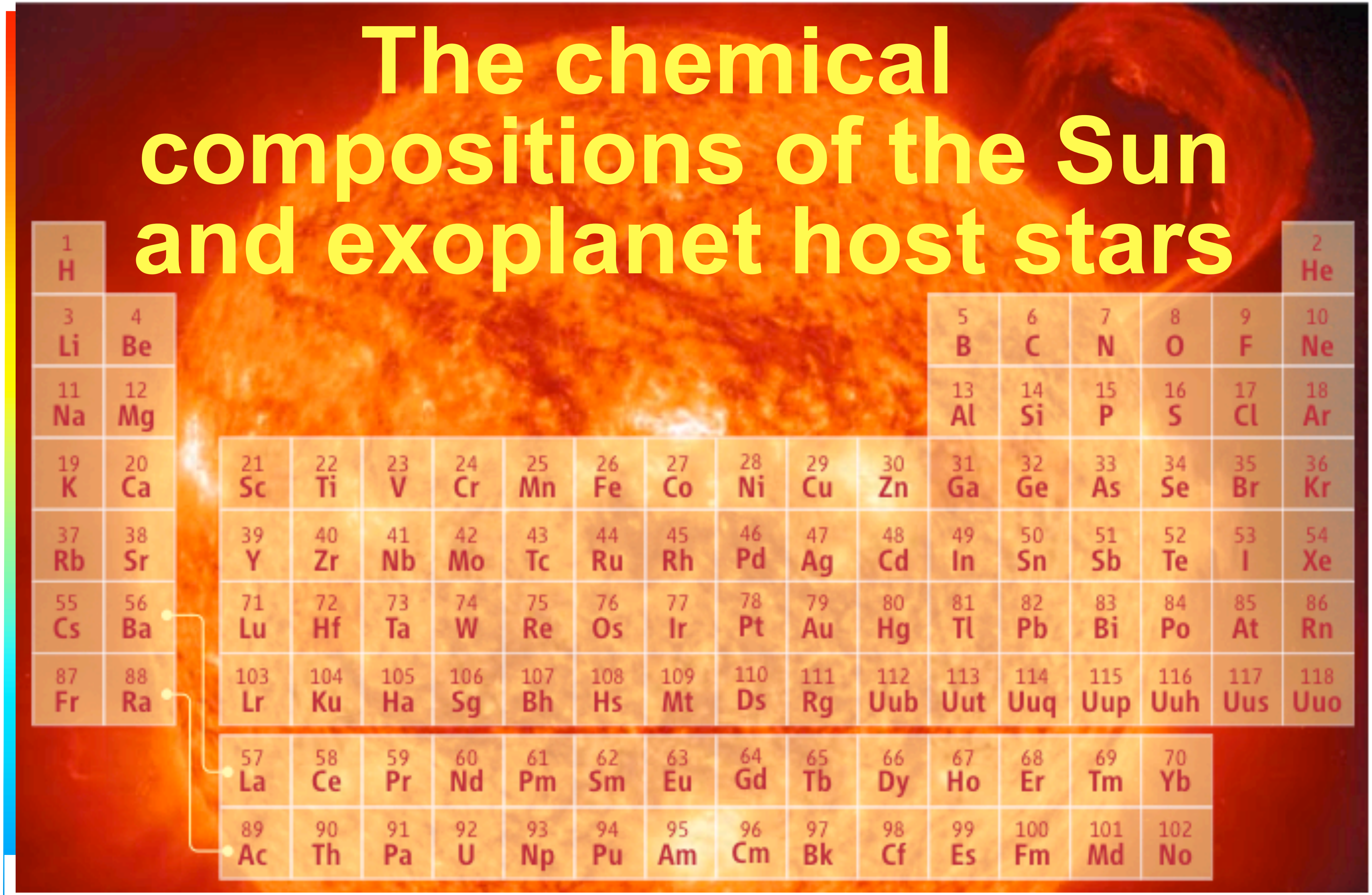
The chemical compositions of the Sun and exoplanet host stars

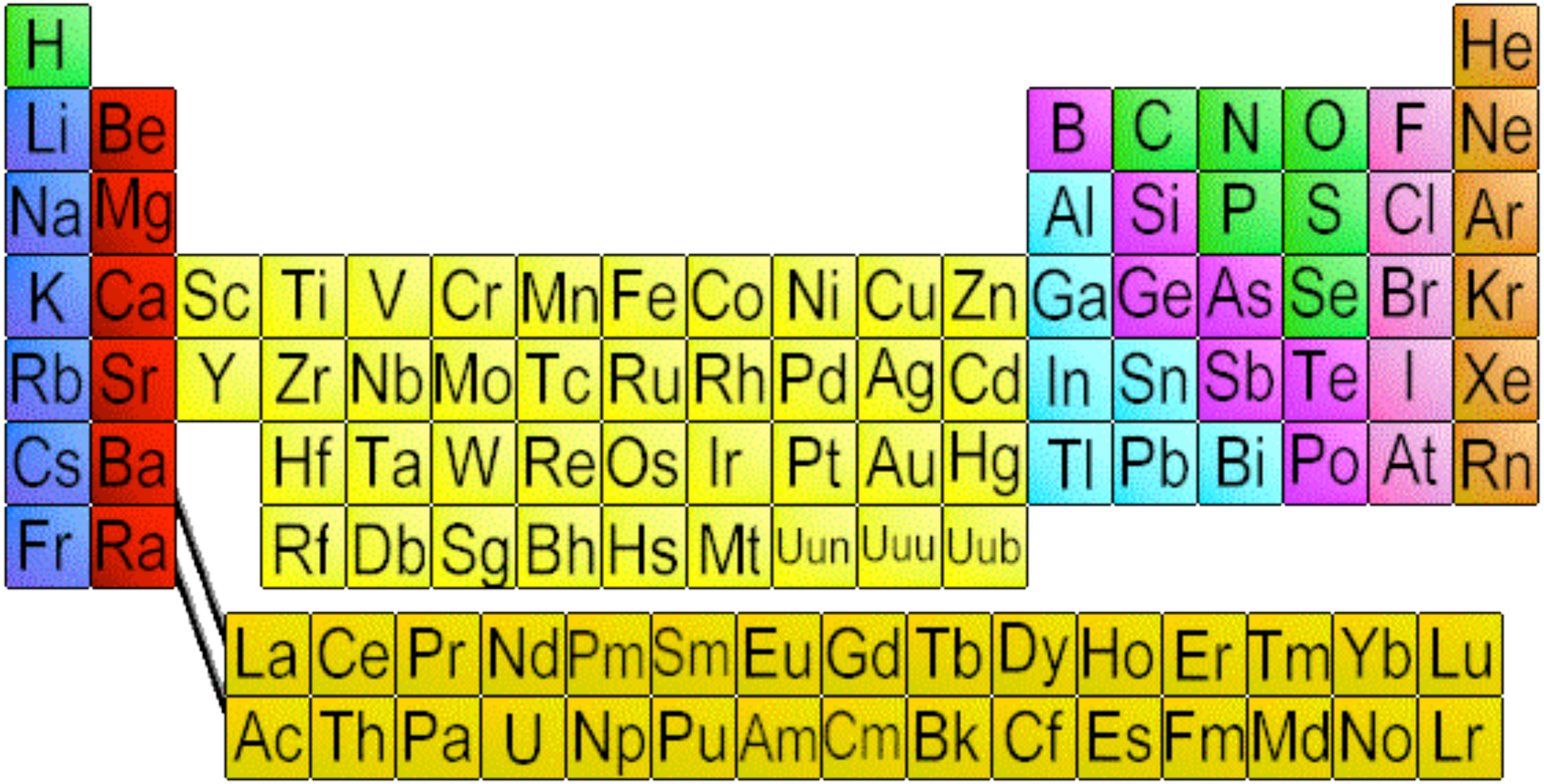


Max Planck Institute
for Astrophysics

Martin Asplund

Origin of the elements

- **When, where and how were the different chemical elements produced in the Universe?**
- **Probing stellar, galactic and cosmic evolution**

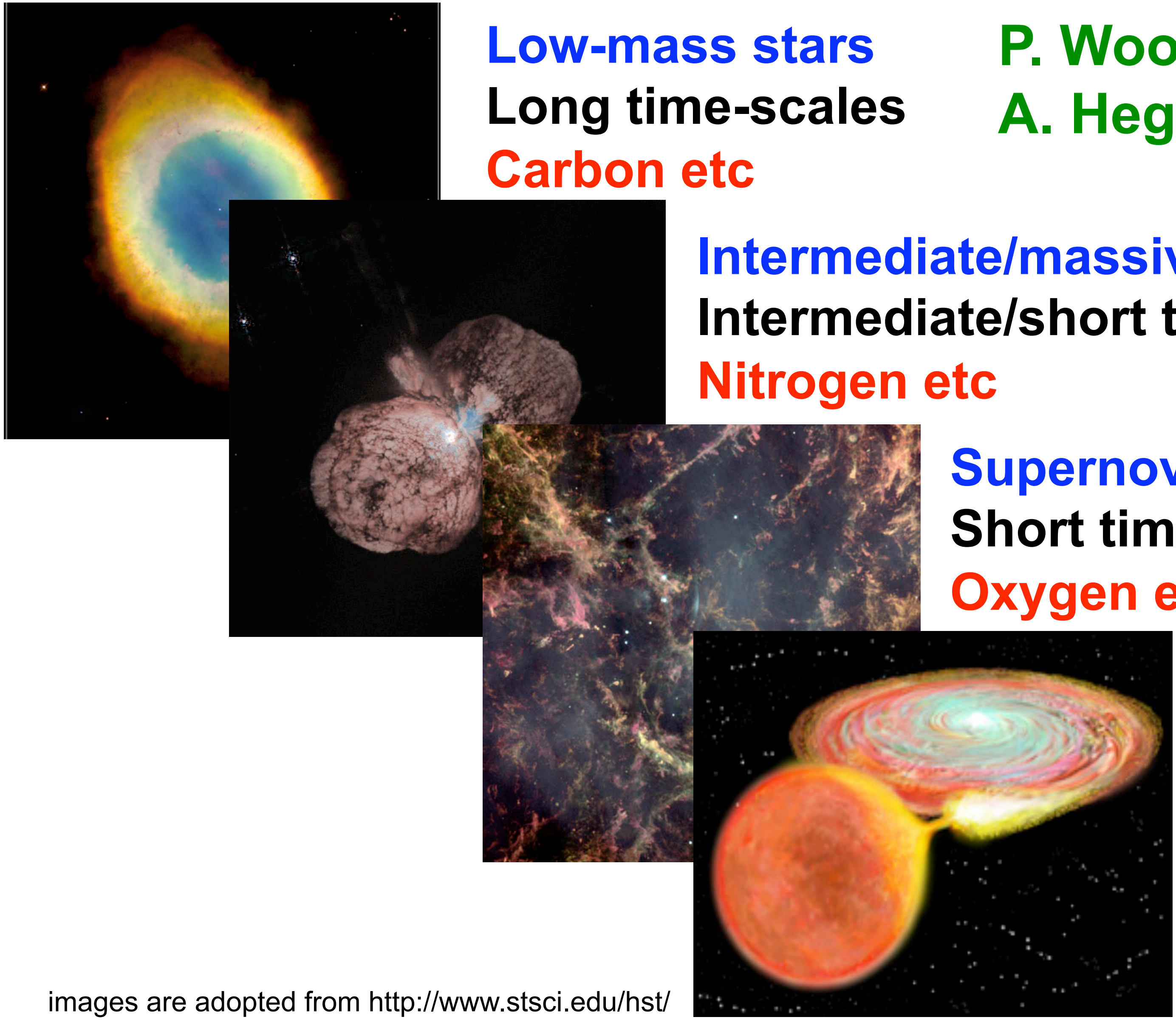


H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Adopted from http://www.coachingindians.com

Stellar production sites

See lectures by
P. Wood, G. Meynet,
A. Heger & S. Wanajo!



Low-mass stars
Long time-scales
Carbon etc

Intermediate/massive stars
Intermediate/short time-scales
Nitrogen etc

Supernovae II
Short time-scales
Oxygen etc

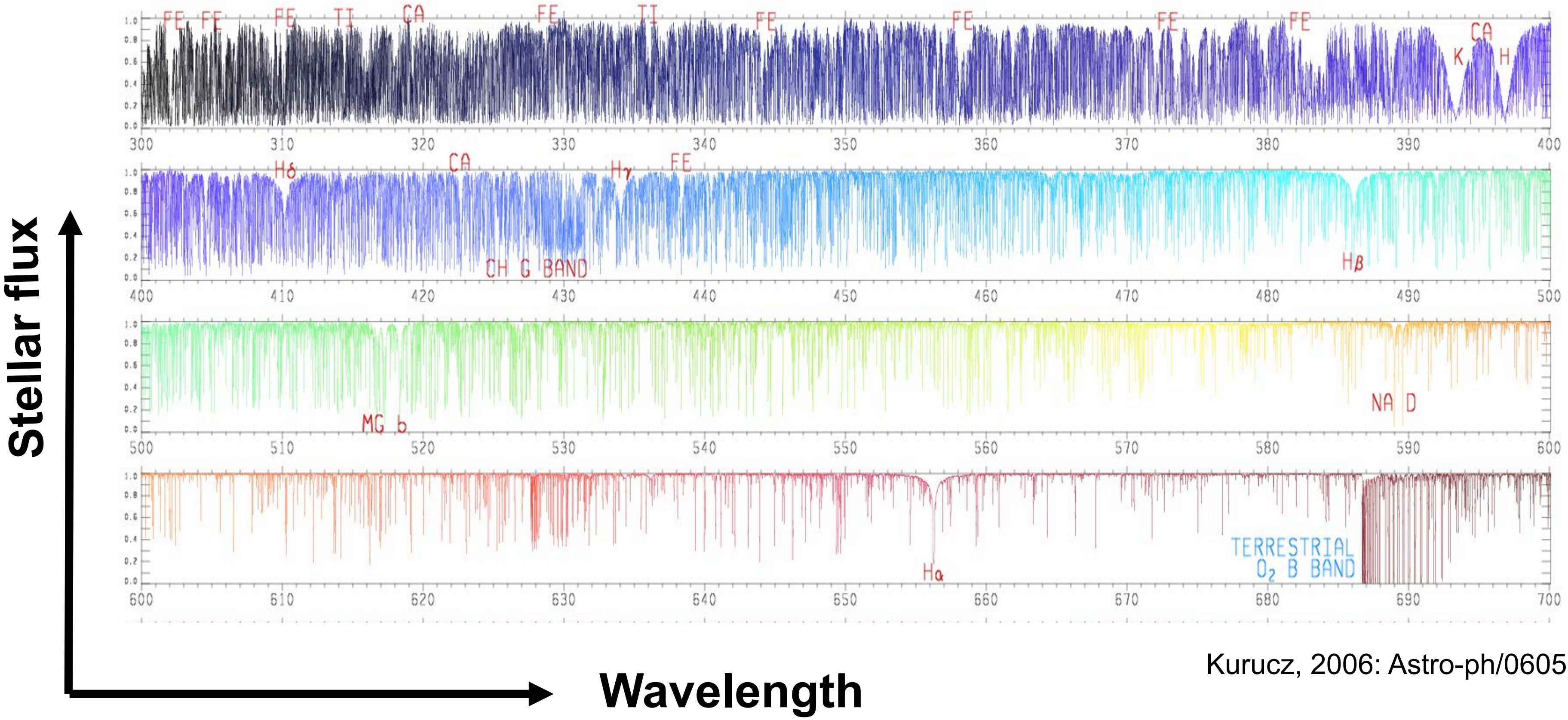
Supernovae Ia
Long time-scale
Iron etc

images are adopted from http://www.stsci.edu/hst/

Elemental fingerprints

The properties of stars are encoded in their light but detailed modeling is required:

- **Stellar atmospheres**
- **Formation of the stellar spectrum**



Kurucz, 2006: Astro-ph/0605029

Outline

Lecture 1: Solar/stellar spectroscopy
- Stellar atmospheres
- Spectral line formation

Lecture 2: Solar chemical composition
- Does the Sun have a subsolar metallicity?
- Solar modeling crisis

Lecture 3: Is the Sun unusual?
- Chemical signatures of (exo)planets?
- Implications for Galactic archaeology

Main partners in crime

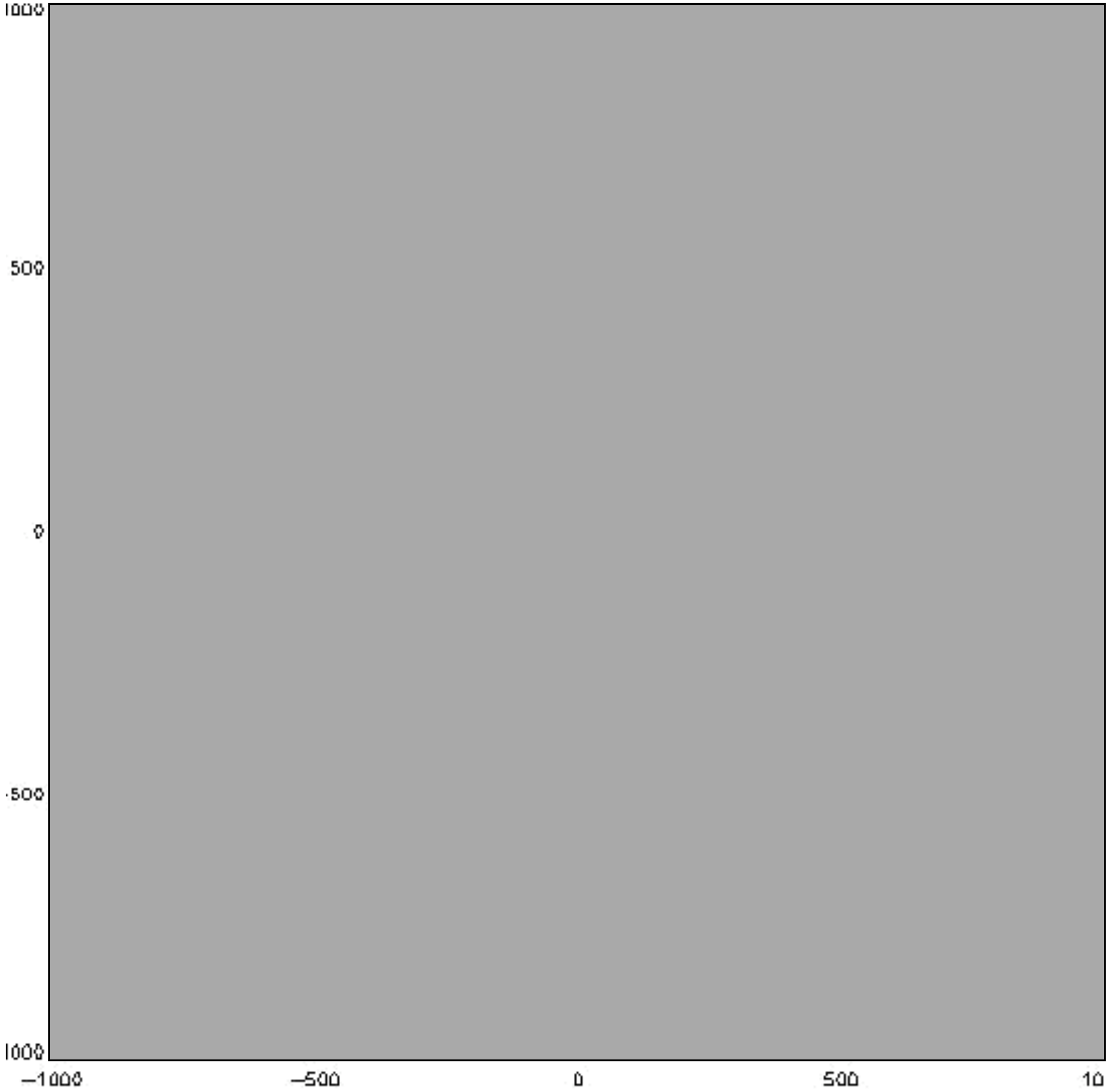
Åke Nordlund

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 atmosphere



Mats Carlsson (Oslo)

