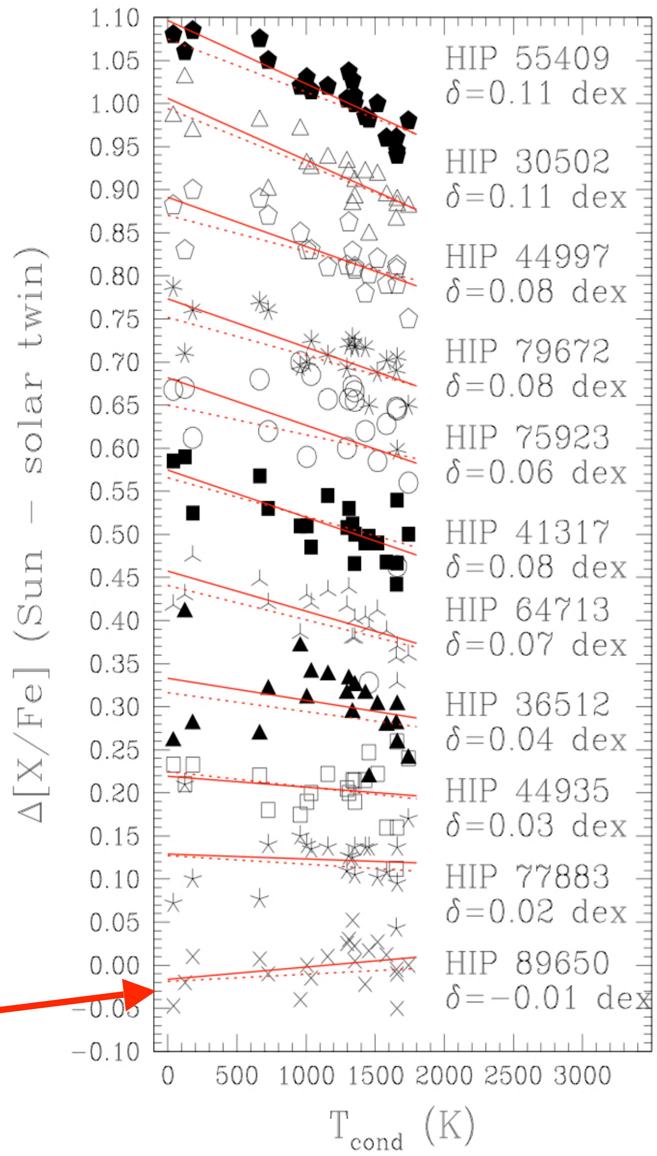


Correlation with condensation temperature highly significant

(probability $<10^{-6}$ to happen by chance)