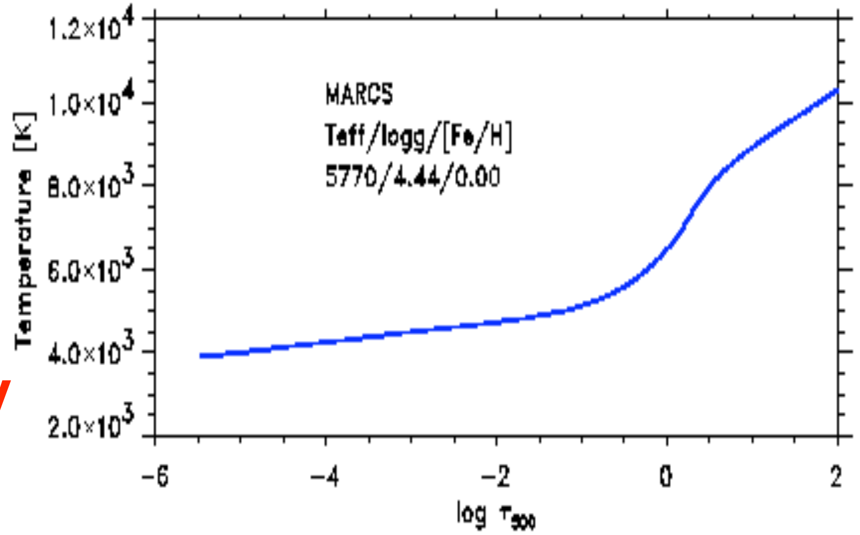
1D solar atmosphere models

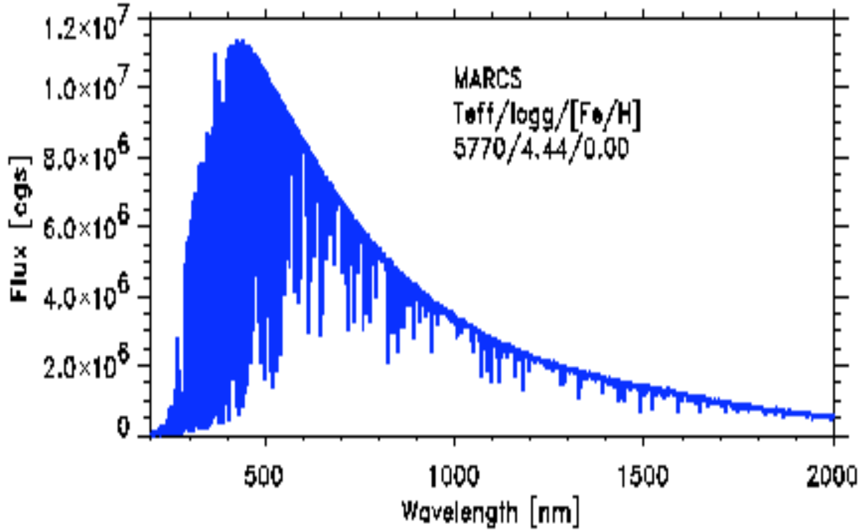
Theoretical models:

- Time-independent
- 1-dimensional
- Hydrostatic
- Convection: mixing length theory
- LTE
- Detailed radiative transfer
- Kurucz, MARCS, Phoenix etc

Semi-empirical models:

- Temperature structure from observations
- Holweger-Mueller (1974)



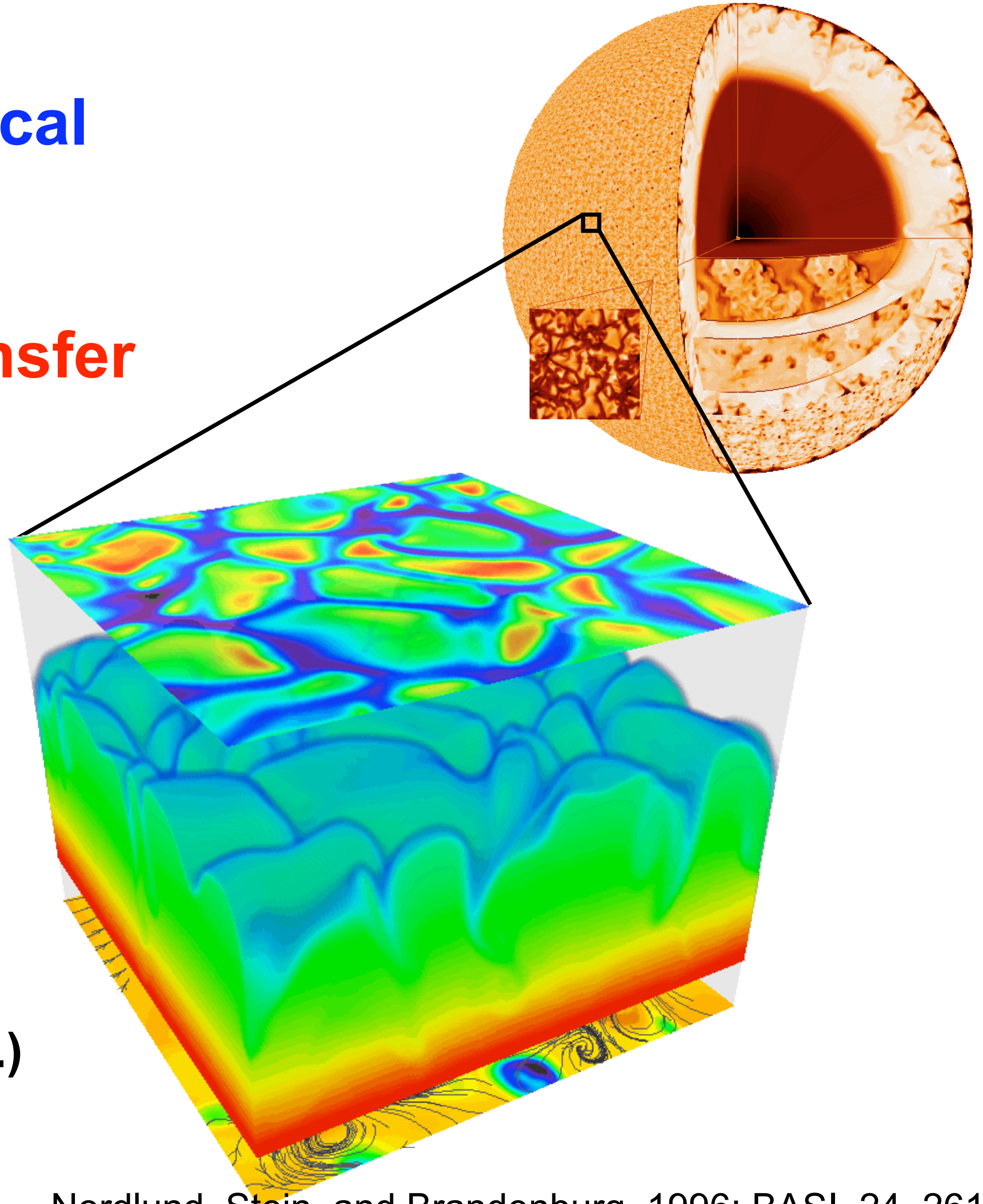


3D solar atmosphere models

Ingredients:

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

Essentially parameter free



Nordlund, Stein, and Brandenburg, 1996: BASI, 24, 261

For the aficionados:

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

Hydrodynamics equations

Conservation of mass:

$$\frac{\partial \ln\rho}{\partial t} = -\bar{\mathbf{v}} \cdot \nabla \ln\rho - \nabla \cdot \bar{\mathbf{v}} \qquad (1)$$

Conservation of momentum:

$$\frac{\partial \bar{\mathbf{v}}}{\partial t} = -\bar{\mathbf{v}} \cdot \nabla \bar{\mathbf{v}} + \bar{\mathbf{g}} - \frac{P}{\rho} \nabla \ln P + \frac{1}{\rho} \nabla \cdot \sigma \qquad (2)$$

Conservation of energy:

$$\frac{\partial e}{\partial t} = -\bar{\mathbf{v}} \cdot \nabla e - \frac{P}{\rho} \nabla \cdot \bar{\mathbf{v}} + Q_{\mathrm{rad}} + Q_{\mathrm{visc}} \qquad (3)$$

Q_{rad} = radiative heating/cooling rate

Q_{rad} obtained from the equation of radiative transfer

Radiative transfer

3D radiative heating/cooling rate:

$$Q_{\mathrm{rad}} = \int_\lambda \int_\Omega \kappa_\lambda (I_\lambda - S_\lambda) \mathrm{d}\Omega \mathrm{d}\lambda \qquad (1)$$

Radiative transfer along a ray:

$$\mathrm{d}I_\lambda / \mathrm{d}\tau_\lambda = I_\lambda - S_\lambda \qquad (2)$$

LTE $\Rightarrow S_\lambda = B_\lambda$ (no scattering)

Opacity binning (Nordlund 1982):

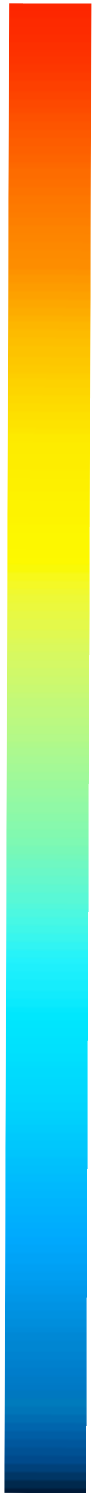
$$\int_\lambda \kappa_\lambda (J_\lambda - B_\lambda) \simeq \sum_i \sum_{j(i)} w_{\lambda_j} \kappa_{\lambda_j} \left(J_{\lambda_j} - B_{\lambda_j} \right)$$

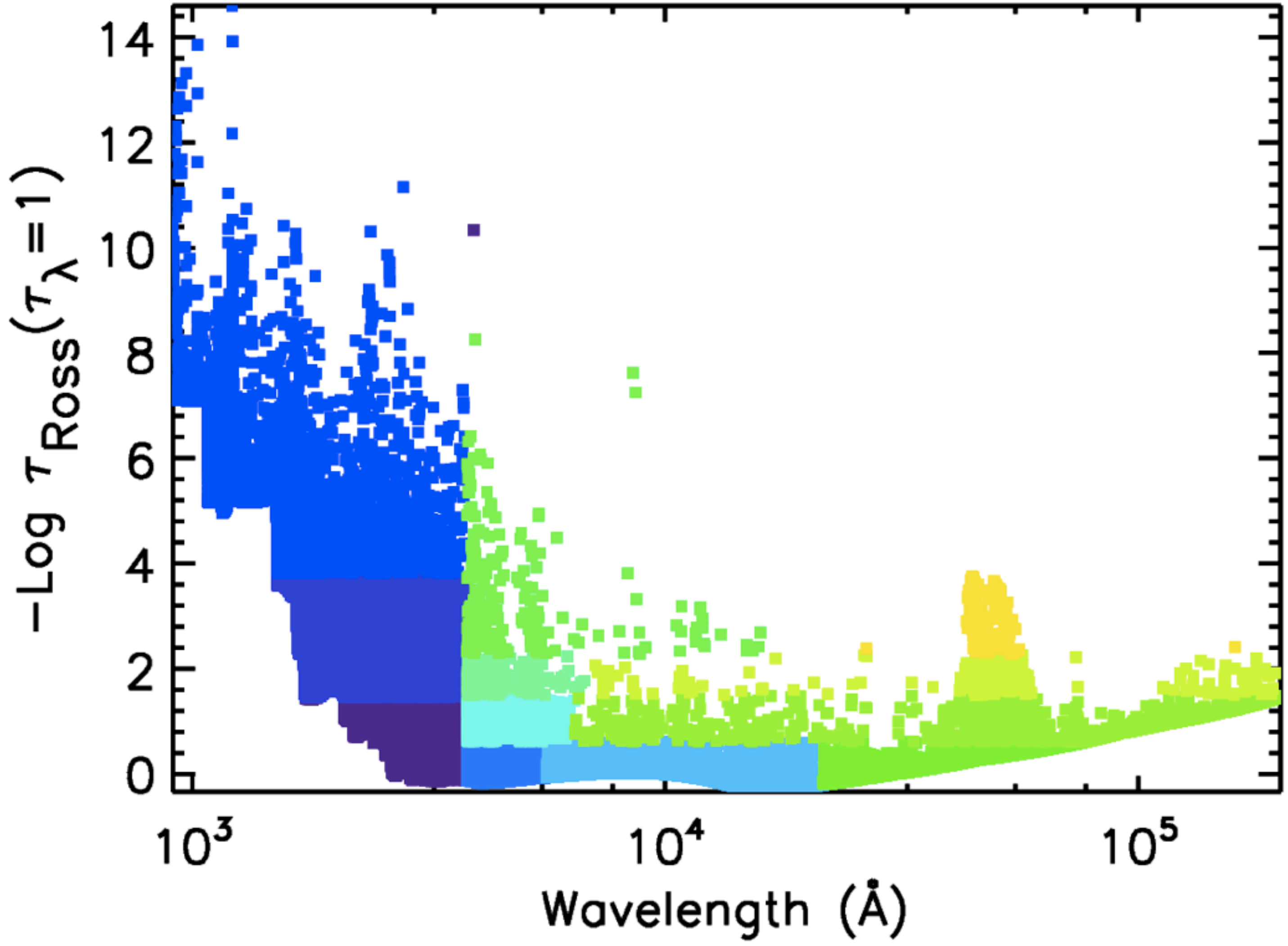
$$\simeq \sum_i w_i \kappa_i (J_i - B_i) \qquad (3)$$

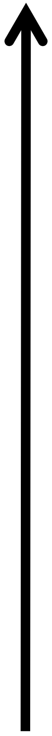
Bins: continuum, weak+intermediate+strong lines

Opacity binning

Group wavelengths together that have similar opacities and wavelengths

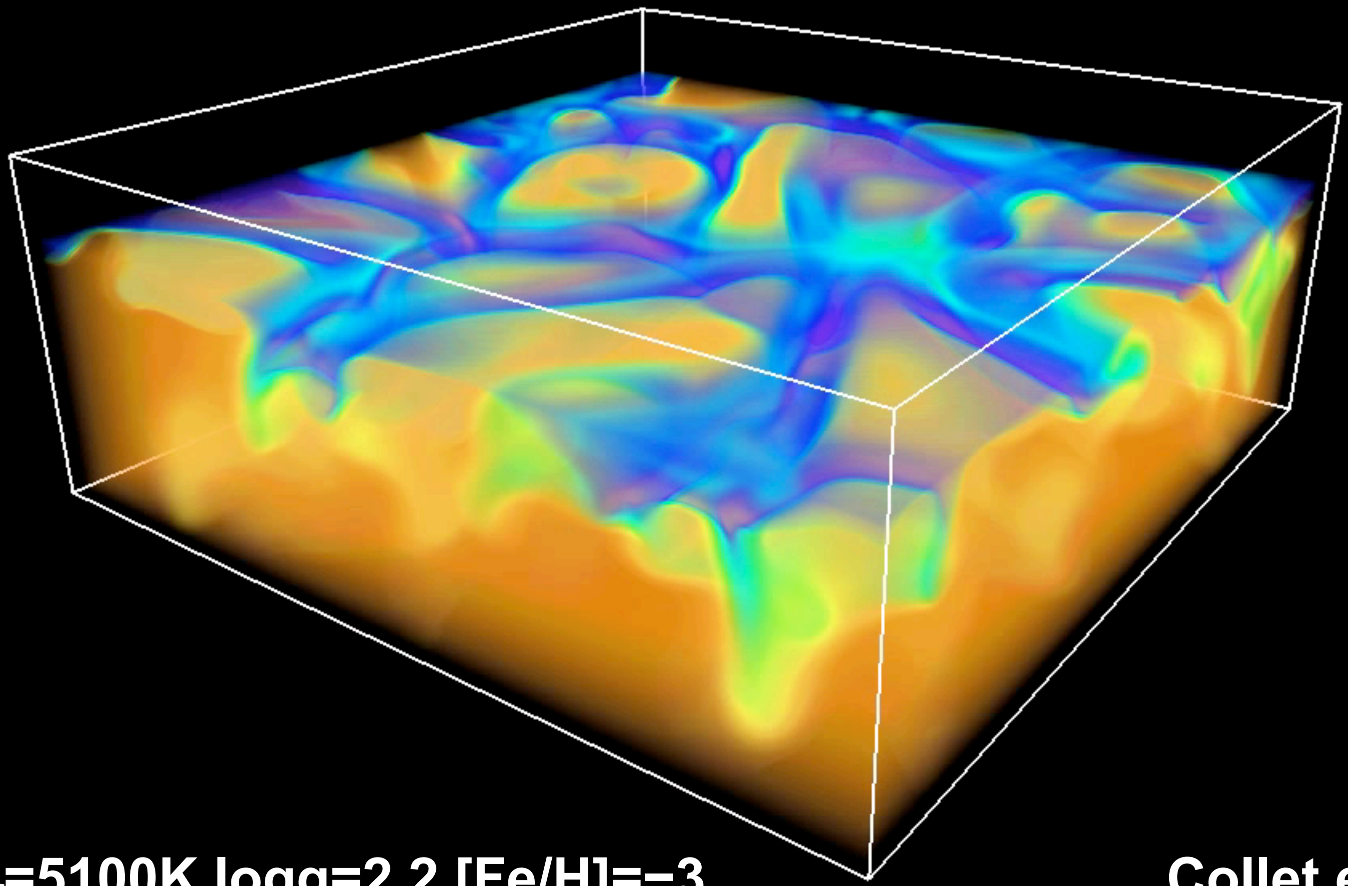





Opacity

3D atmosphere simulation

Temporal evolution of entropy in atmosphere of metal-poor red giant



T_{eff}=5100K logg=2.2 [Fe/H]=−3

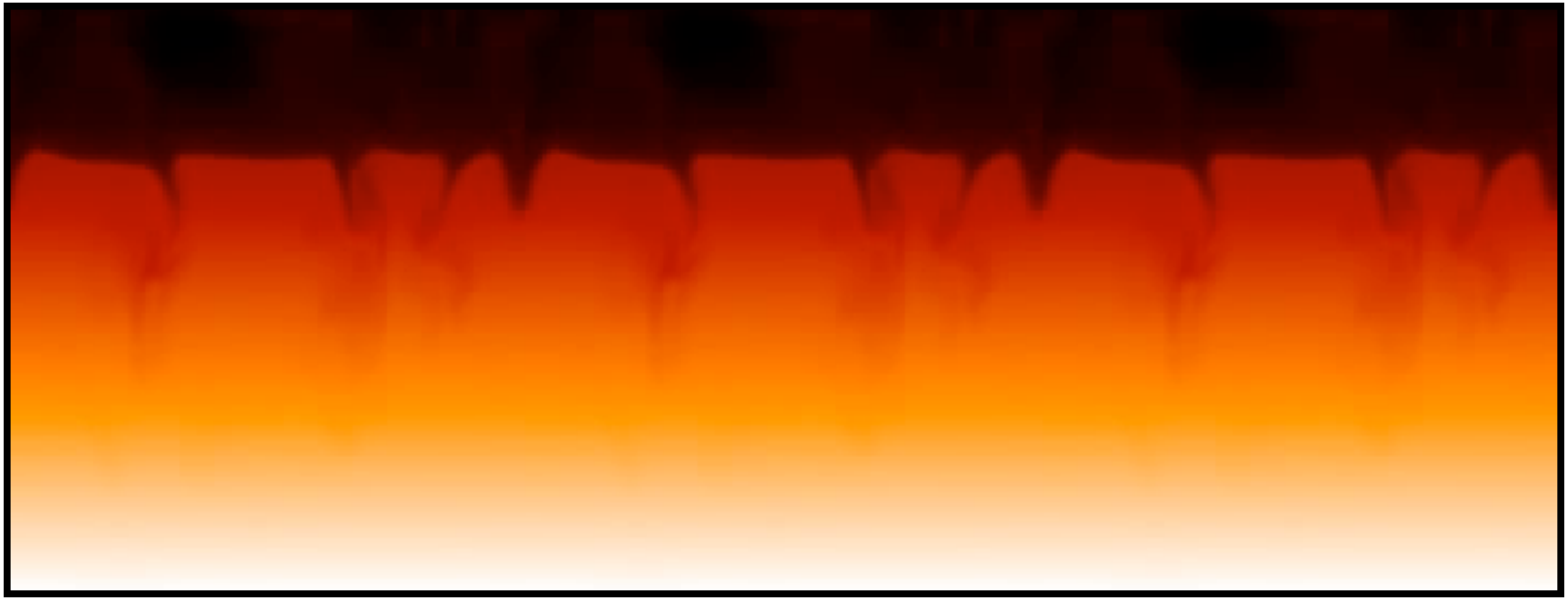
Collet et al.