The Sun is unusual





Only a minority of our solar twins resemble the Sun

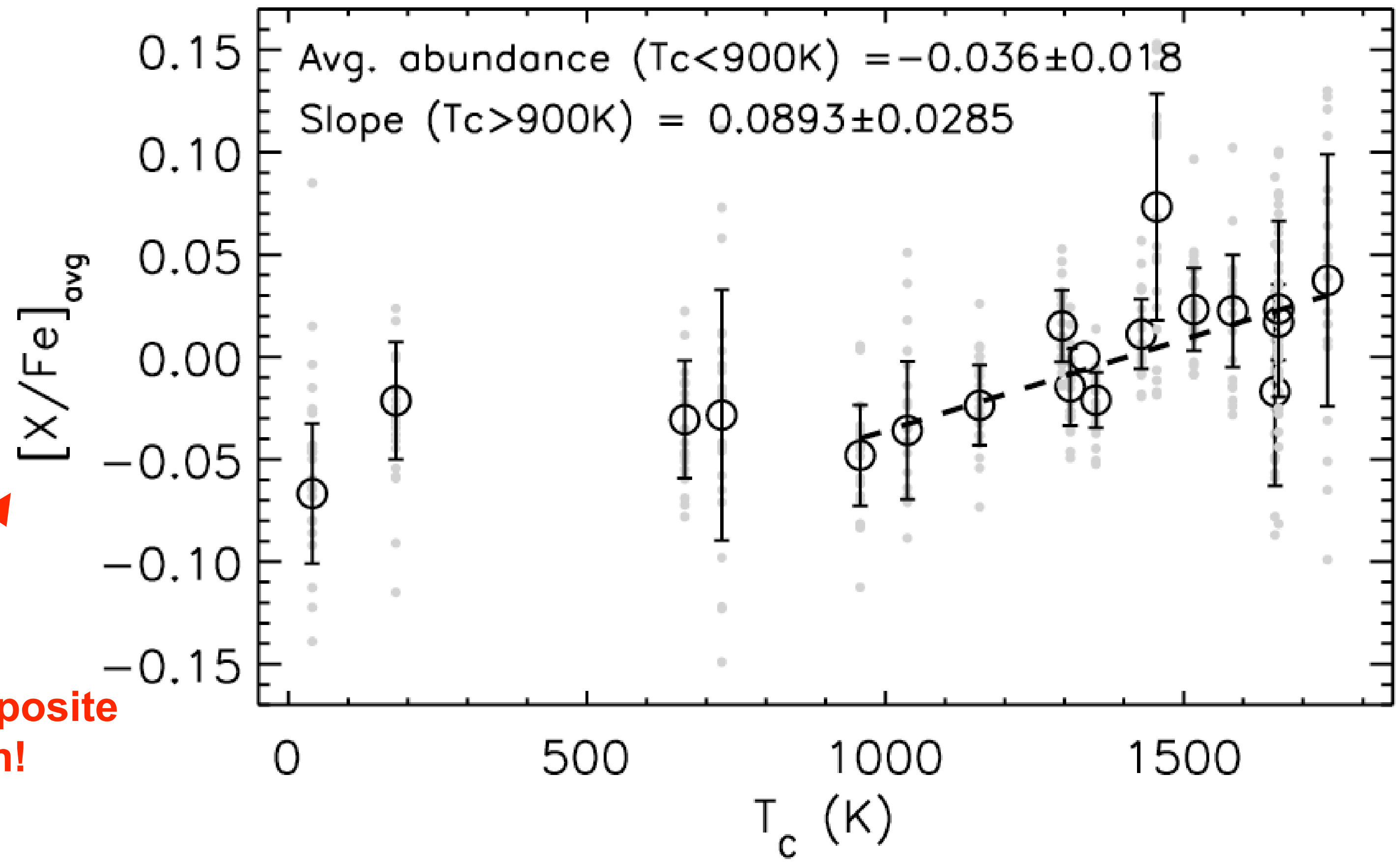
Confirmation of trend

Ramirez et al. (2009):

Observations of 22 solar twins with McDonald 2.7m

R=60,000, S/N~200

~0.02 dex accuracy in [X/Fe]

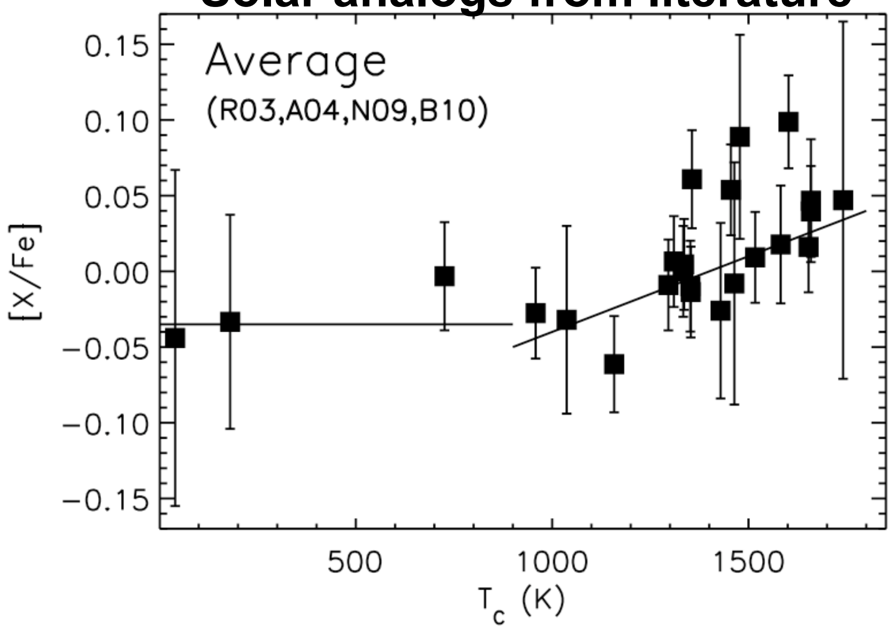


Note: opposite definition!