Driving mechanism

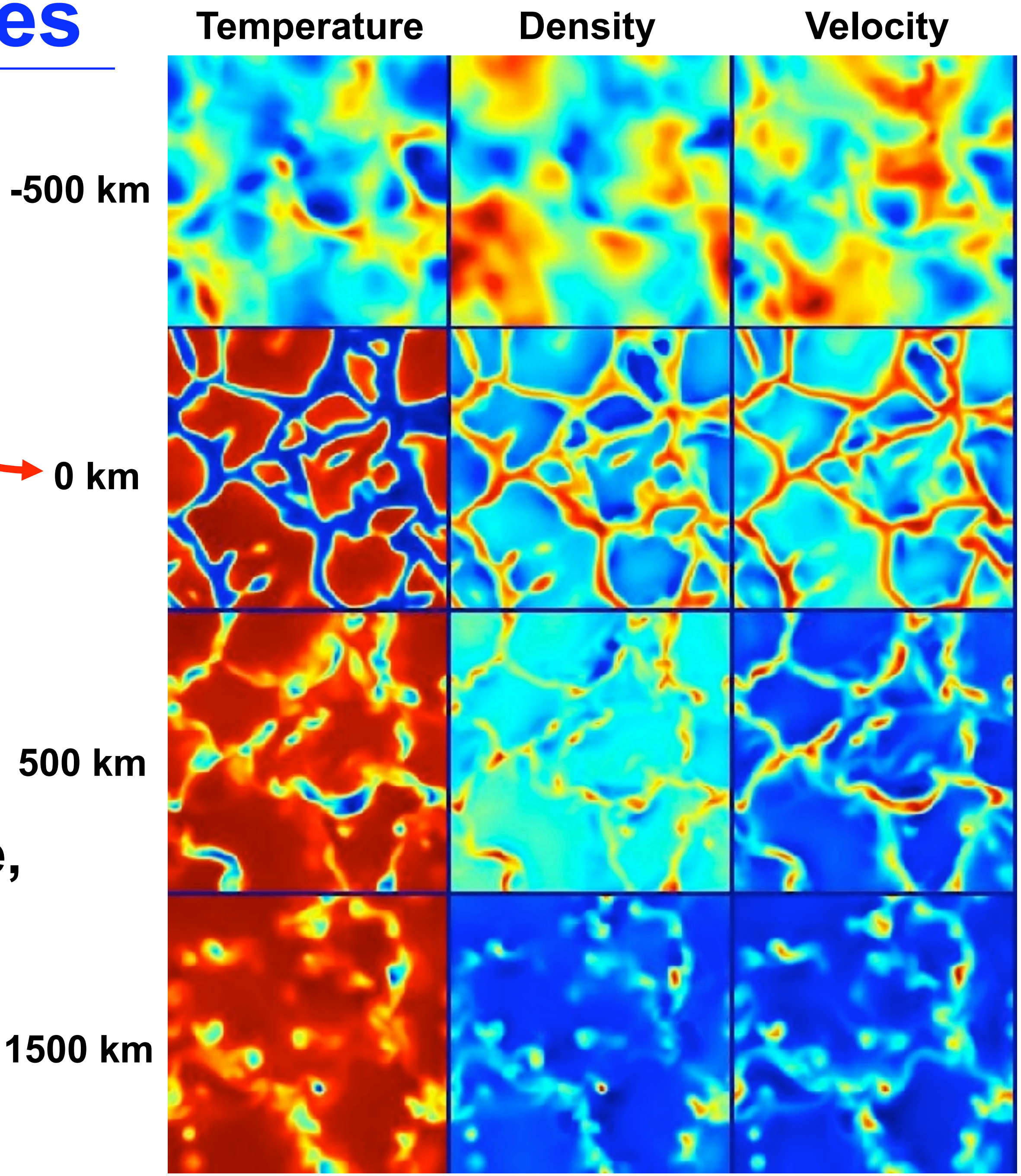
- **Ascending warm gas cools by radiation at the surface**

  Cooling ⇒ photons escape more easily ⇒ more cooling
- **Cool, entropy-deficient gas pulled down amidst...**
- **... warm, isentropic gas**

→ **Convection driven by radiative cooling at surface!**



Horizontal slices

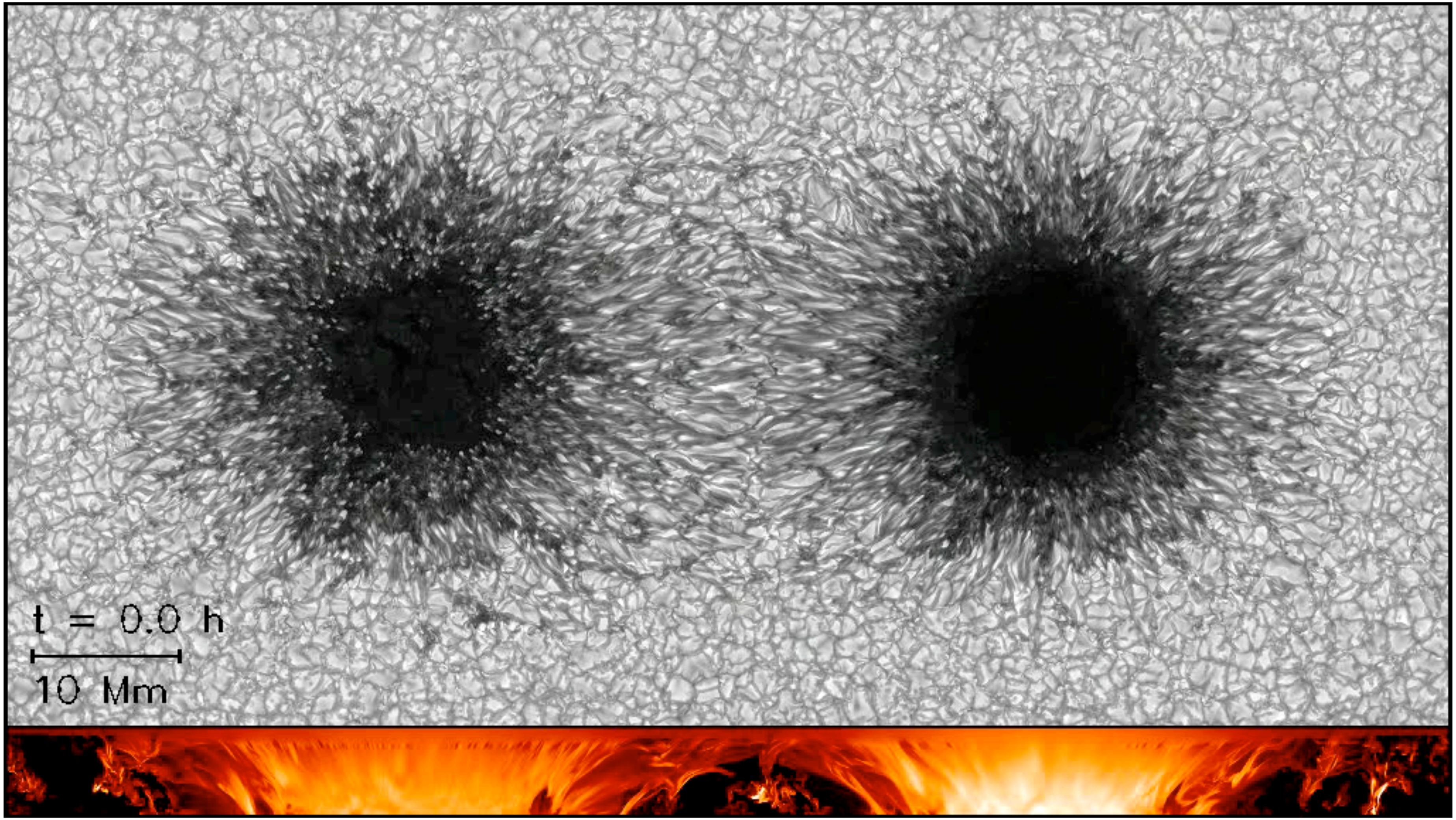


Solar “surface”

(Anti-)correlations between temperature, density and vertical velocity

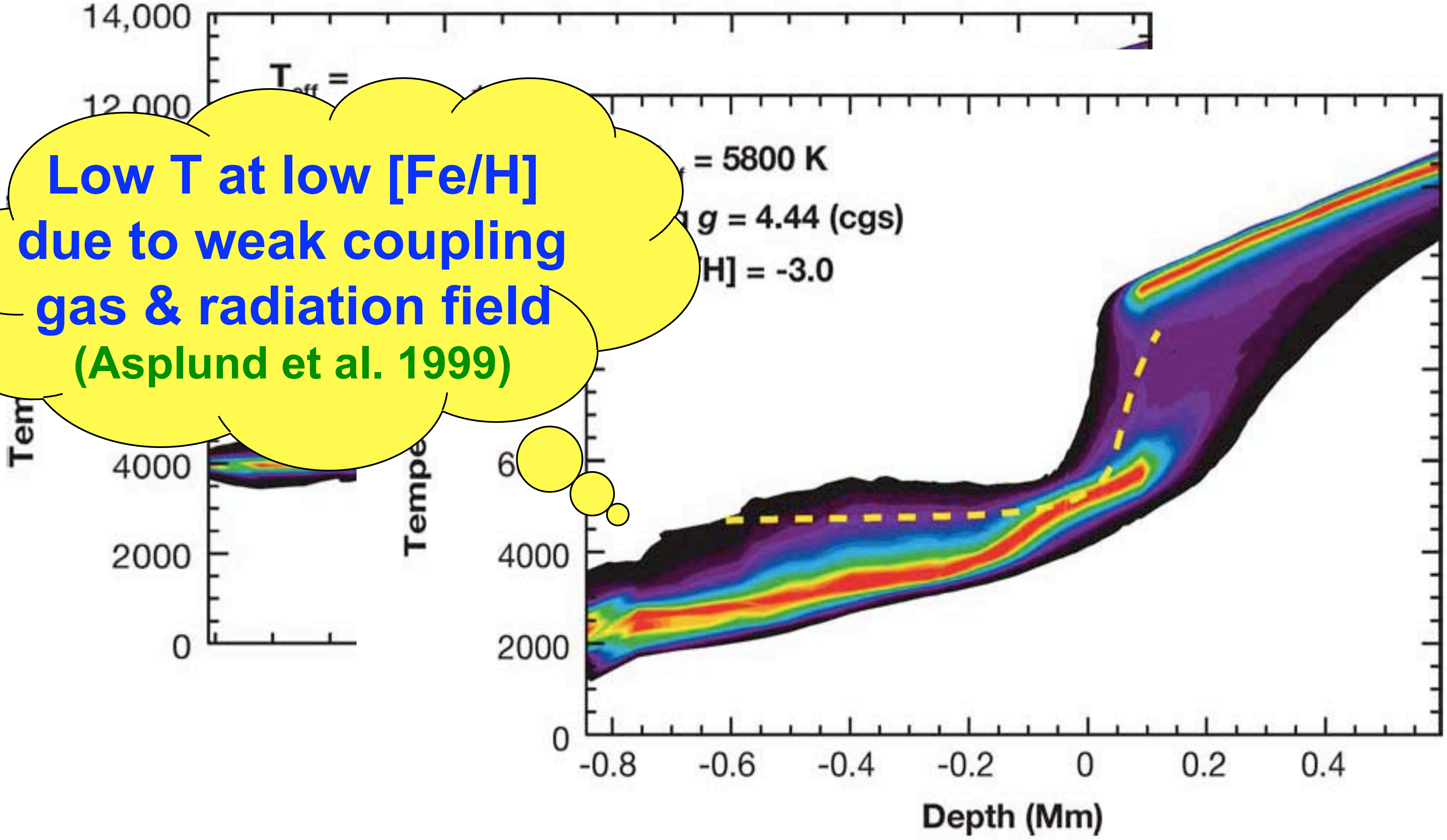
Magneto-convection

Full 3D radiative magneto-hydrodynamics simulations of sunspots (Rempel et al. 2009)



Temperature structure

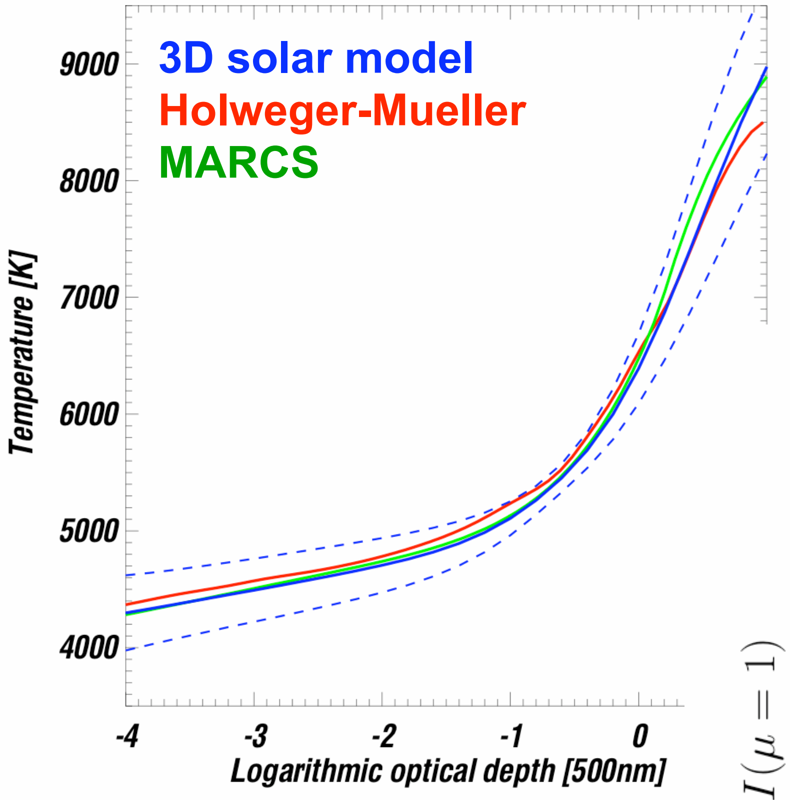
- Very steep temperature structure in upflows
- Significant temperature inhomogeneities



Low T at low [Fe/H] due to weak coupling gas & radiation field

(Asplund et al. 1999)

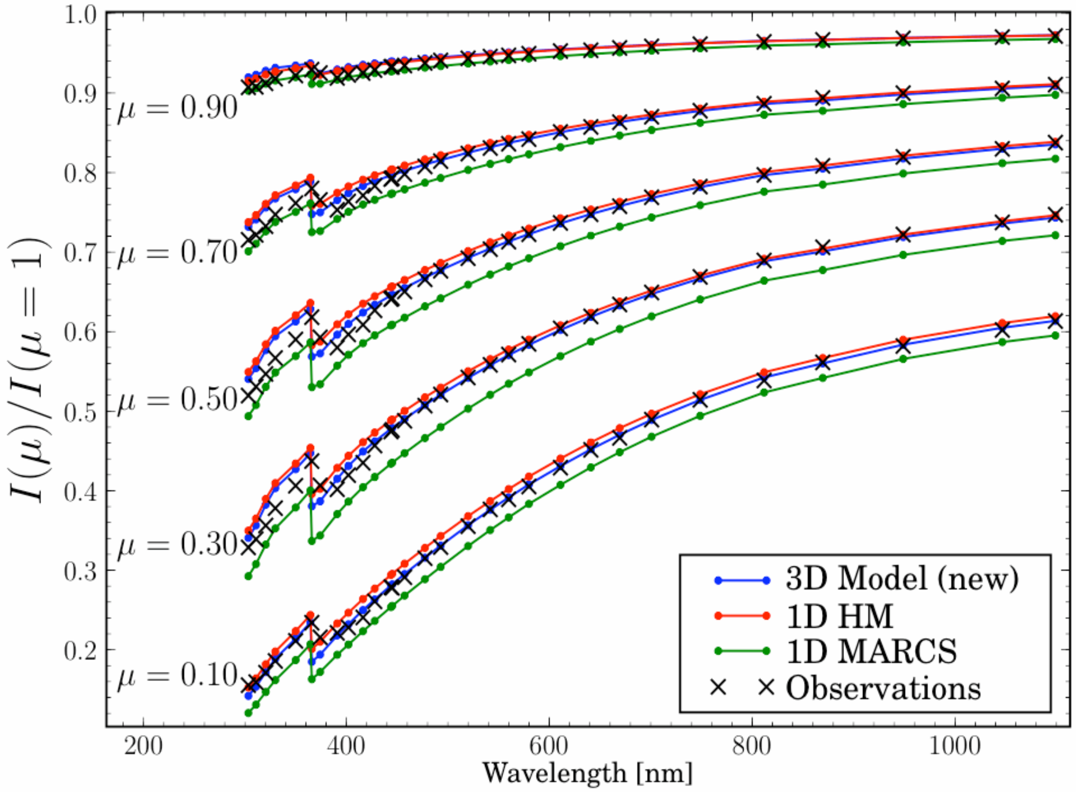
Temperature structure



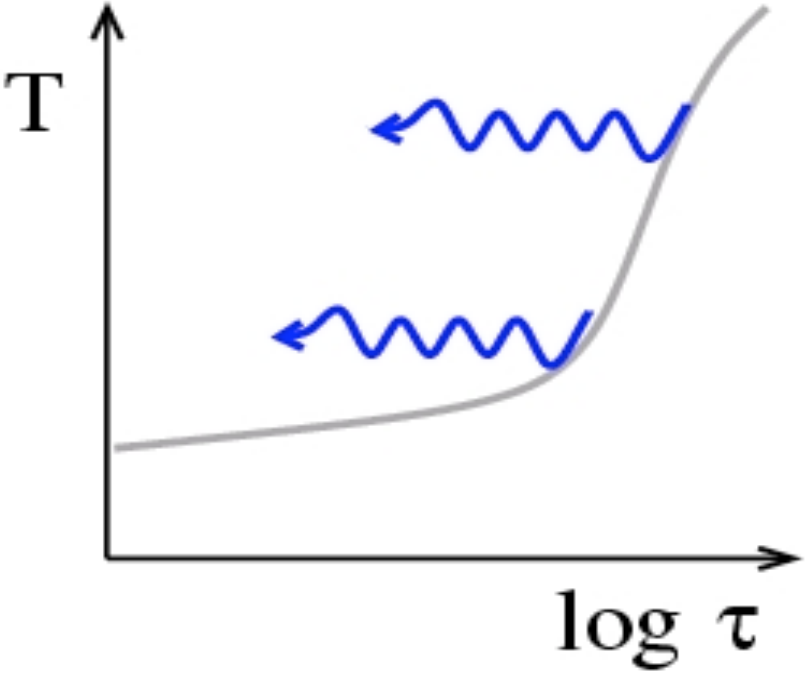
Asplund et al., 2009, ARAA, 47, 481

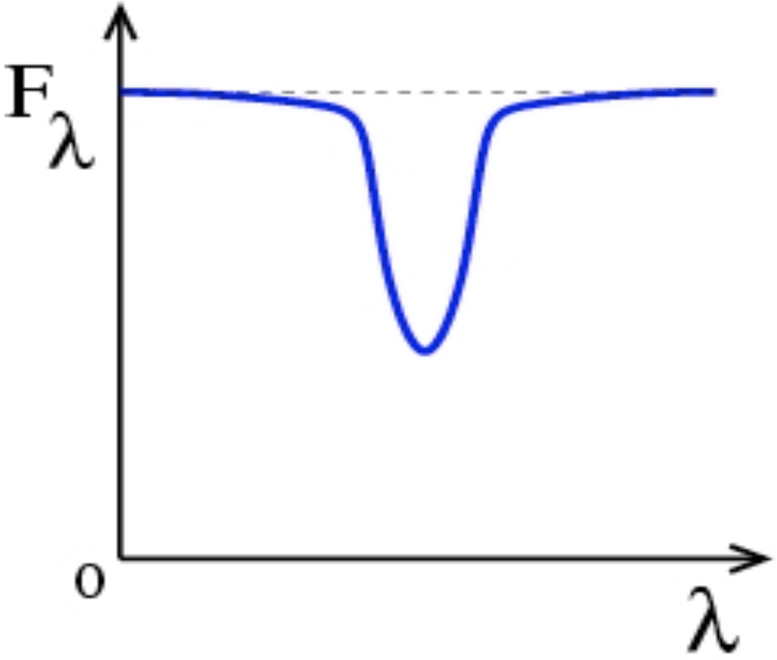
Atmospheric temperature structure is critical