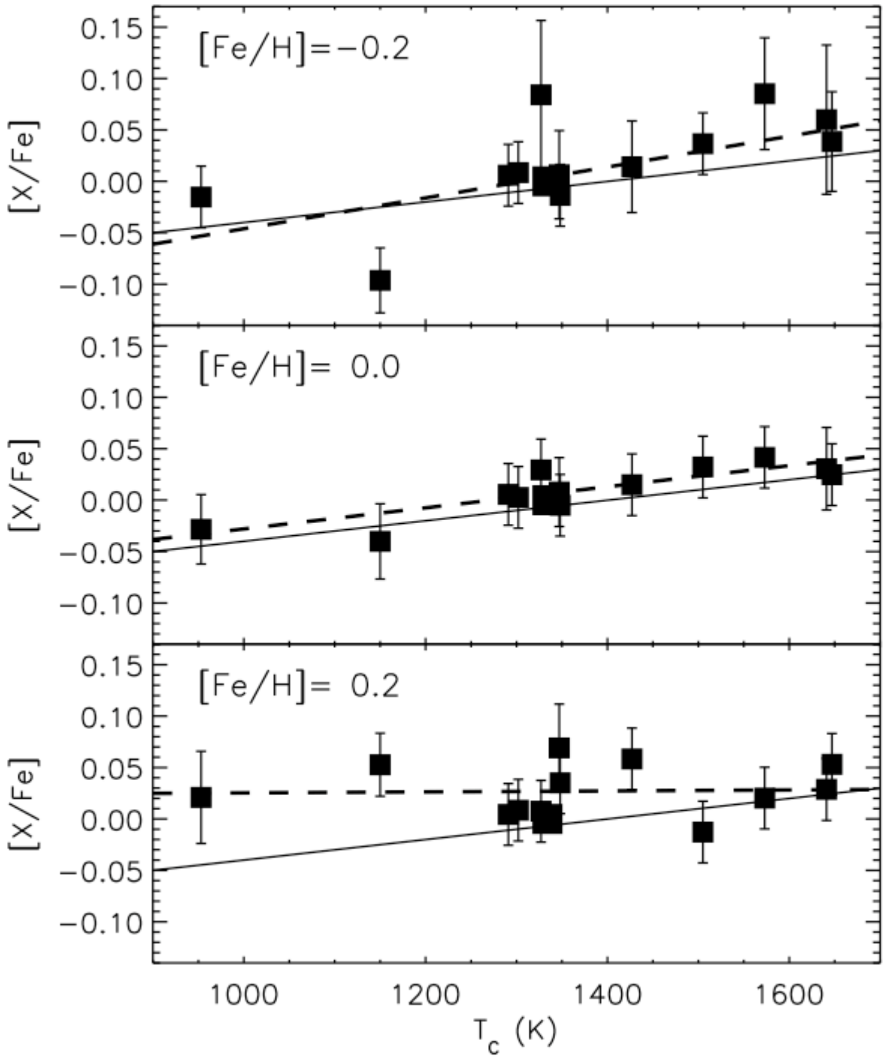
Re-analyzing previous studies

Ramirez et al. (2010):
Signature exists also in previous stellar samples but disappears at high [Fe/H]
⇒ Metallicity-dependence of planet formation