Our 3D model performs remarkably well



Spectral line formation

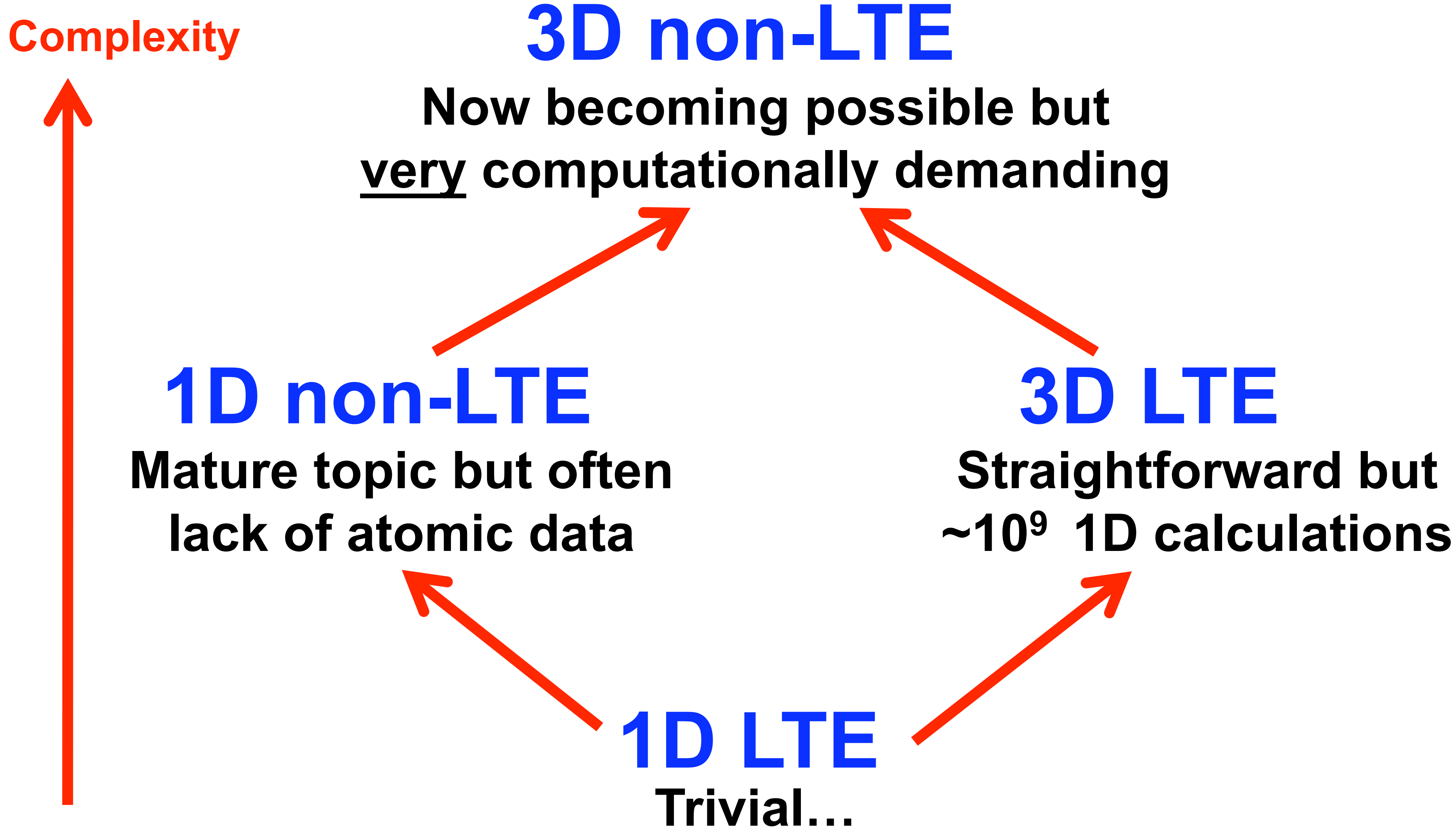




$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = S_\nu - I_\nu$$

$$S^l_\nu = \frac{j^\mathrm{a}_\nu + j^\mathrm{s}_\nu}{\alpha^\mathrm{a}_\nu + \alpha^\mathrm{s}_\nu} = (1 - \varepsilon_\nu)\, J_\nu + \varepsilon_\nu B_\nu.$$

Radiative transfer



Complexity

3D non-LTE

Now becoming possible but
<u>very</u> computationally demanding

1D non-LTE

Mature topic but often
lack of atomic data

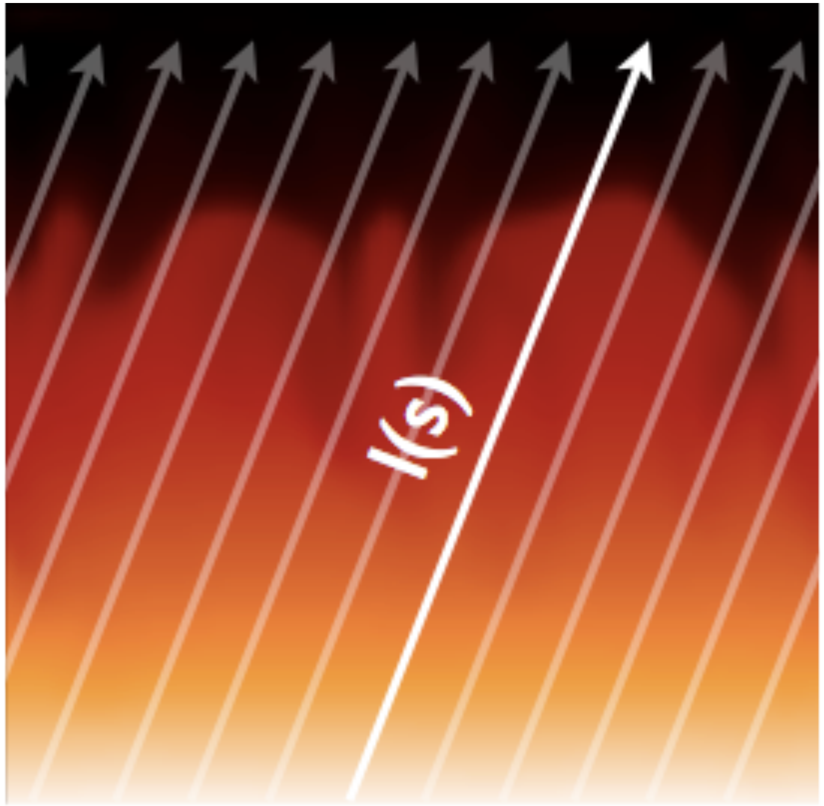
3D LTE

Straightforward but
$\sim 10^9$ 1D calculations

1D LTE

Trivial…

3D LTE radiative transfer



Radiative transfer:

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

~~**Non-LTE:**~~

~~$$S^l_\nu = (1-\varepsilon_\nu)\,J_\nu + \varepsilon_\nu B_\nu$$~~

LTE:

$$S^l_\nu(\vec{r}) = B_\nu\left[T(\vec{r})\right]$$

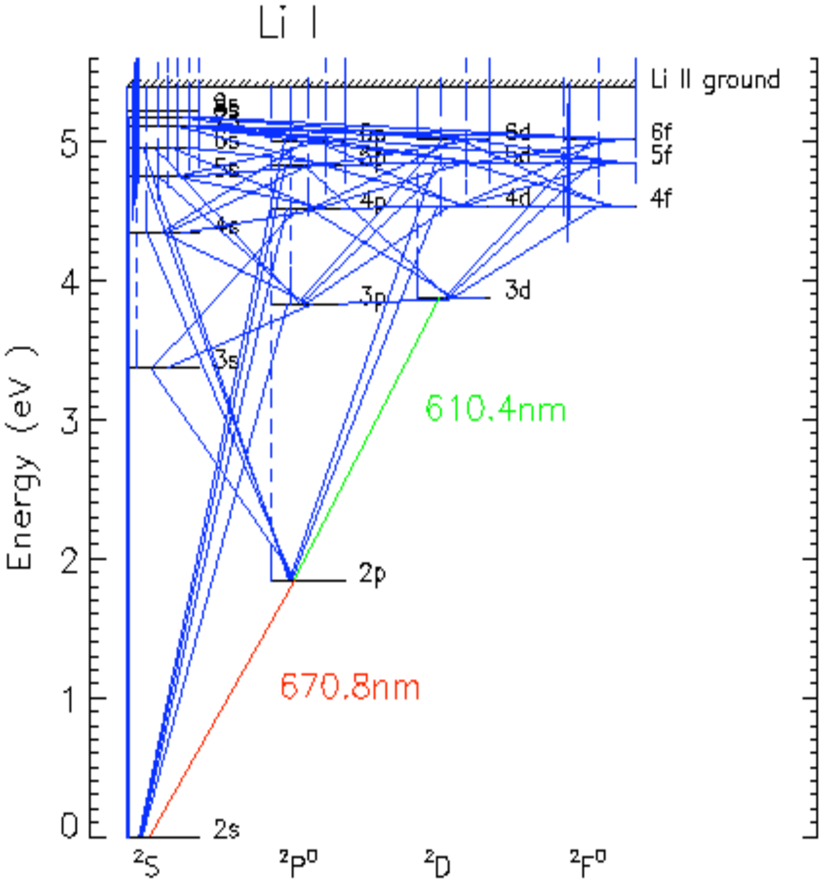
3D LTE: $N_x * N_y * N_{\text{frequency}} * N_{\text{angle}} * N_{\text{time}} \sim 10^9$ 1D radiative transfer solutions

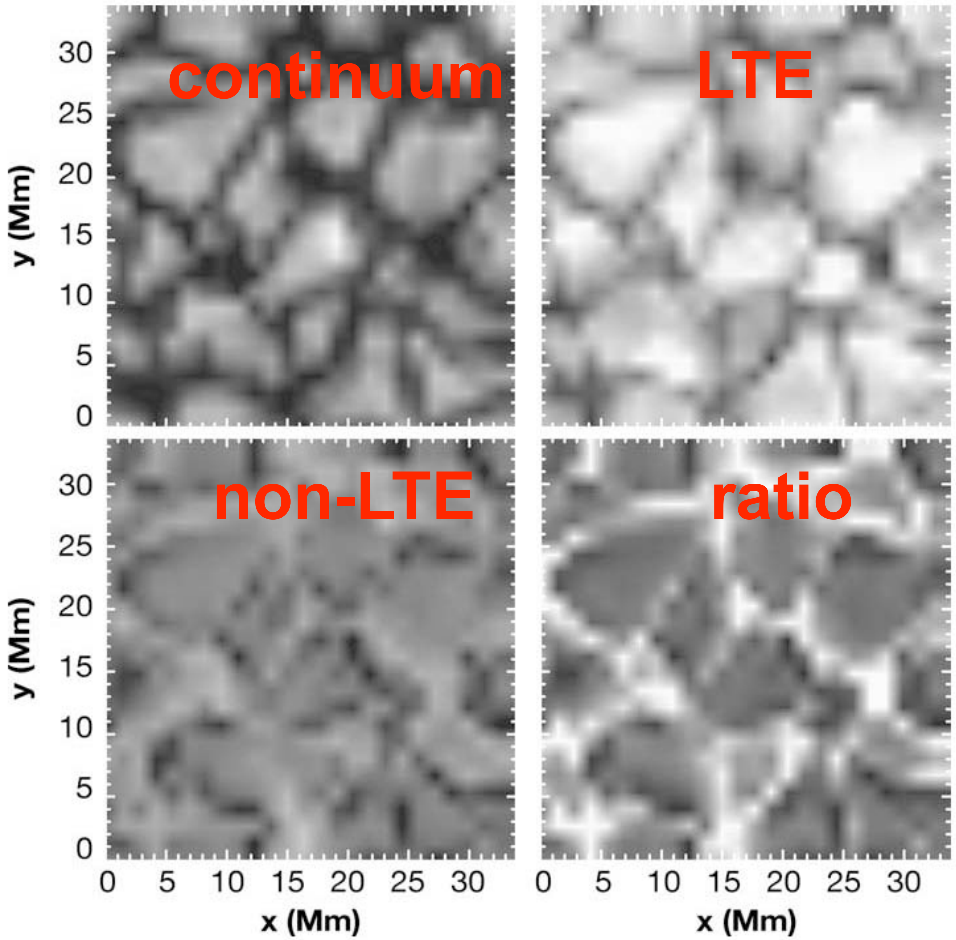
3D non-LTE radiative transfer

Non-LTE: solve RT for all transitions (>100) and iterate (>10x) to get level populations…

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = \sum_{j\neq i}^{N} n_j P_{ji} - n_i \sum_{j\neq i}^{N} P_{ij} = 0$$

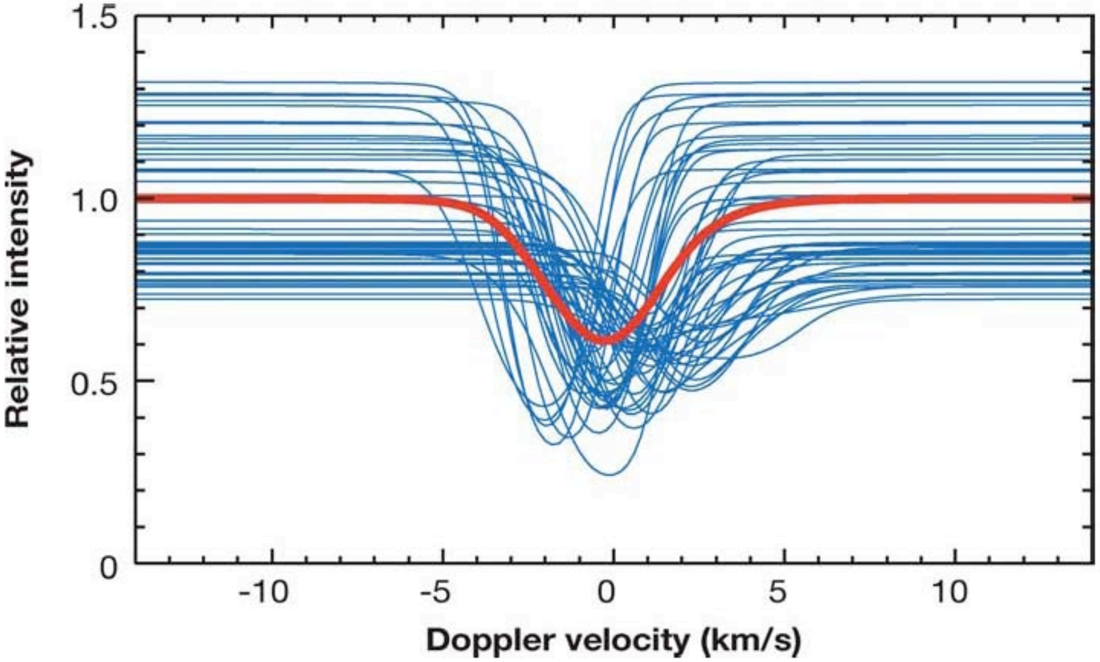
$$P_{ij} = A_{ij} + B_{ij}\bar{J}_{\nu_0} + C_{ij}.$$





Asplund et al. (2003)

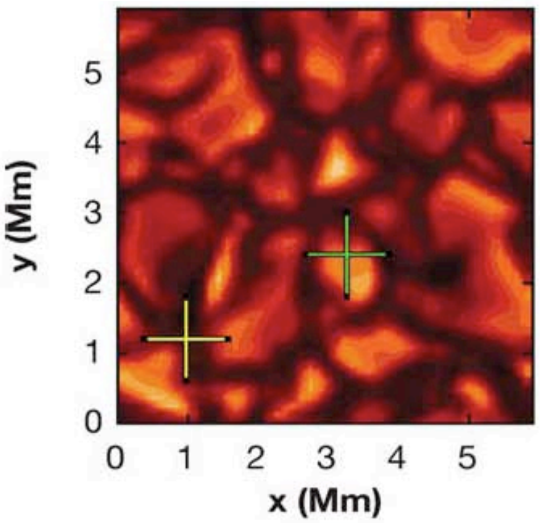
Spatially resolved lines

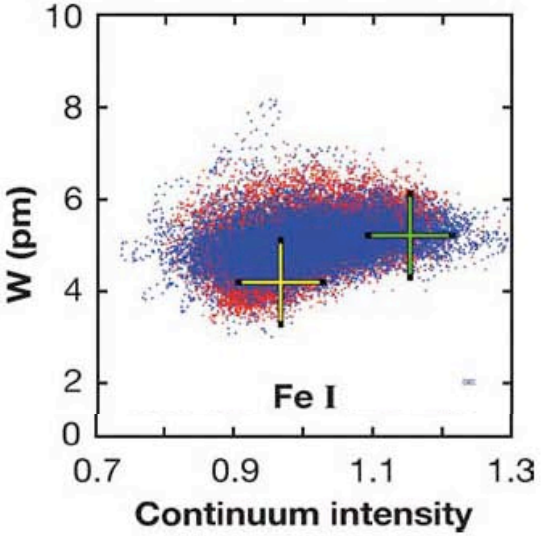


Line profiles vary tremendously across the solar surface

Asplund et al., 2009, ARAA, 43, 481

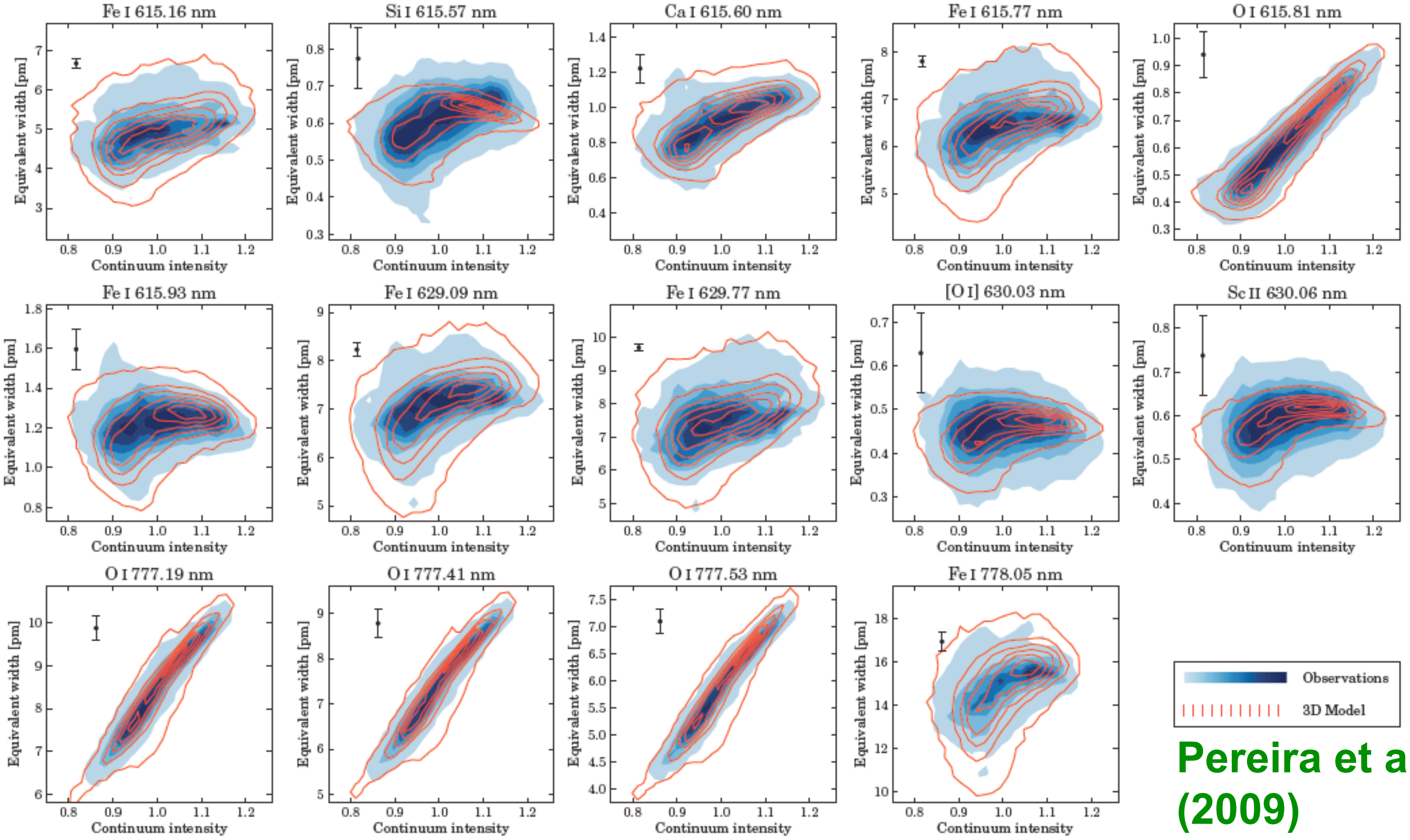
3D model describes observations very well in most cases





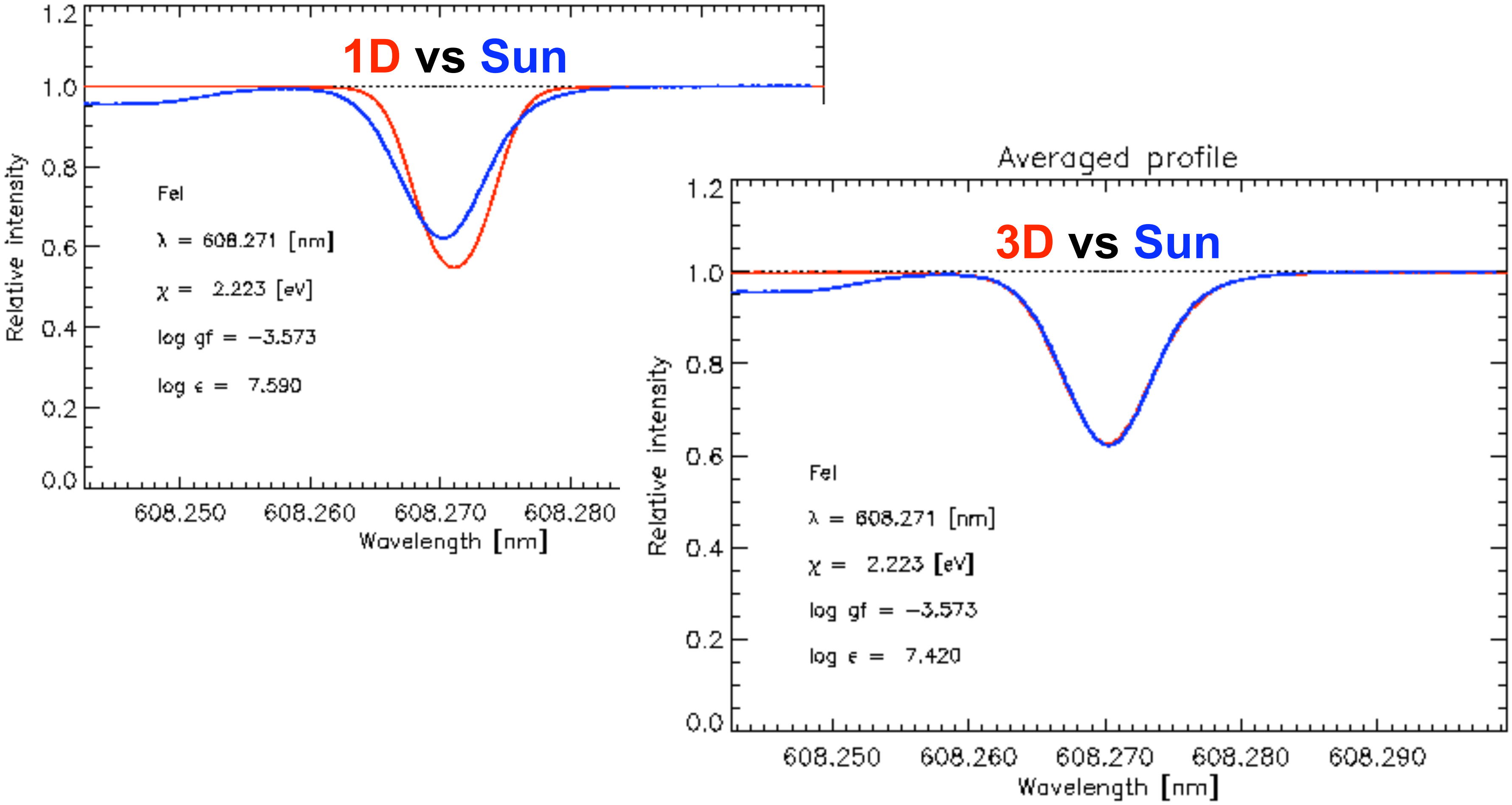
More spatially resolved lines

Different behaviour due to varying sensitivity to temperature, pressure, velocity and height of formation



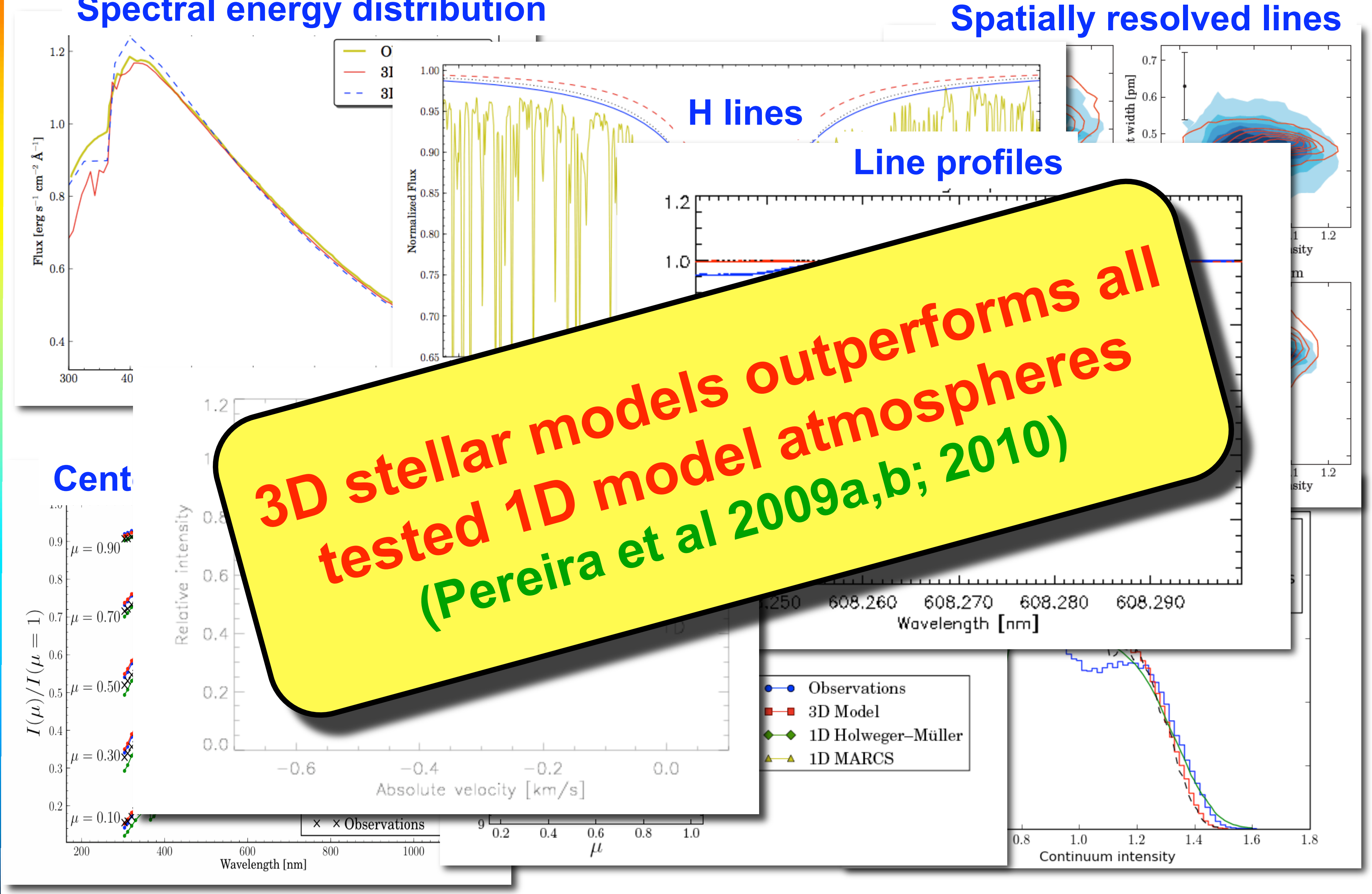
Pereira et al. (2009)

Averaged line profiles



No free parameters (micro-/macroturbulence, mixing lengths) needed in 3D analysis!

More observational tests



Spectral energy distribution

Spatially resolved lines

H lines

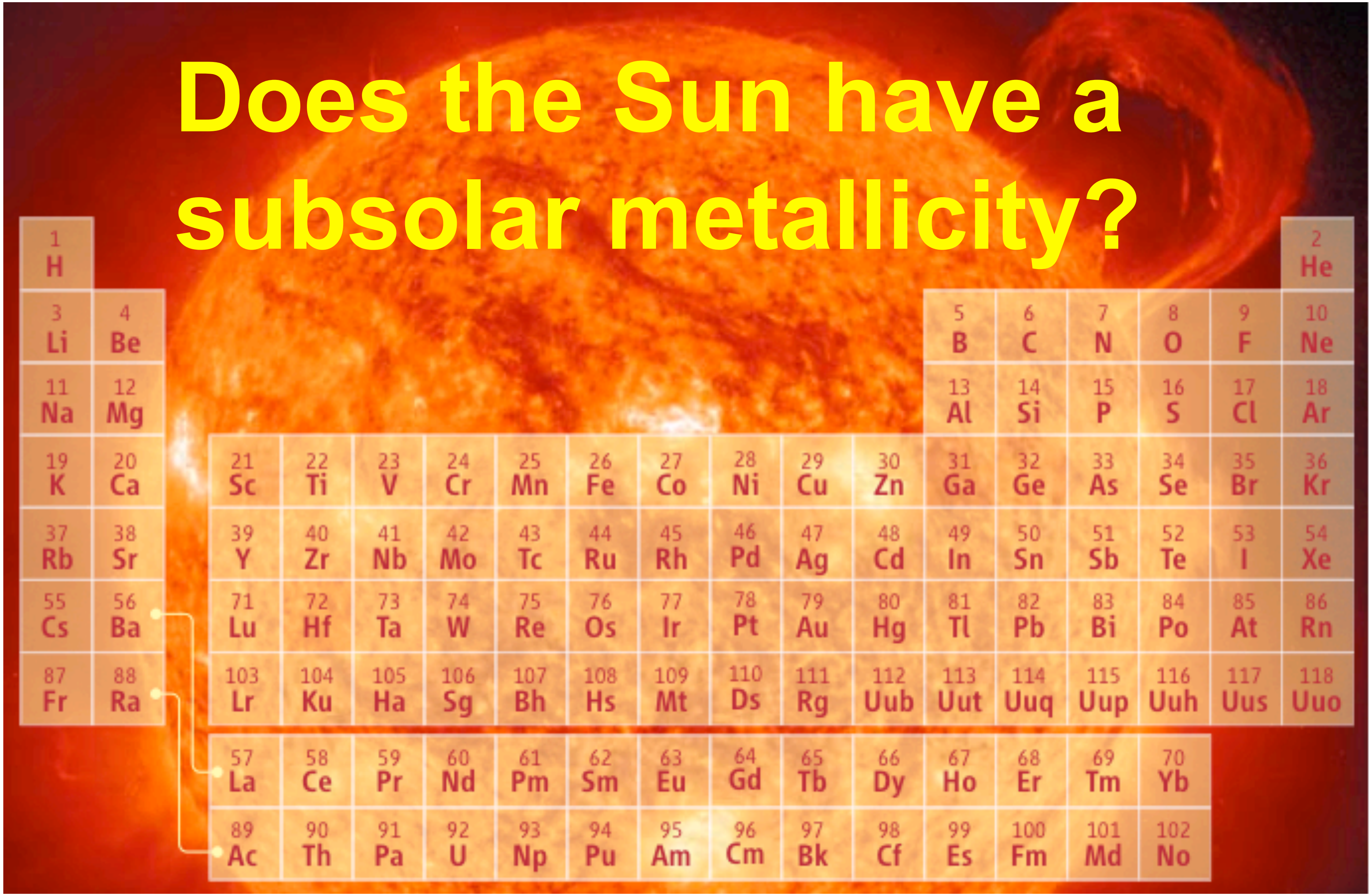
Line profiles

Cent

3D stellar models outperforms all tested 1D model atmospheres

(Pereira et al 2009a,b; 2010)

Lecture 2: Solar abundances



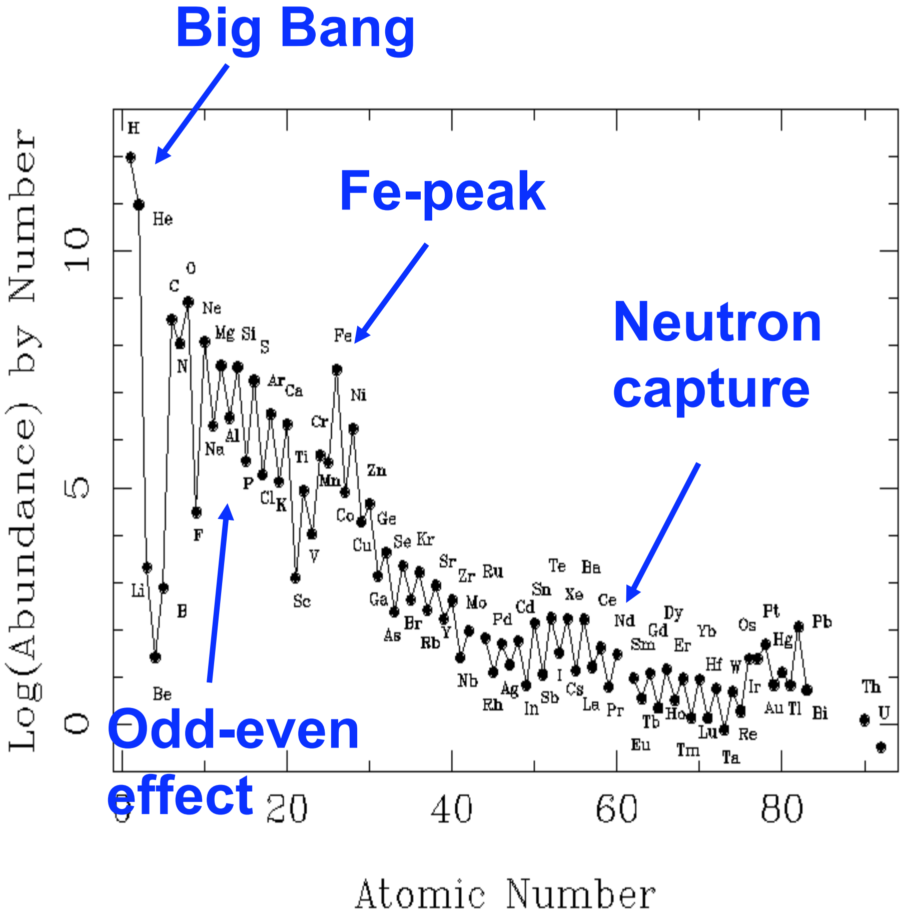
Does the Sun have a subsolar metallicity?

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)



Big Bang

Fe-peak

Neutron capture

Odd-even effect

Solar system abundances

Meteorites

Mass spectroscopy

Very high accuracy

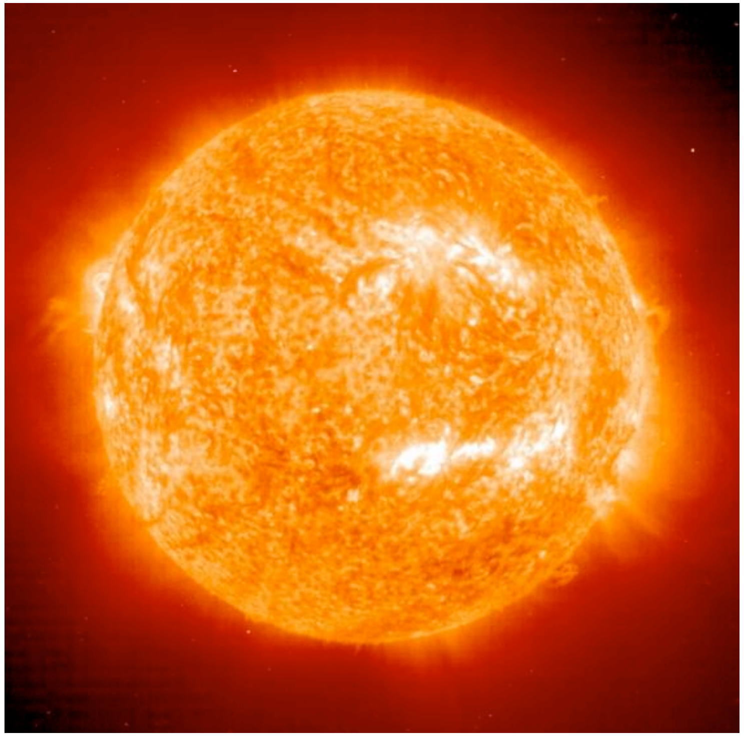
Element depletion

Solar atmosphere

Solar spectroscopy

Modelling-dependent

Very little depletion



Adopted from http://sohowww.nascom.nasa.gov/

Solar abundances revisited

- Asplund, Grevesse, Sauval, Scott, 2009, ARAA, 47, 481 + series of A&A papers
- 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=8.69±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

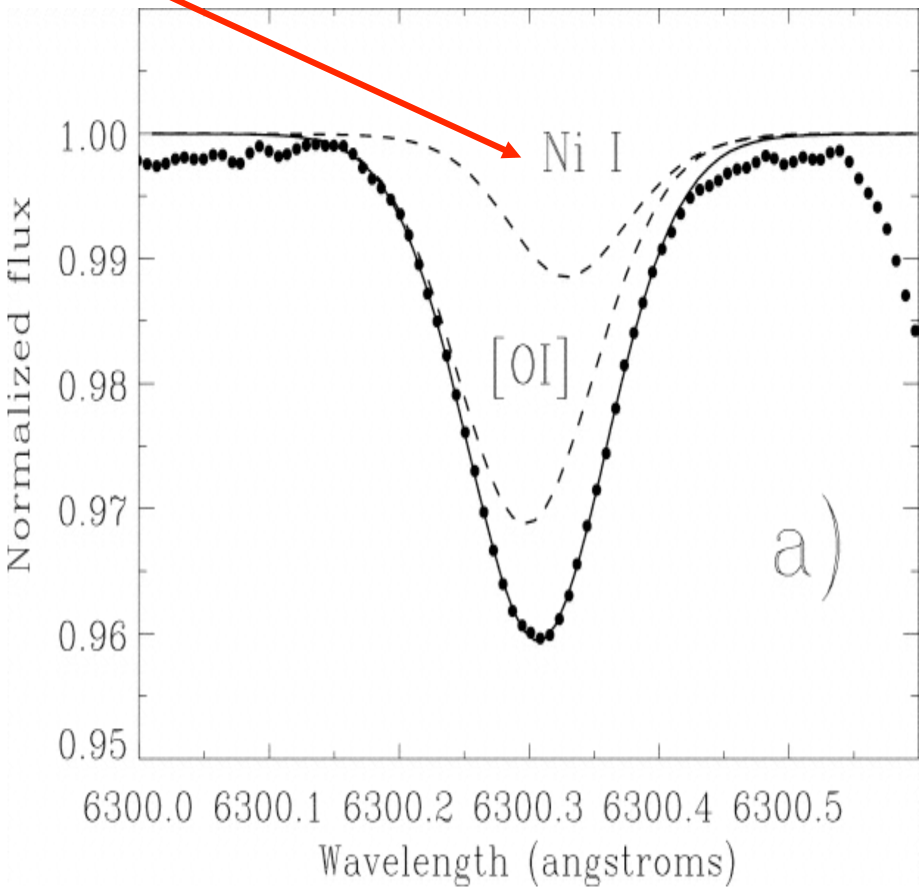
Allende Prieto et al. 2001:
Blend with Ni: -0.19 dex

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

Allende Prieto et al., 2001, ApJ, 558, 830



(Similar results for other [OI] lines)

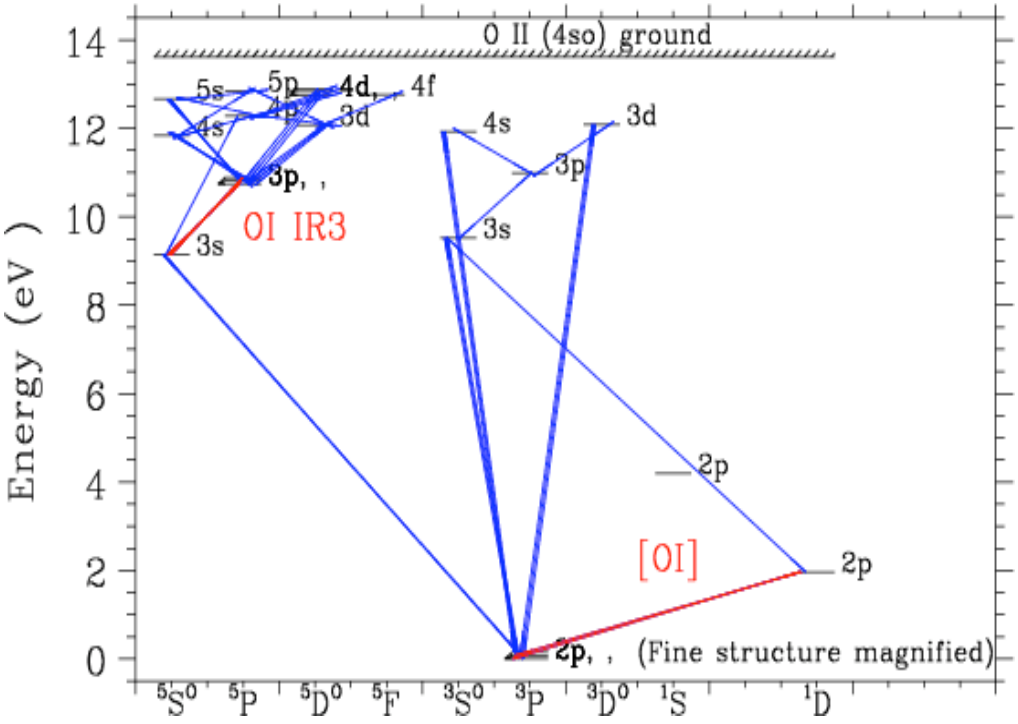
O I: non-LTE and collisions

Electron collisions

New QM calculations

Barklem 2007

Fabbian et al. 2009



Hydrogen collisions

Use Drawin 1968 recipe with scaling factor S_H

S_H guessed until recently:

Asplund et al. 2004: $S_H=0$ (other elements)