Solar analogs from literature

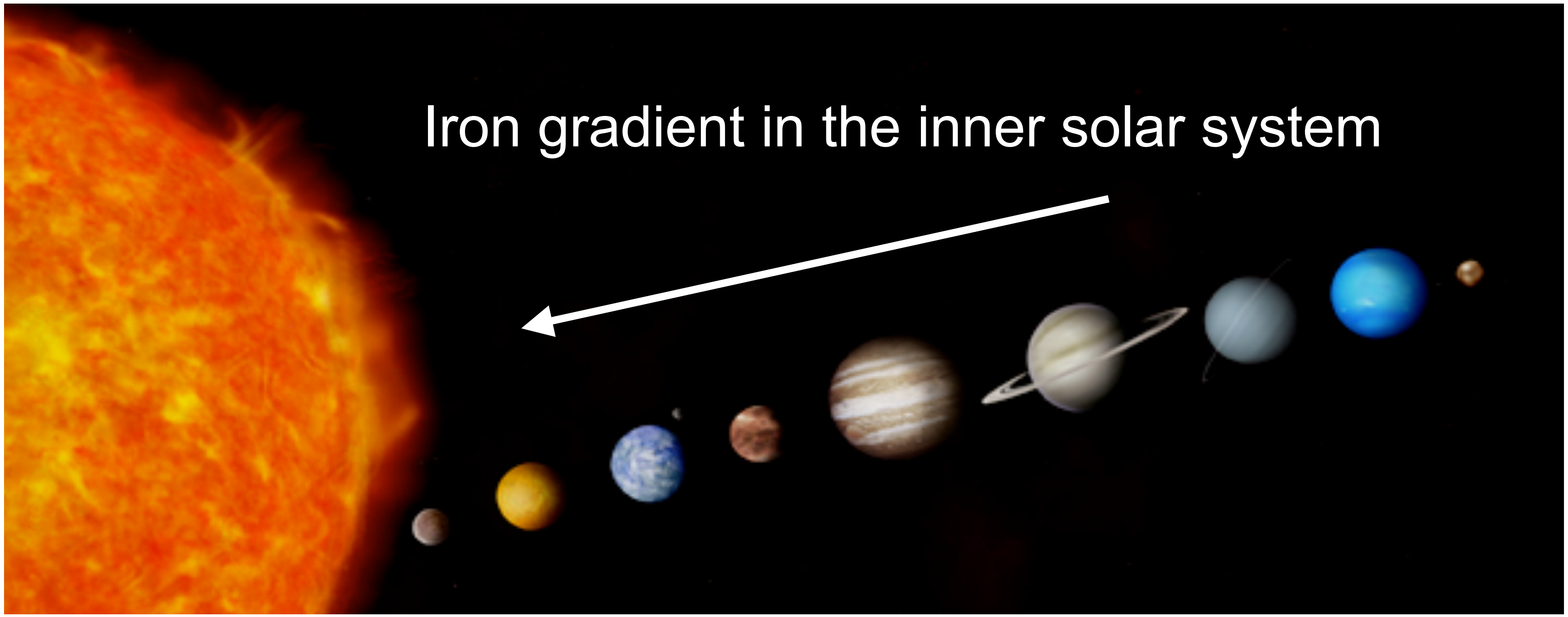


Data from Neves et al. 2009



Scenario

Sun: planet formation locked up refractories but less of volatiles during accretion phase
Solar twins: less planet formation and thus more refractories than Sun



Terrestrial or giant planets?

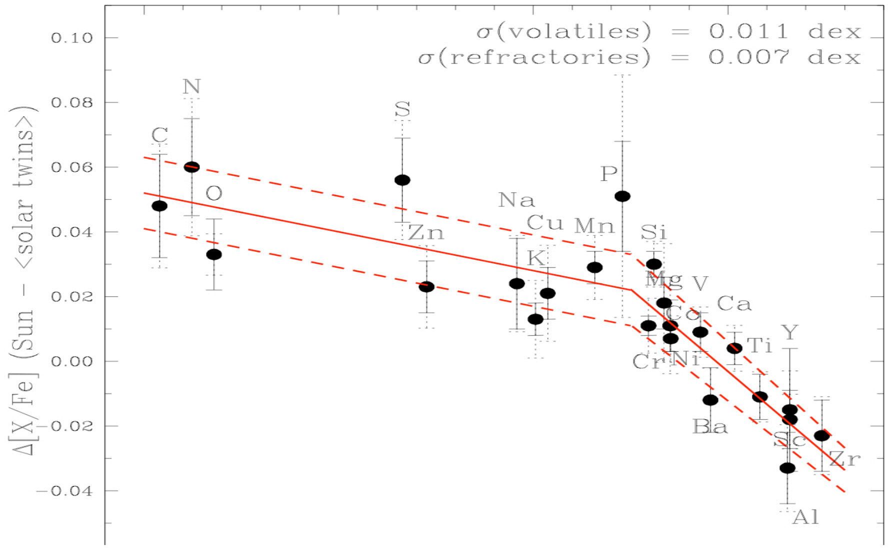
How much dust-cleansed gas accretion is required?

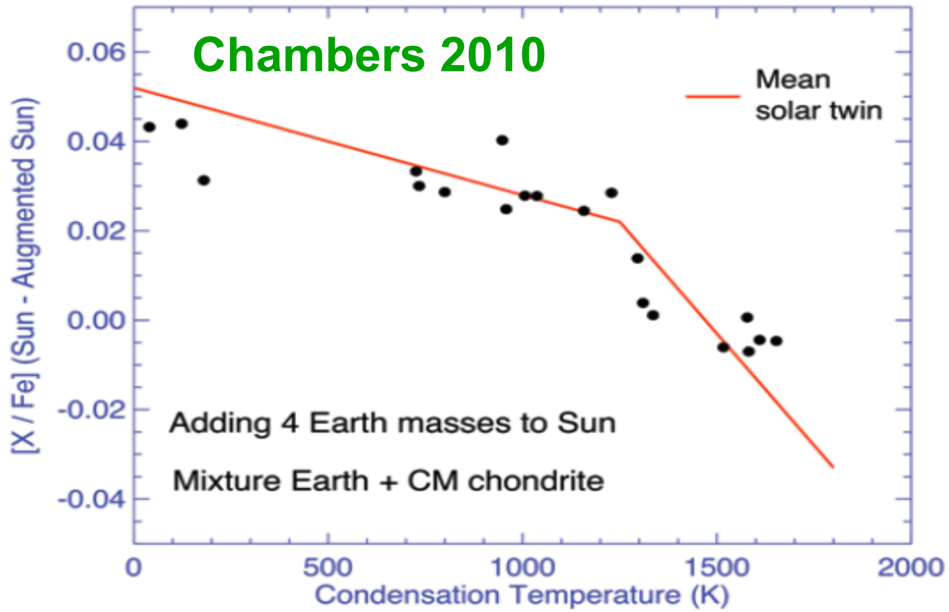
Assume gas accretion once solar convection zone reached ≈ present size (~0.02 M_o):

Refractories ~2*10^{28} g ≈4 $M_{\oplus}$

Rocky planets: ~8*10^{27} g ≈1.3 $M_{\oplus}$
Cores of giant planets: ≈30 $M_{\oplus}$?