Caffau et al. 2008: $S_H=1/3$ (why not)

O I: non-LTE effects

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

Non-LTE - LTE ≈ -0.2 dex

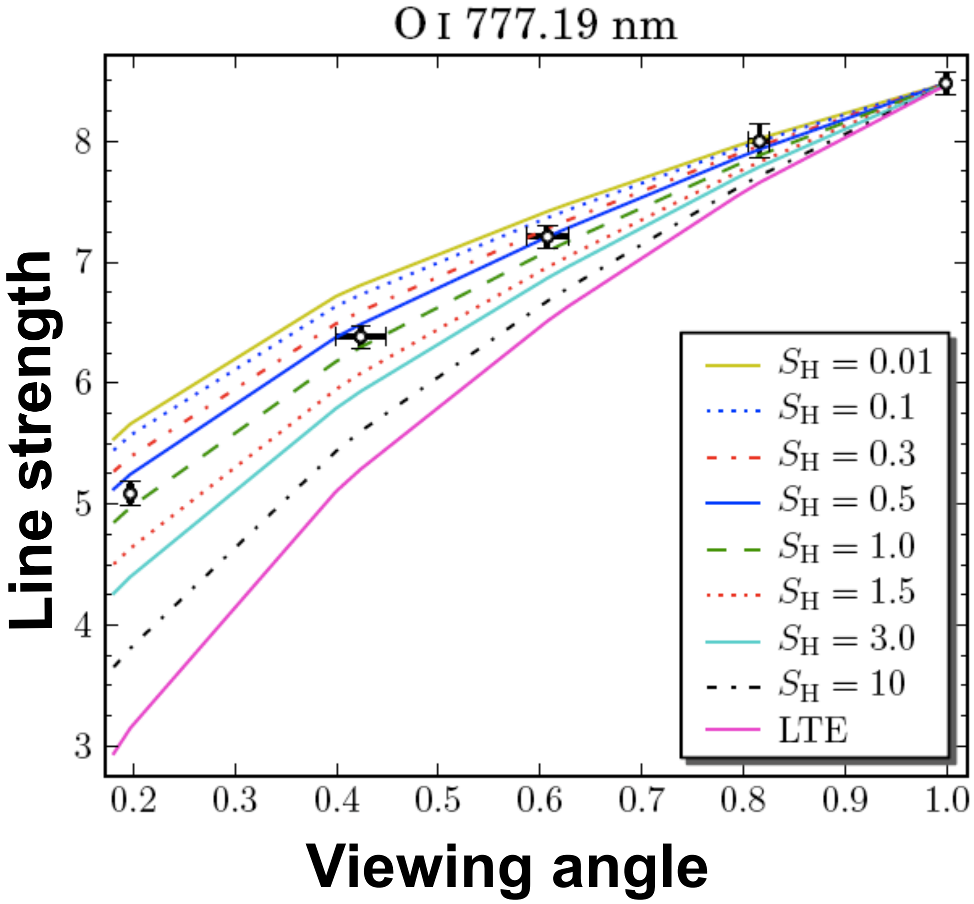
Pereira et al. 2009a:

Use observed center-to-limb variations to determine poorly known H collisions

↓

Asplund et al. 2009a:

log O=8.69±0.05

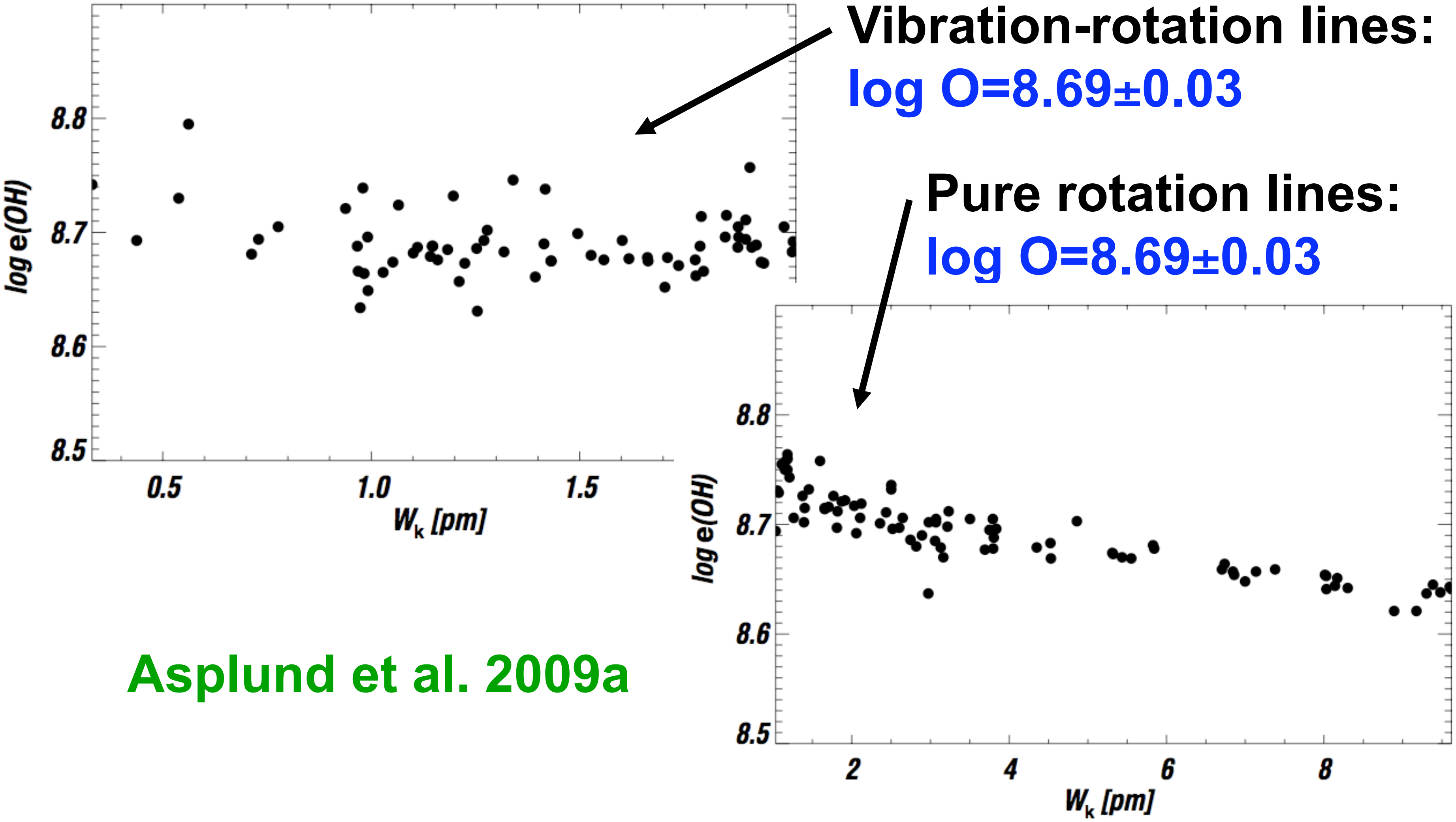


Note: S_H only makes sense for a given model atom and atmosphere

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

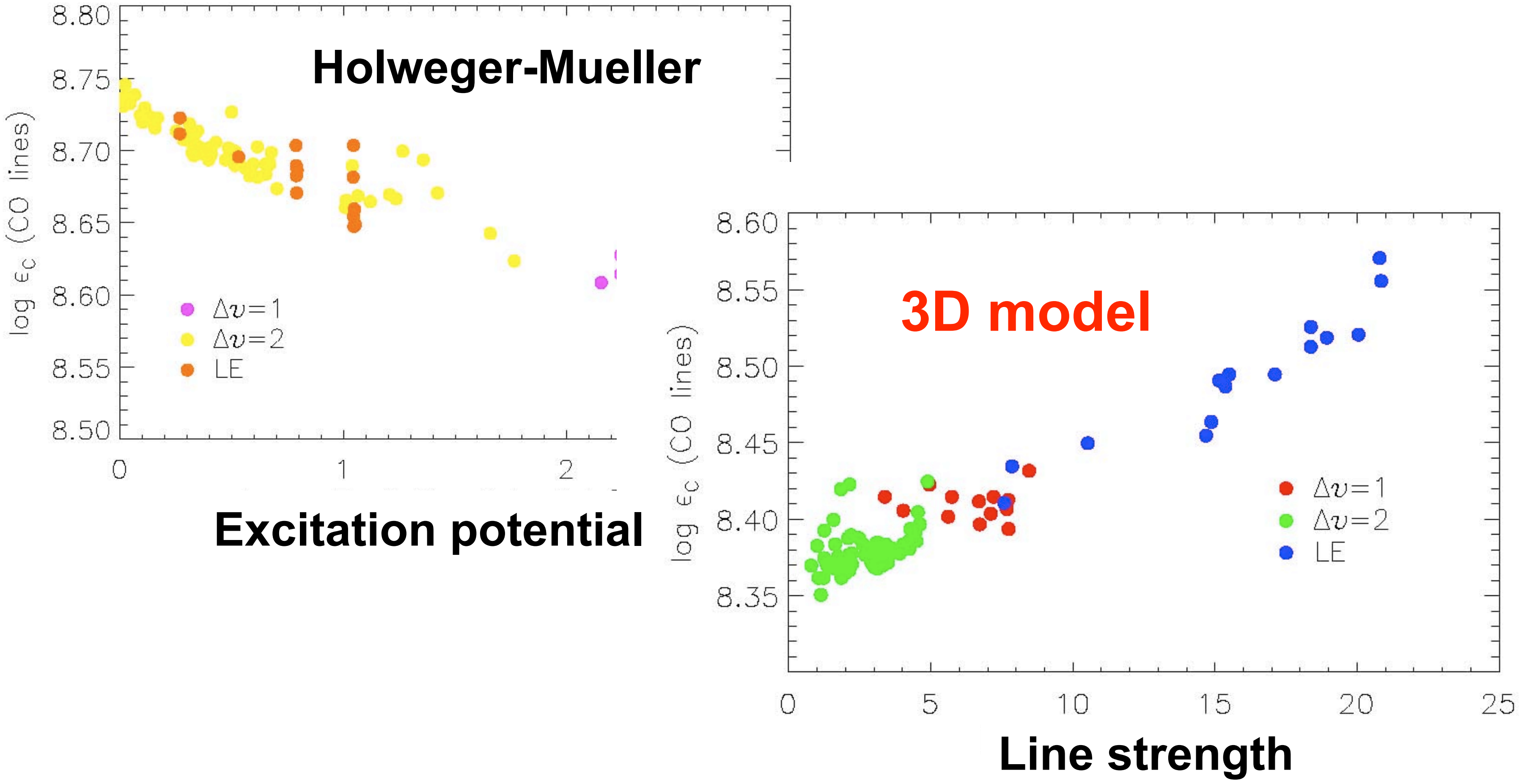
- Discordant results in 1D: log C~8.4-8.7
- Excellent agreement in 3D: log C=8.43±0.05
- C/O=0.55±0.07
- Asplund et al. (2009)

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

CO vib-rot lines

- **O isotopic ratio:** $^{16}O/^{18}O=480\pm30$
- **C isotopic ratio:** $^{12}C/^{13}C=87\pm4$
- **Scott et al. (2006)**

= Terrestrial:
$^{16}O/^{18}O=498.7\pm0.1$
$^{12}C/^{13}C=89.4\pm0.2$



Solar Fe abundance

3D model:

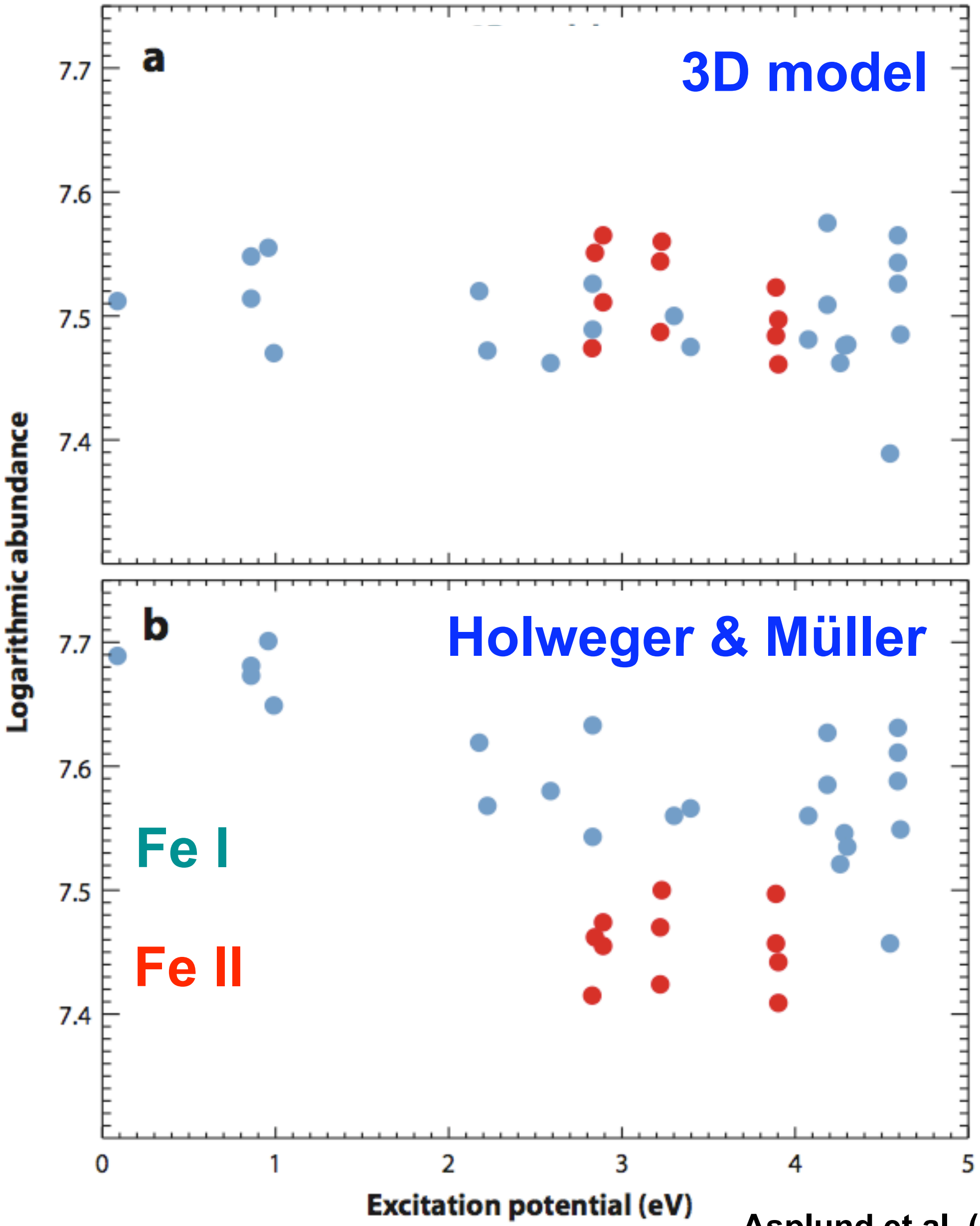
log Fe I =7.51±0.05

log Fe II=7.50±0.04

Holweger & Müller:

Fe I trend with χ_{ex}

Fe I and Fe II offset



Asplund et al. (2009)

Independent studies

3D-based solar analysis by CO5BOLD collaboration

Caffau, Ludwig, Steffen, Freytag et al.

Element	Caffau et al. (2008, 2009, 2010)	Asplund et al. (2009)
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

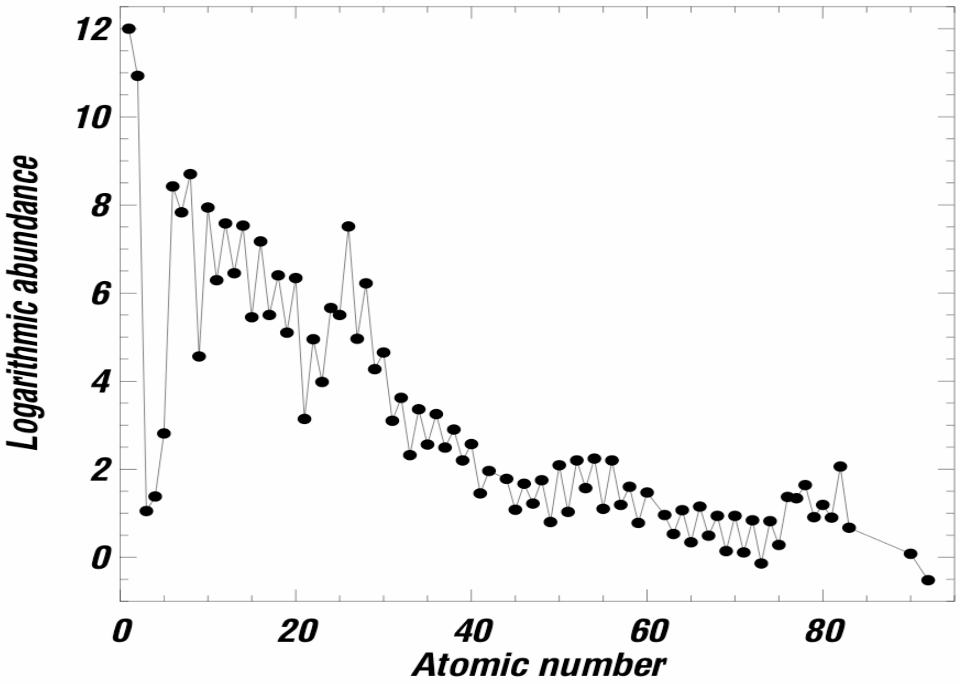
(Caffau et al. do not consider molecular lines)

Complete solar inventory

Asplund et al. (2009, ARAA):