Characteristic temperature of ~1200 K only encountered at <<1 AU in proto-planetary disks

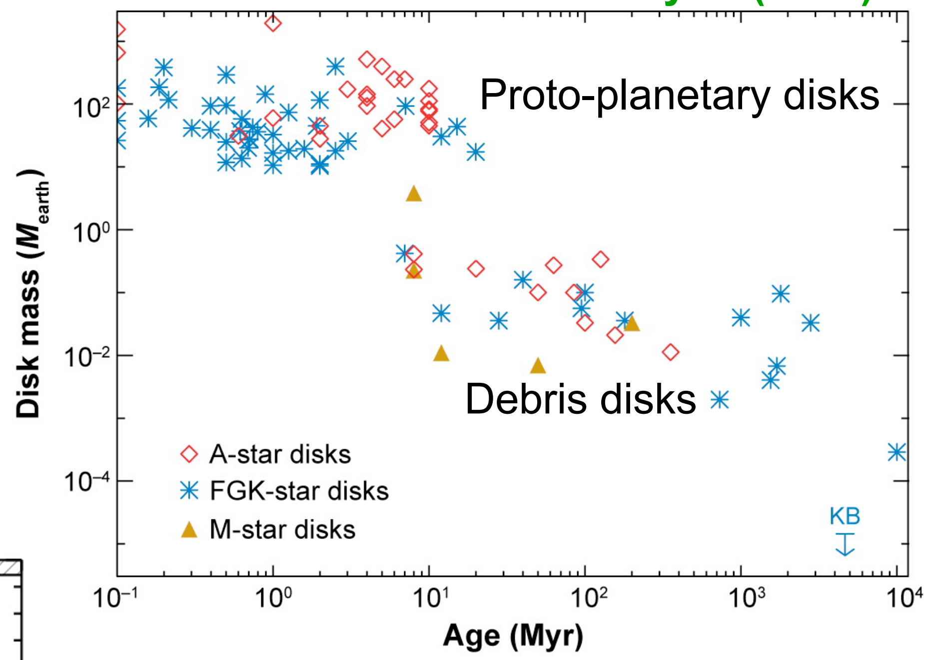




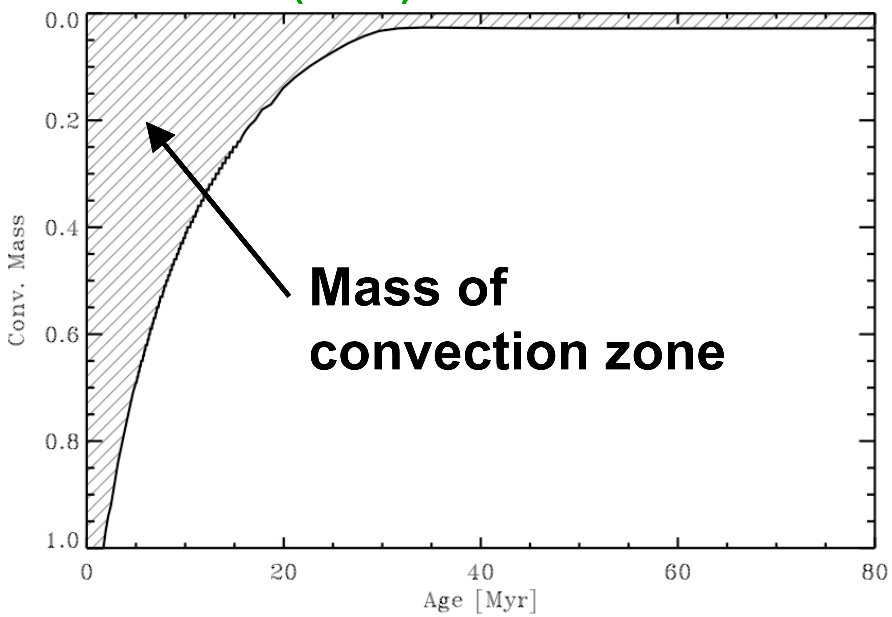
Time-scale problems

Ages of proto-planetary disks typically ≤10 Myr

Wyatt (2008)



Serenelli (2009)



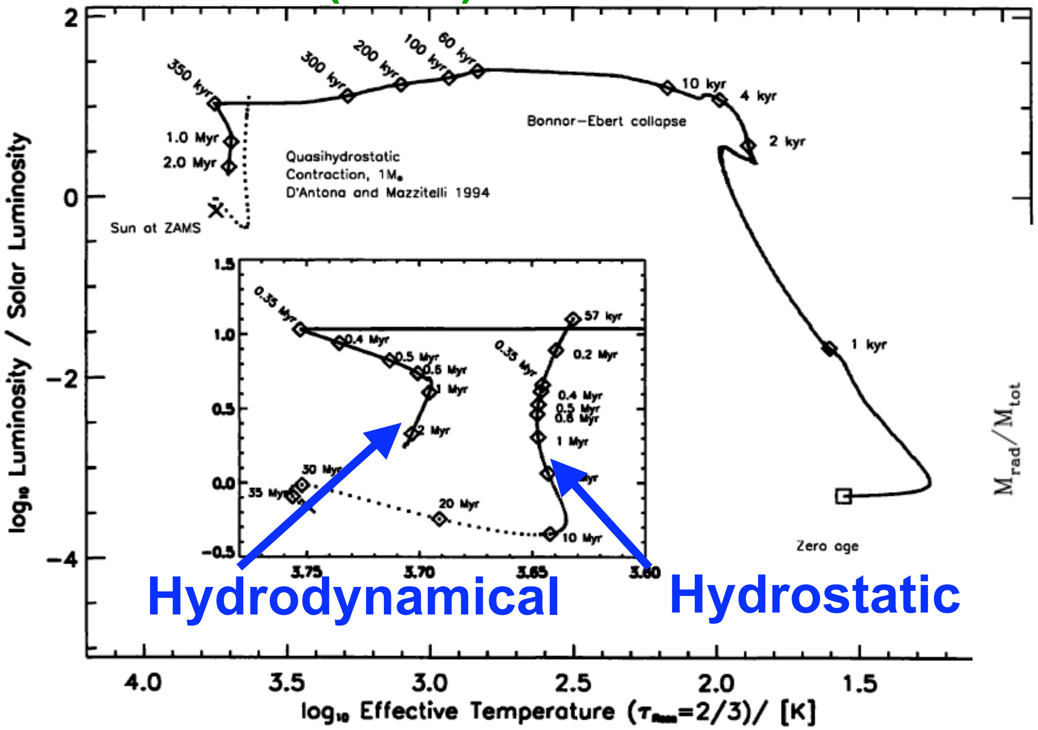
M_{cz} ~0.02 M_o only >30 Myr
M_{cz} ~0.4 M_o at ~10 Myr

Sun had unusually long-lived disk?

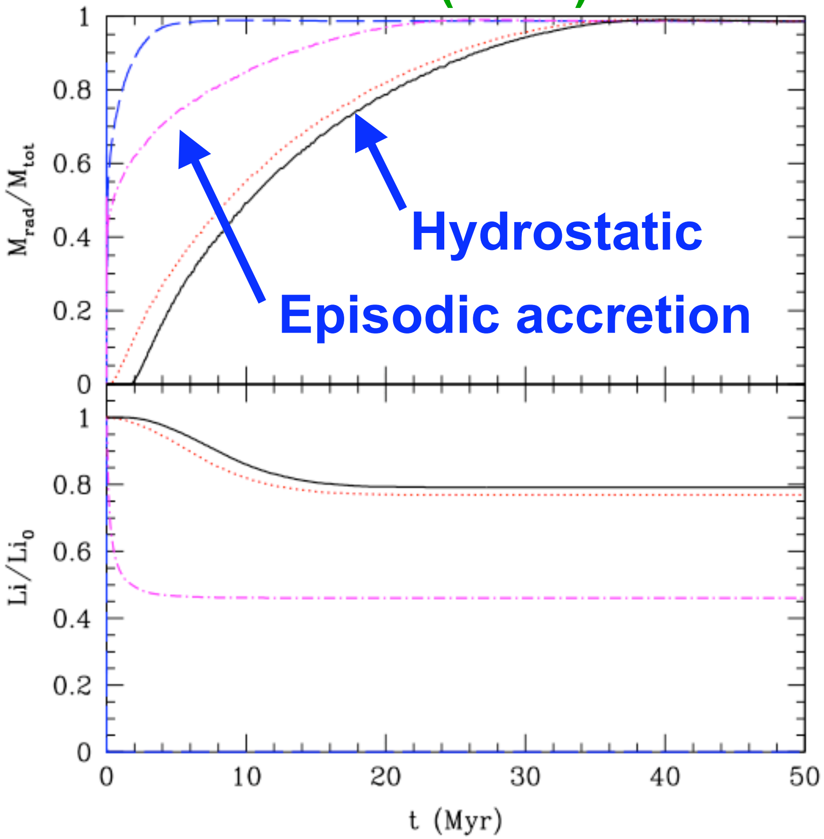
Pre-main sequence

Smaller convection zone in hydrodynamical models?