3D-based analysis of all elements

Statistical and systematic errors included in total uncertainties



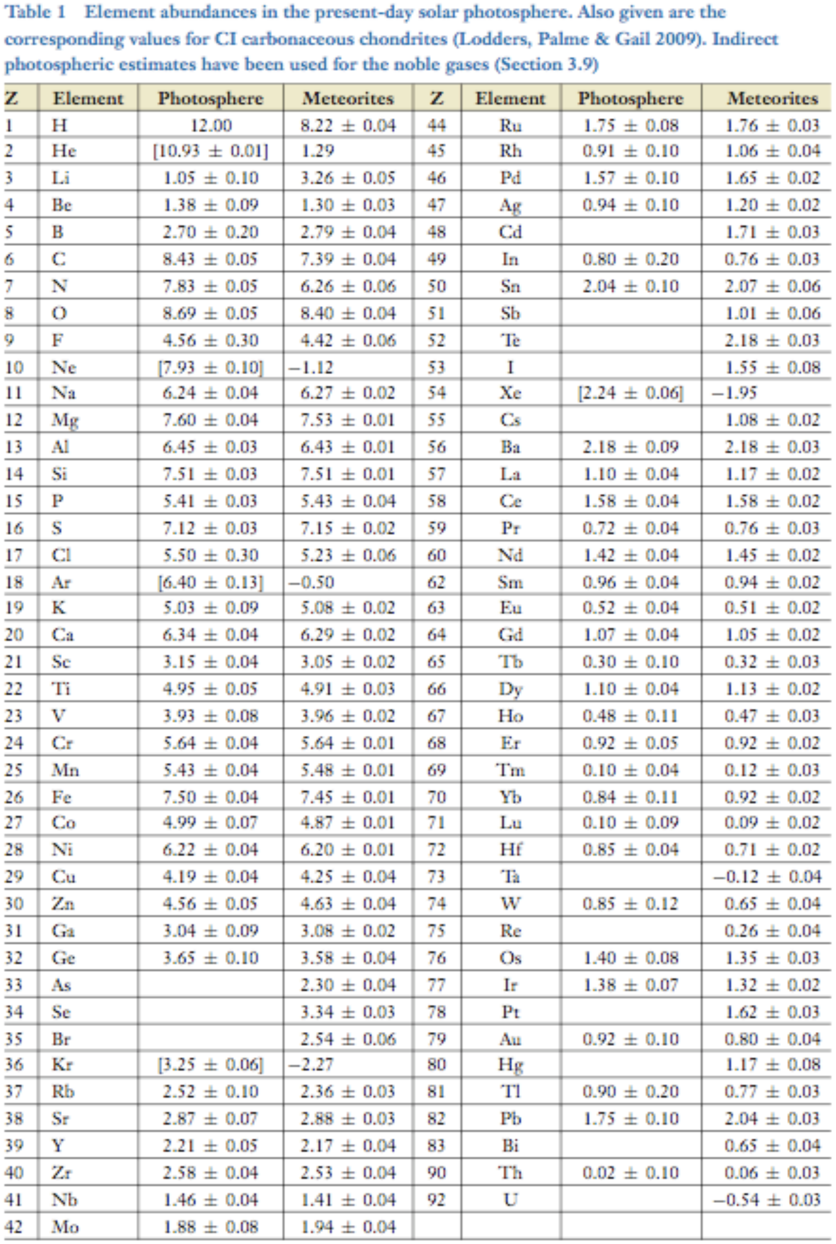
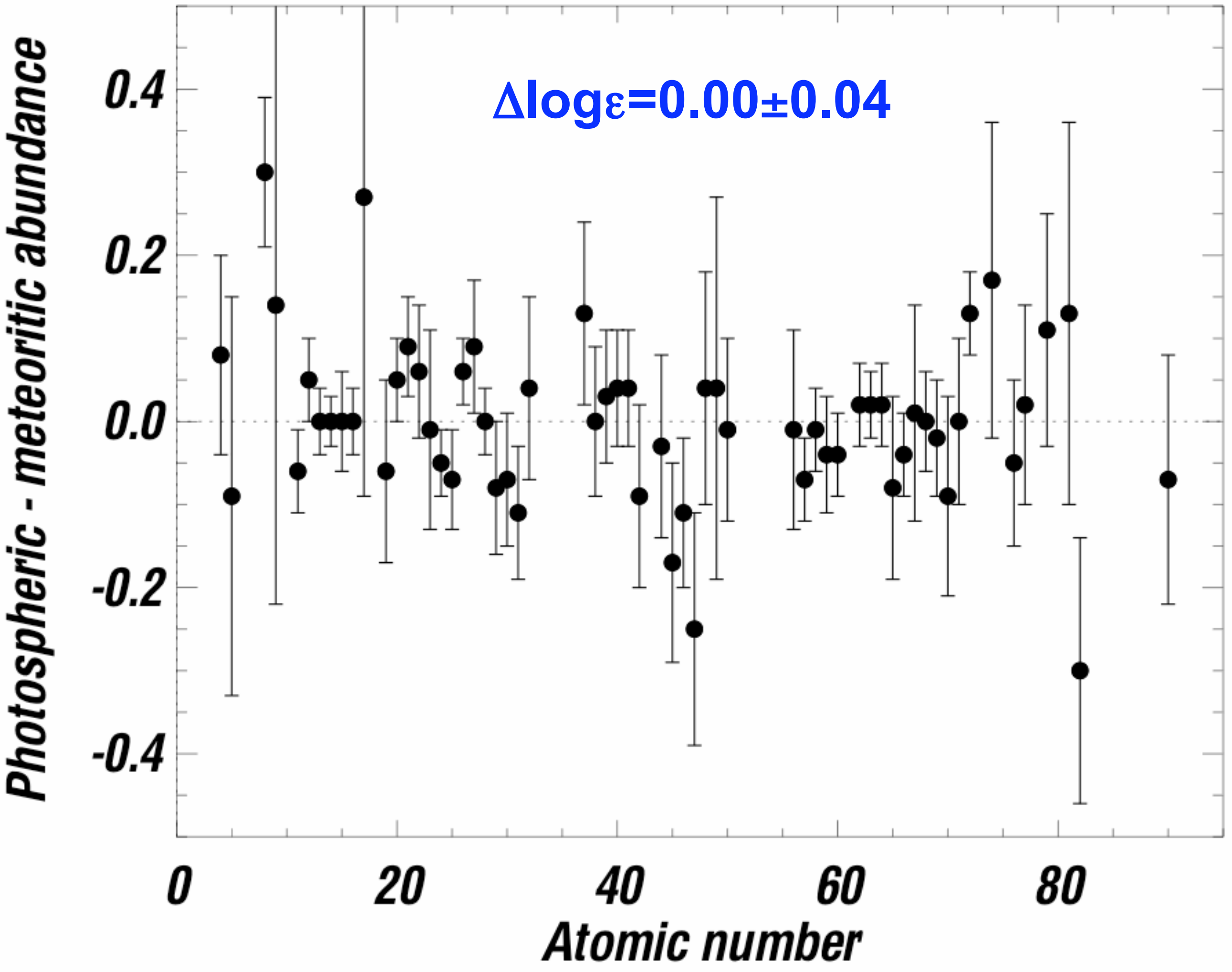


Table 1 Element abundances in the present-day solar photosphere. Also given are the corresponding values for CI carbonaceous chondrites (Lodders, Palme & Gail 2009). Indirect photospheric estimates have been used for the noble gases (Section 3.9)

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				

Meteorites

Excellent agreement with the most pristine meteorites (CI chondrites)



Asplund et al., 2009, ARAA, 47, 481

(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

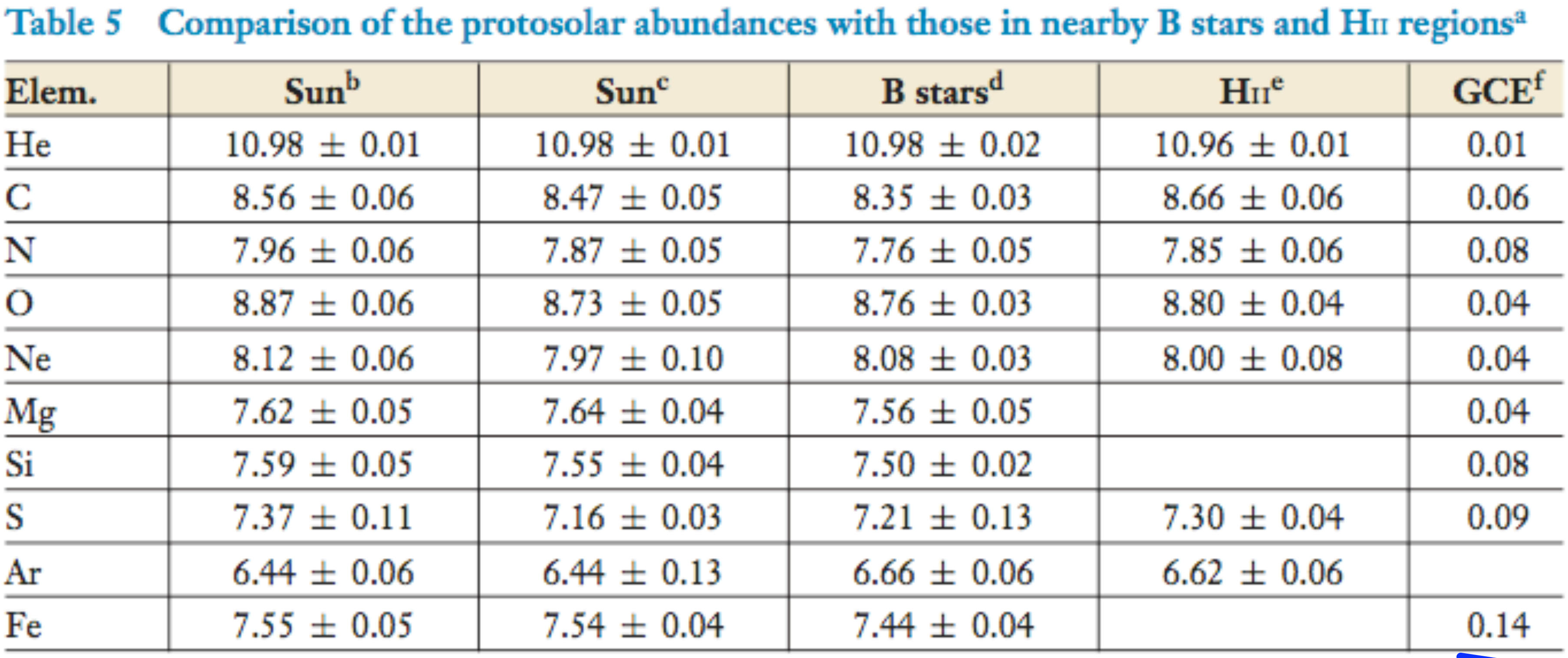


Table 5 Comparison of the protosolar abundances with those in nearby B stars and H II regions[a]

Elem.	Sun[b]	Sun[c]	B stars[d]	H II[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)

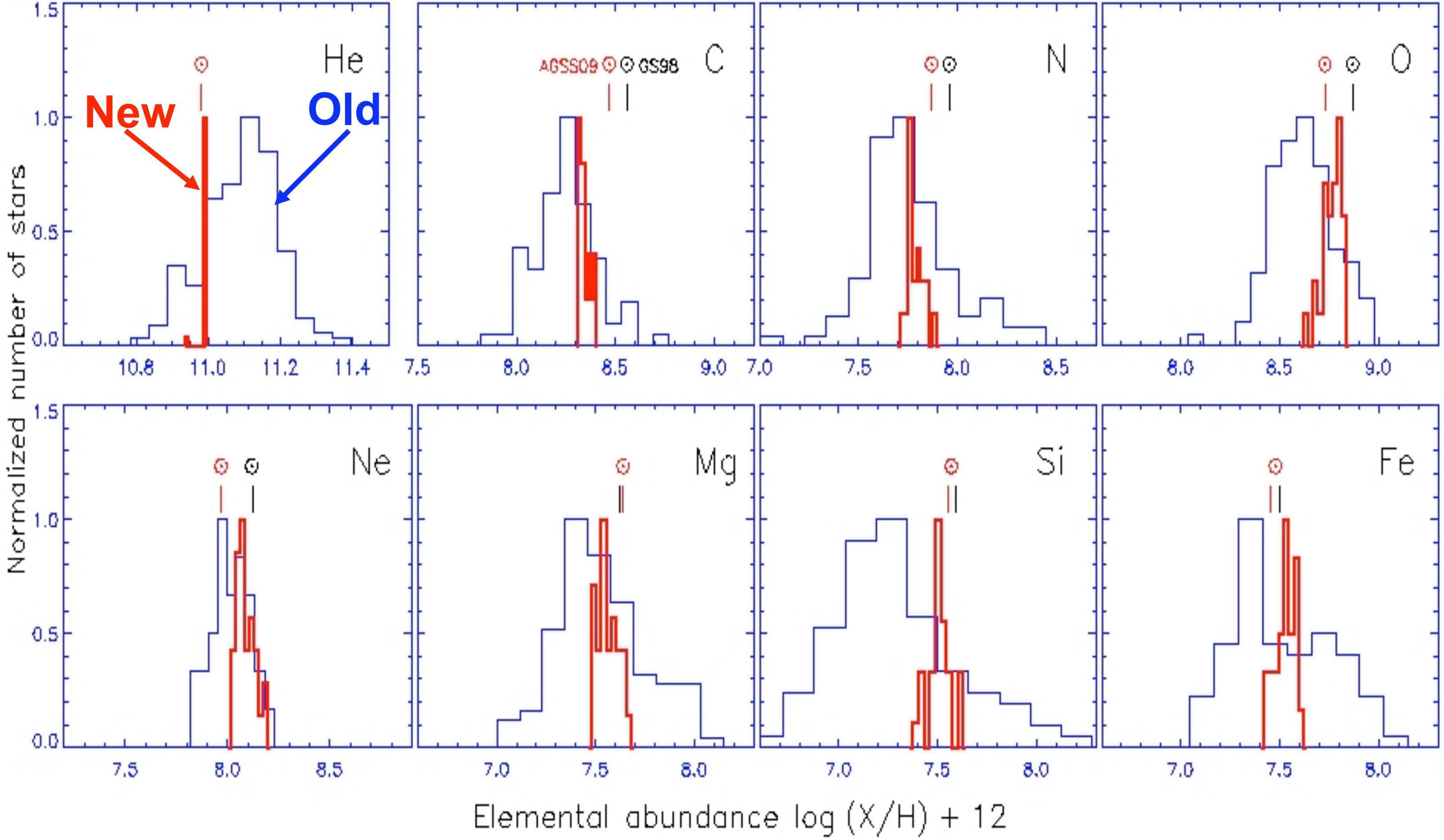
Comparison with OB stars

Improved non-LTE analysis of OB stars

⇒ Extremely homogeneous solar neighborhood

⇒ Agreement with new solar abundances

Nieva et al. (2010)



(Some) Implications

- Significantly lower solar metal mass fraction Z
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- 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

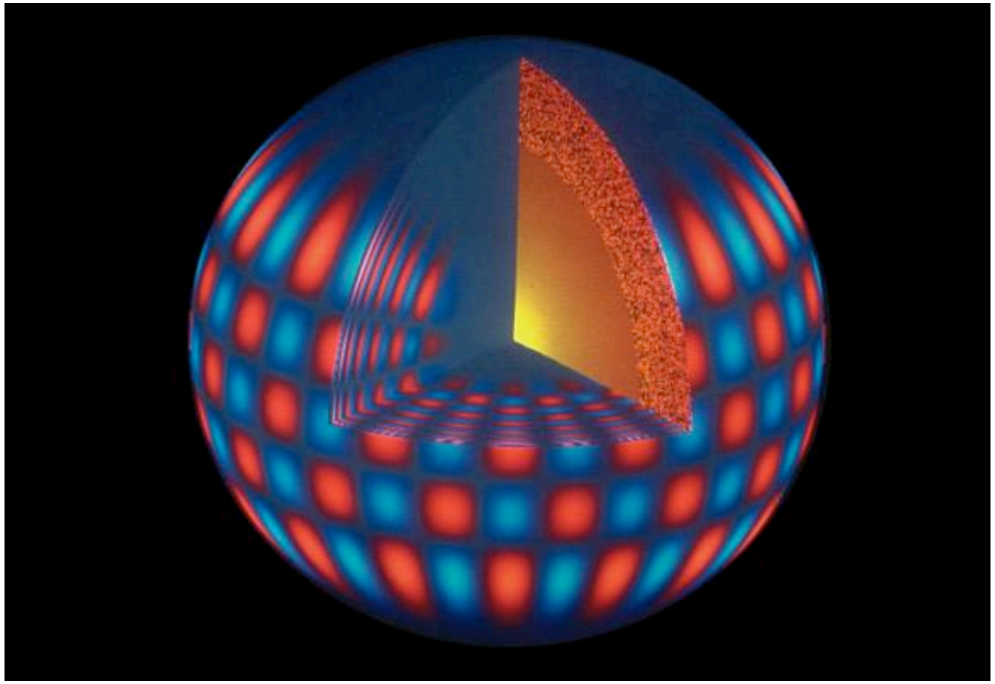
Helioseismology I

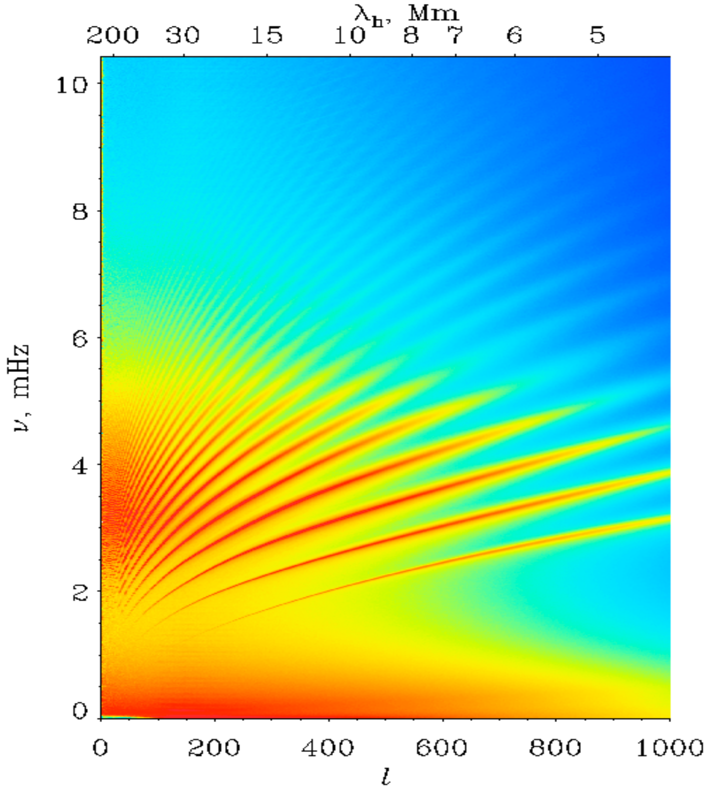
Solar oscillations

Period: ~5 minutes

Acoustic standing waves (p-modes)

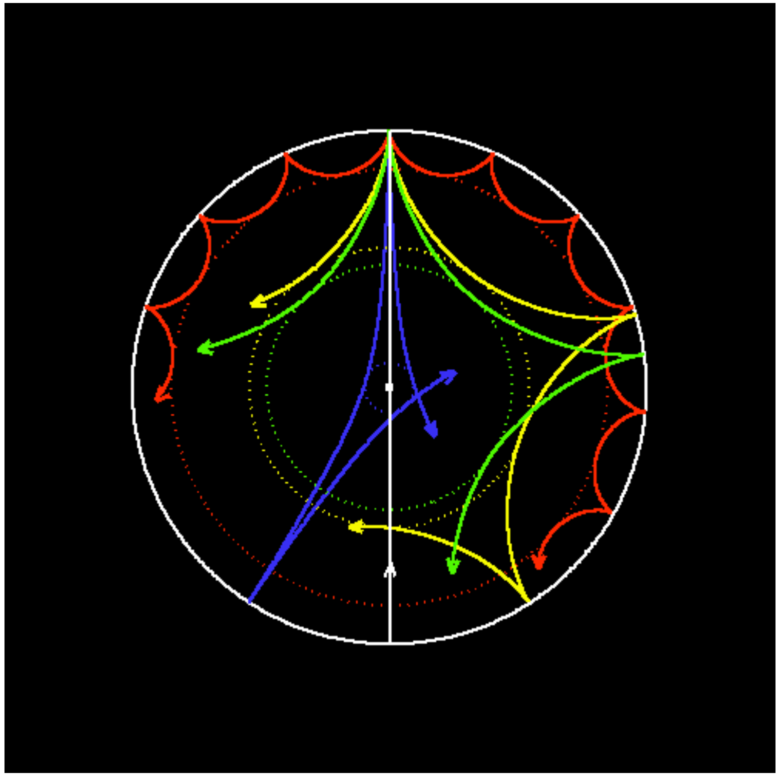
Surface amplitudes: ~10cm/s (cf. convection ~2km/s)





See lectures by A. Noels!