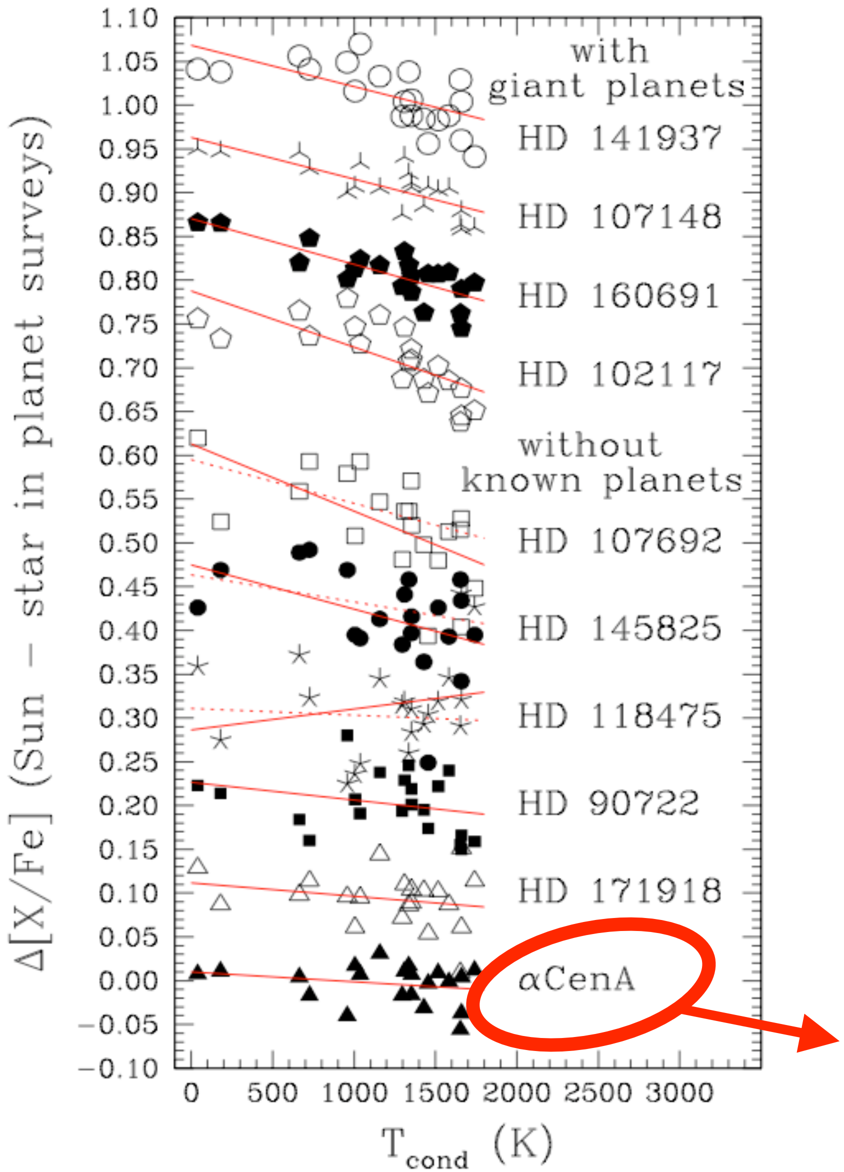
Wuchterl (2004):



Baraffe et al. (2010):



Stars with/without giant planets



Analysis of solar-like stars followed with radial velocity monitoring (HARPS)

Fraction of stars resembling the Sun:

⇒ With hot Jupiters: ~0%

⇒ Without hot Jupiters: ~70%

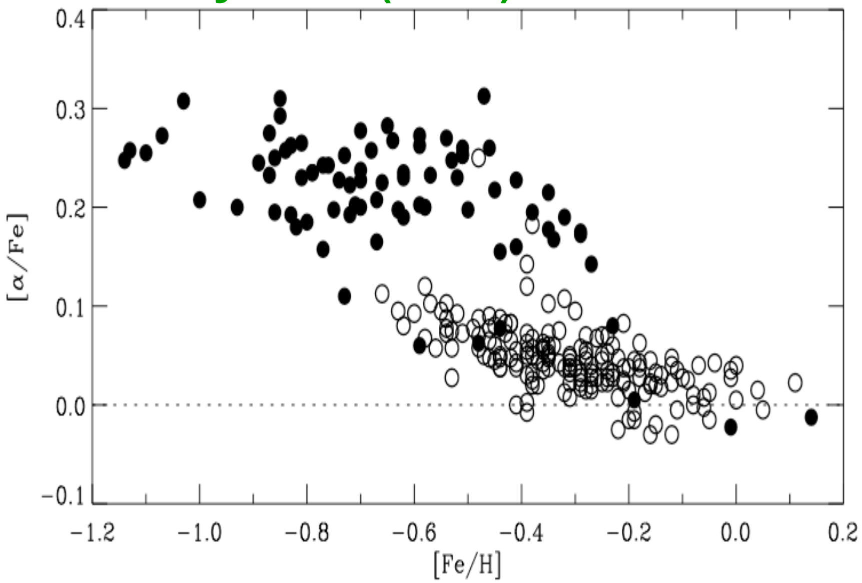
⇒ Stars in general: ~20%

Close-in giant planets prevent long-lived disks and/or formation of terrestrial planets?

An ideal candidate for terrestrial planet searches

Galactic archeology

Reddy et al. (2006)



Disk substructure and chemical tagging

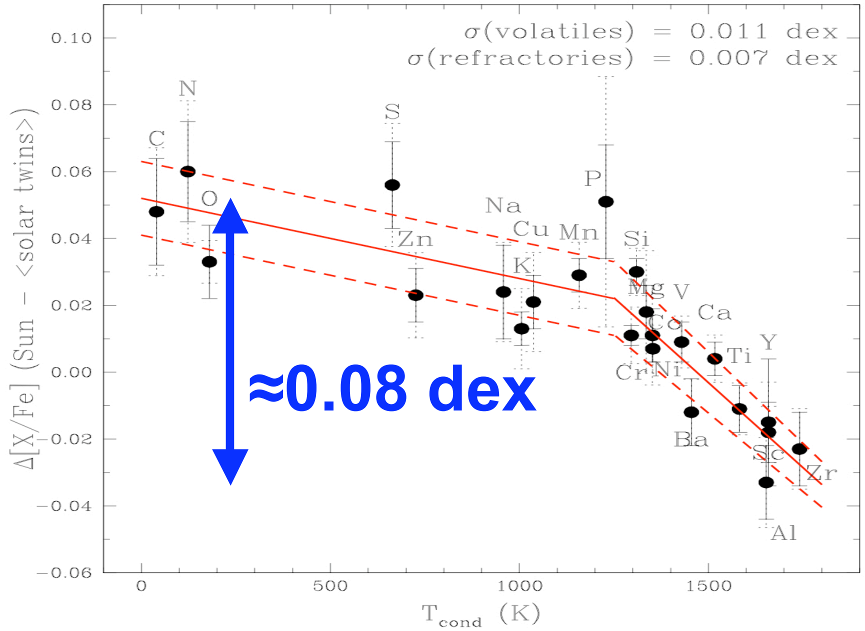
Δ(Thick-thin) ≈ 0.1 dex

Δ(Thin) ≈ 0.01 dex?

⇒ Planet signature larger!

Implications for Galactic archeology:

- **Identify stars with planets!**
- **High resolution + S/N**
- **Many elements (oxygen!)**
- **Improve stellar analysis**
  - **3D, non-LTE, parameters**



Near-field cosmology

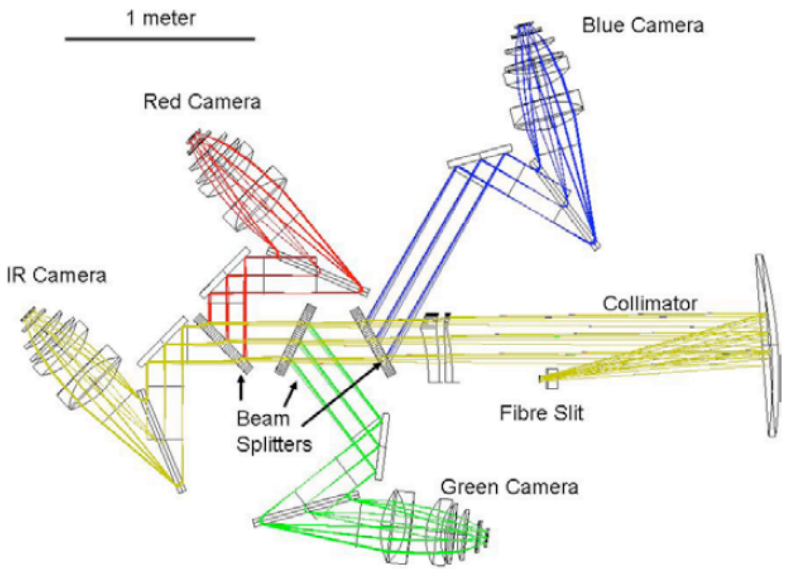


Figure 1: *schematic layout of the four-band HERMES spectrometer, showing the three dichroic beamsplitters, four VPH gratings and four cameras.*

HERMES @ AAT 4m R=30k & S/N~100 spectra of 10^6 stars for "*chemical tagging*":

⇒ Reconstruct chemical, dynamical and SF history of Milky Way

⇒ Identify solar siblings

Observe >10,000 dwarfs @ R=50k and S/N>200 to search for planet signature!

Summary

- Solar chemical composition
  - New abundances for <u>all</u> elements
  - Low C, N, O and Ne abundances
- Precision stellar spectroscopy
  - Sun is unusual
  - Signatures of planet formation
- Galactic archeology
  - Complicates finding solar siblings
  - Planet formation as a mask