Helioseismology II



Inner turning point depends on mode (n,l)

Reconstruction of solar interior structure
(sound speed and thus temperature and density)

Standard solar model

Input parameters

- **Solar age:** 4.57 Gyr
- **Solar mass:** 1.989×10^{33} g
- **Chemical composition:** X_{in}, Y_{in}, Z_{in}
- **Convection parameter (mixing length theory):** α_{MLT}

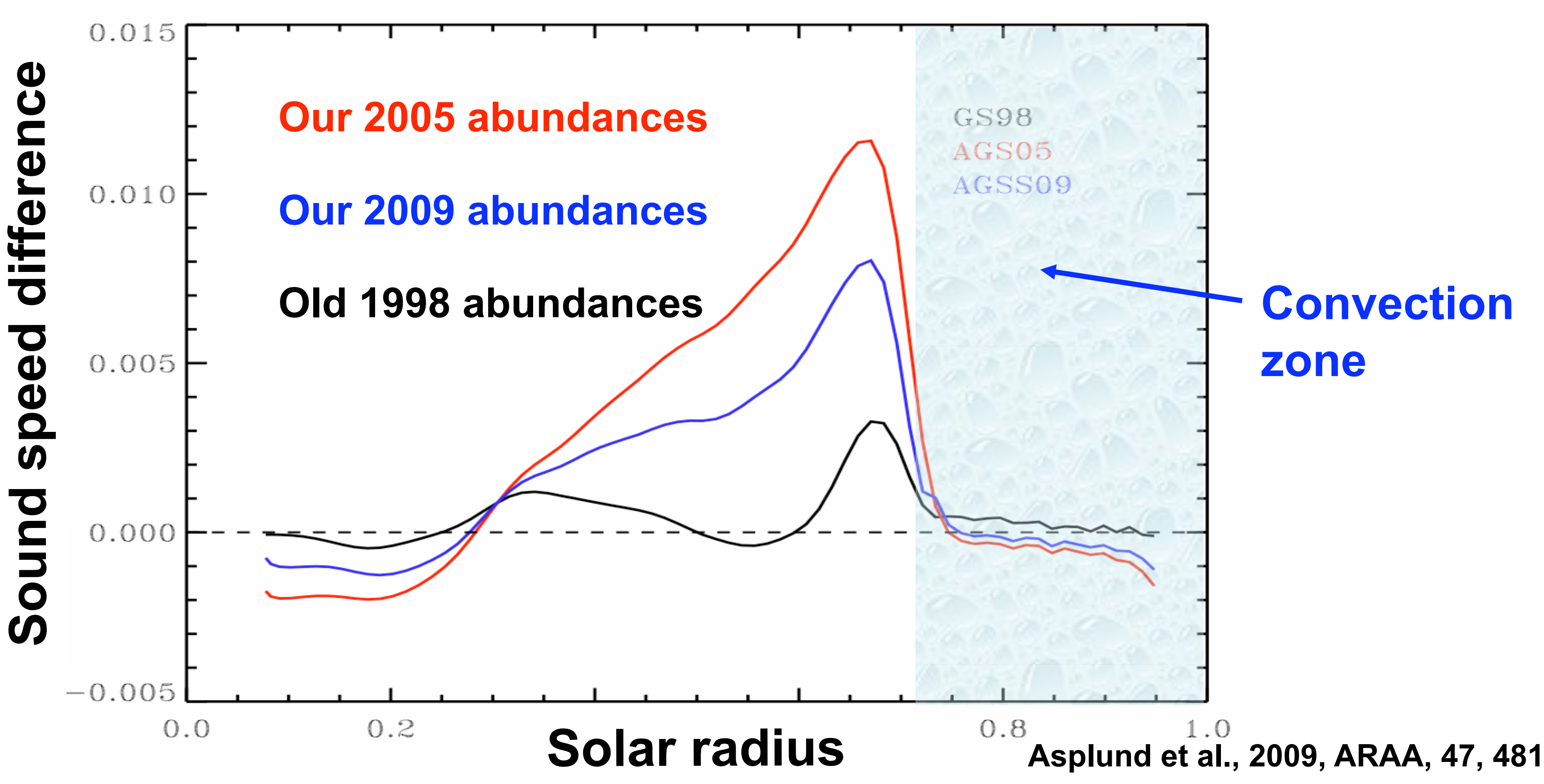
Evolve solar model until present-day

Present-day constraints

- **Solar luminosity:** $L_{\odot} = 3.842 \times 10^{33}$ erg/s
- **Solar radius:** $R_{\odot} = 6.9598 \times 10^{10}$ cm
- **Atmospheric composition:** $(Z/X)_{atmo}$

$$L_{\odot}\text{-}R_{\odot}\text{-}(Z/X)_{atmo} \Leftrightarrow Y_{in}\text{-}Z_{in}\text{-}\alpha_{MLT}$$

Trouble in paradise



Asplund et al., 2009, ARAA, 47, 481

Solar interior models with new abundances are in conflict with helioseismology

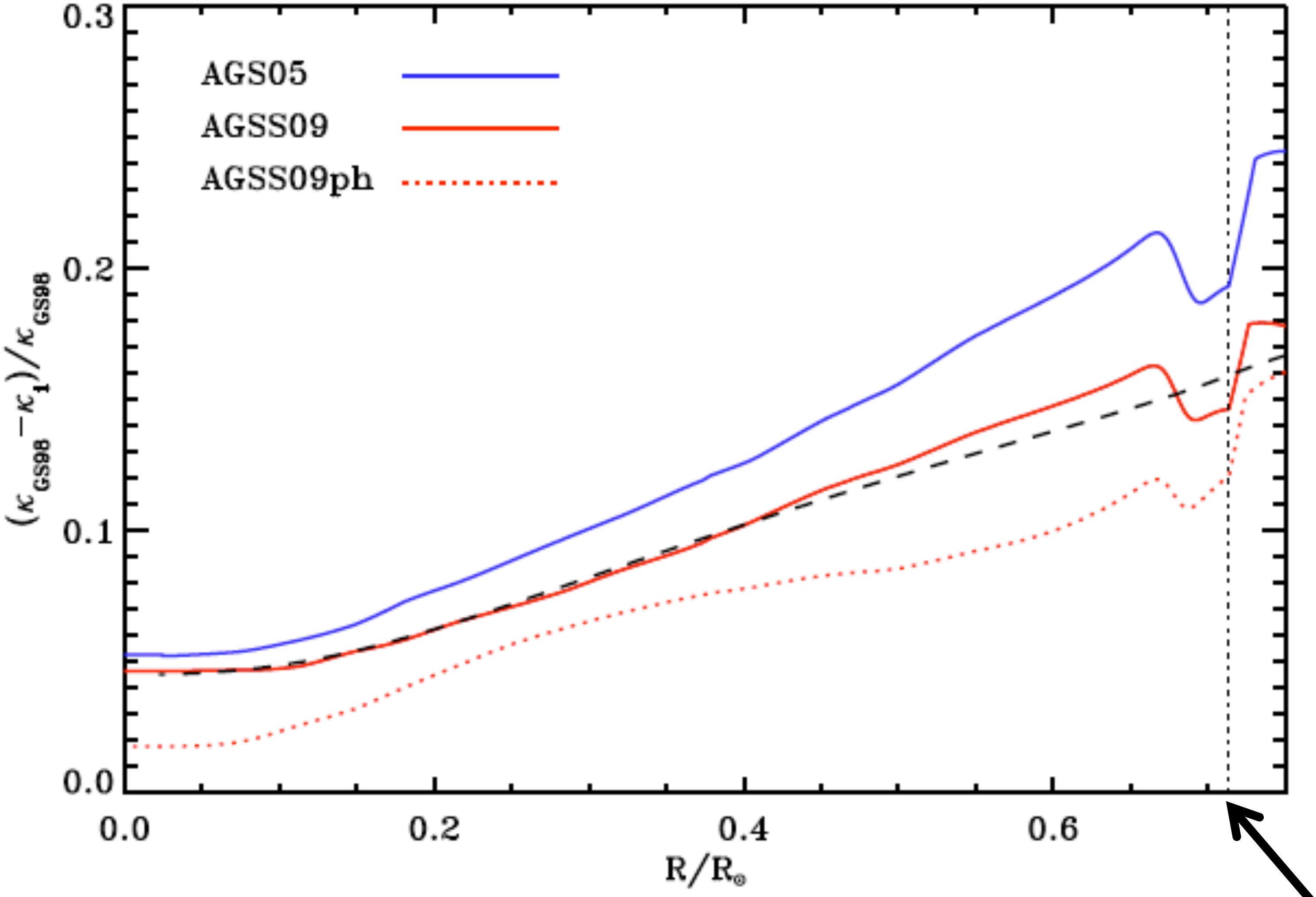
- Wrong sound speed
- Wrong depth of convection zone: R=0.723 vs 0.713±0.001
- Wrong surface helium abundance: Y=0.235 vs 0.248±0.004

Possible solutions

- Missing opacity?
  - Possibly?
- Underestimated element diffusion?
  - Unlikely
- Accretion of low-Z material?
  - Unlikely
- Internal gravity waves?
  - Possibly
- Underestimated solar Ne abundance?
  - Unlikely
- Erroneous solar abundances?
  - Hopefully not
- Combination of some of the above?
  - Contrived?

Missing opacity?

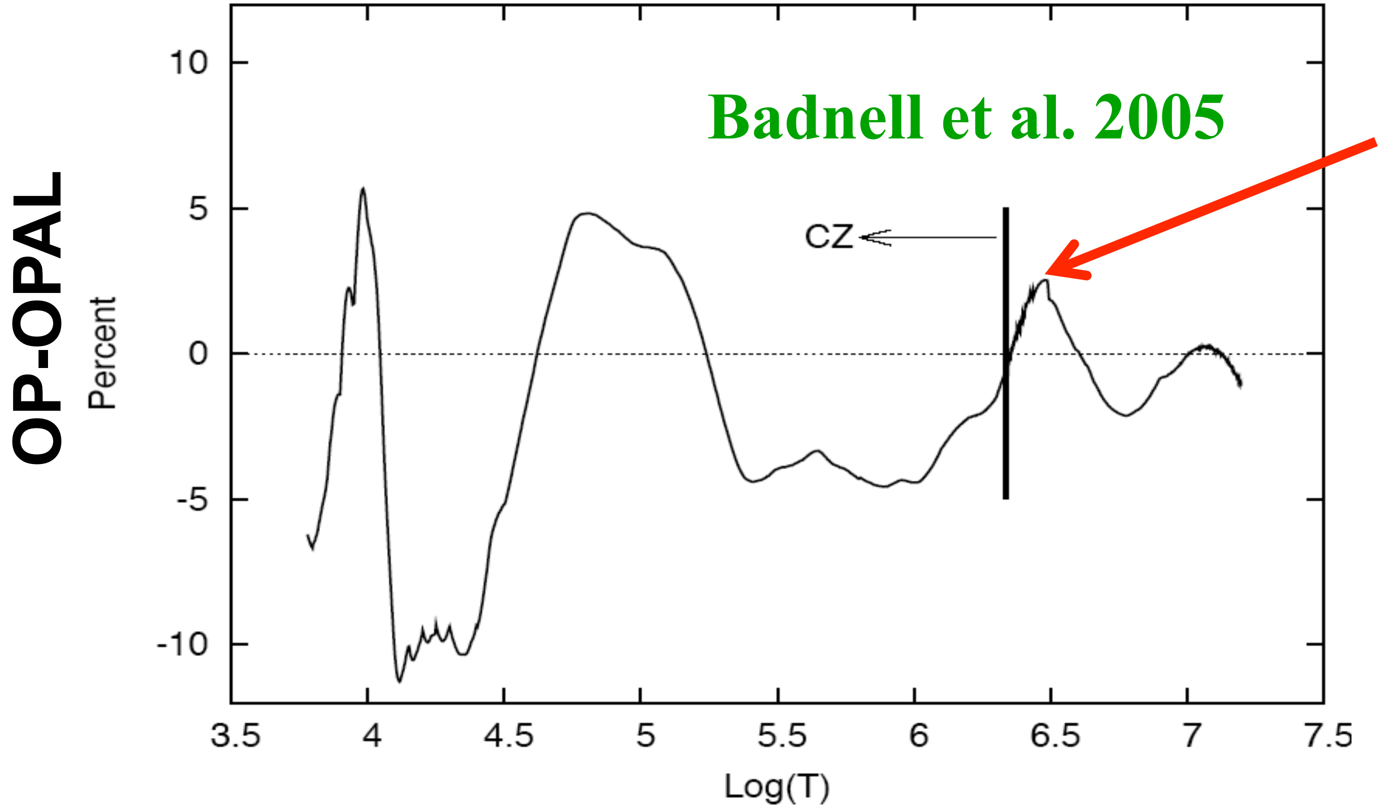
Serenelli (2009): Higher opacities by ~10-15% below the convection zone would restore agreement



Bottom of CZ

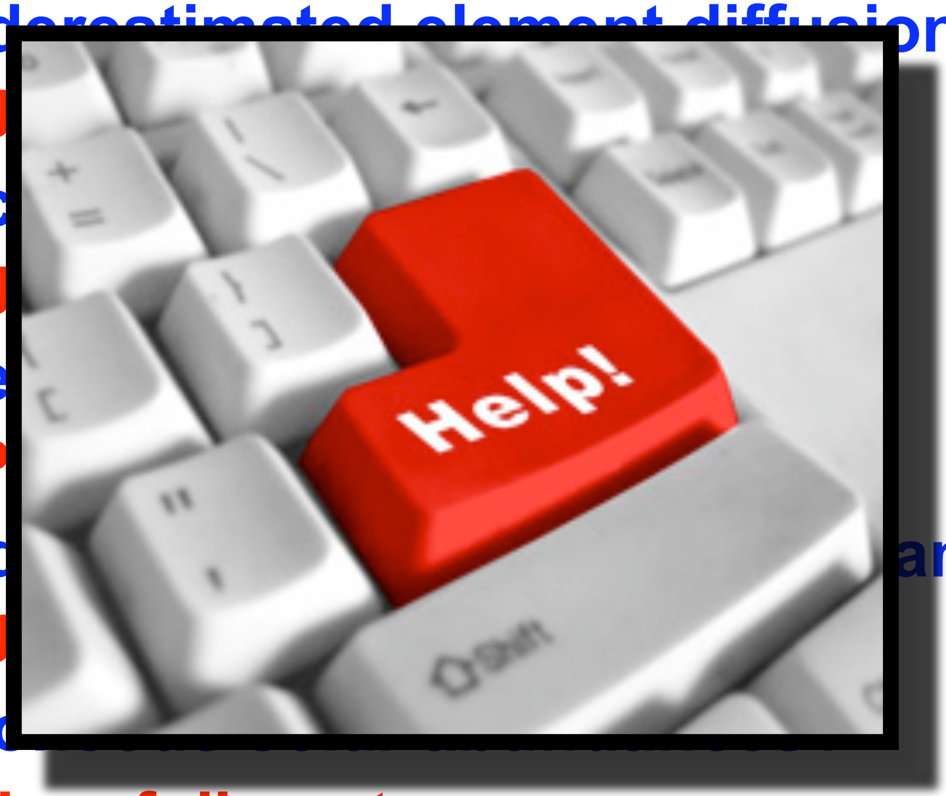
Missing opacity?

- Higher opacities by ~10-15% below the convection zone would restore agreement
- Atomic physicists say at most 5% missing opacity
- But caution: history may repeat itself…
- Soon: experimental opacity data (laser facilities)



Possible solutions

- Missing opacity?
  - Possibly?
- Underestimated element diffusion?
  - U
- Acc
  - U
- Inte
  - P
- Unc ance?
  - U
- Err

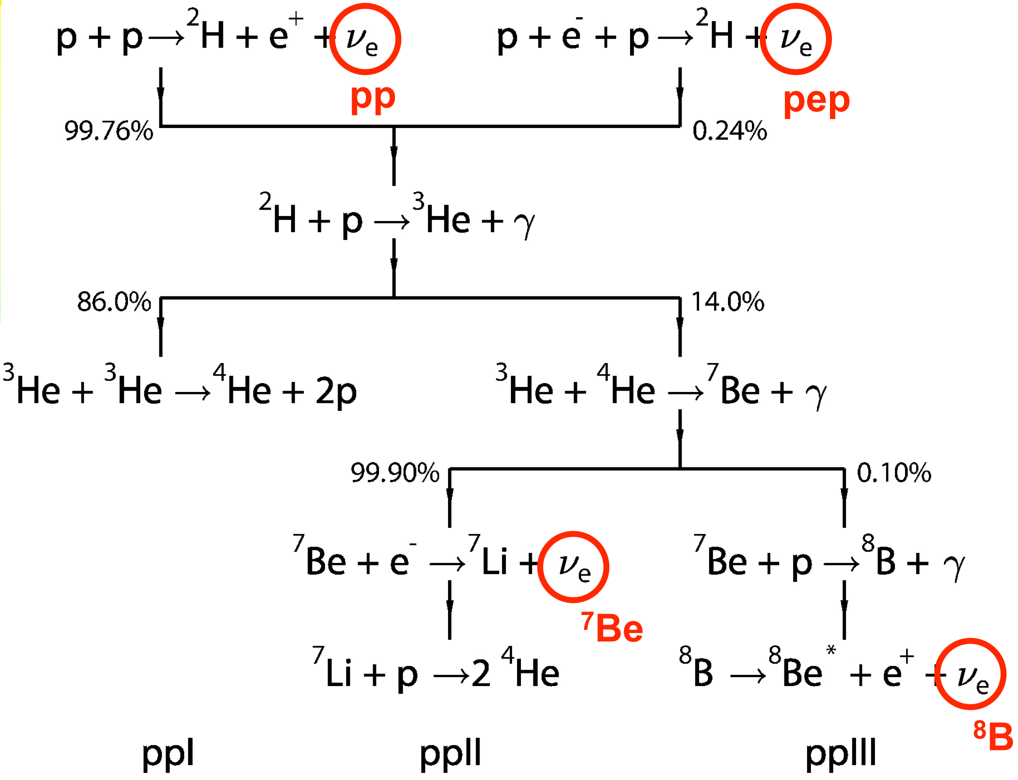


  - Hopefully not
- Combination of some of the above?
  - Contrived?

Solar neutrinos

Solar hydrogen burning

pp chains



$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$ **pp**

$p + e^{-} + p \rightarrow {}^{2}H + \nu_e$ **pep**

99.76%

0.24%

$^{2}H + p \rightarrow {}^{3}He + \gamma$

86.0%

14.0%

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$

$^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

99.90%

0.10%

$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$ **^{7}Be**

$^{7}Be + p \rightarrow {}^{8}B + \gamma$

$^{7}Li + p \rightarrow 2\,{}^{4}He$

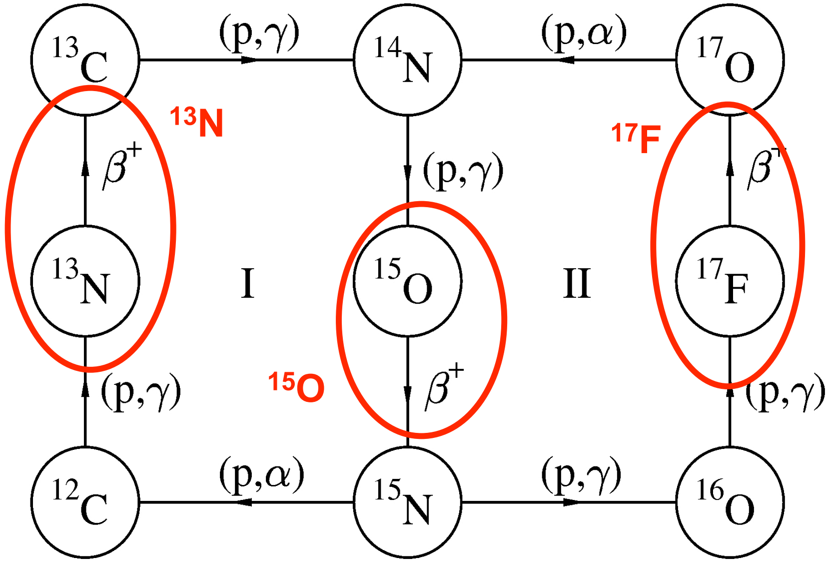
$^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$ **^{8}B**

ppI

ppII

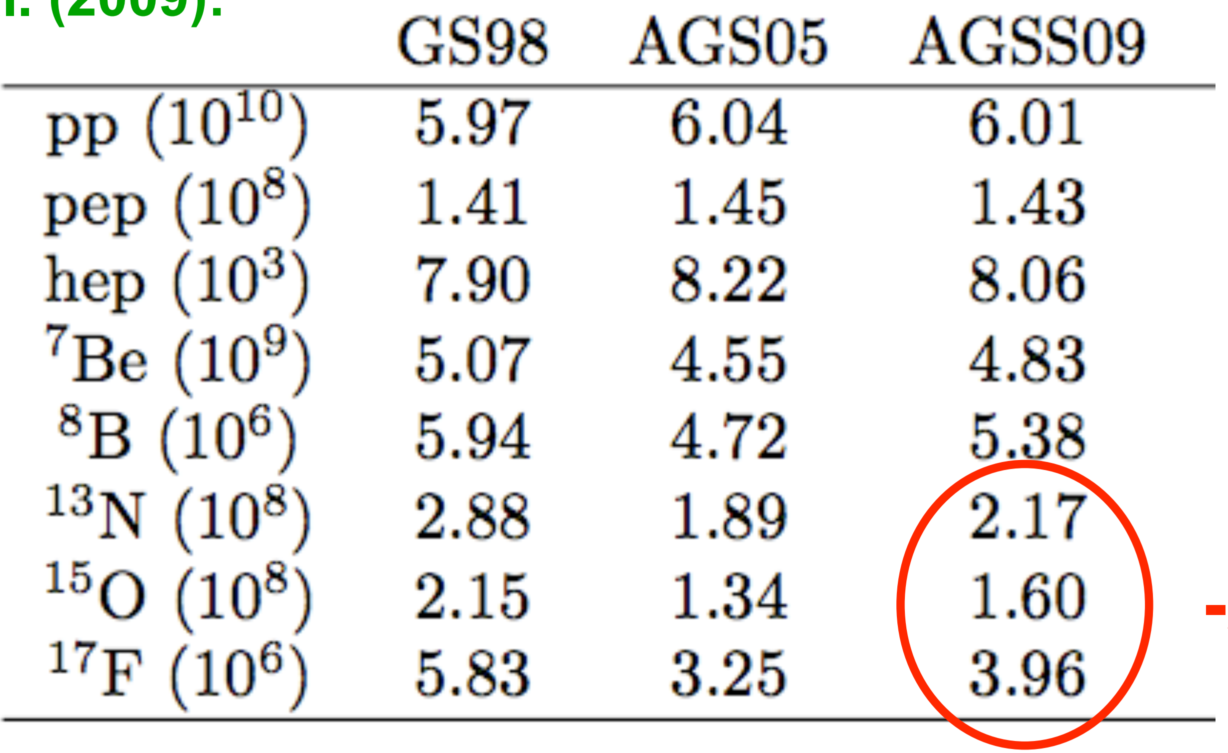
ppIII

CNO cycle



Predicted neutrino fluxes

Serenelli et al. (2009):



	GS98	AGS05	AGSS09
pp (10^{10})	5.97	6.04	6.01
pep (10^8)	1.41	1.45	1.43
hep (10^3)	7.90	8.22	8.06
^{7}Be (10^9)	5.07	4.55	4.83
^{8}B (10^6)	5.94	4.72	5.38
^{13}N (10^8)	2.88	1.89	2.17
^{15}O (10^8)	2.15	1.34	1.60
^{17}F (10^6)	5.83	3.25	3.96

-25%

New abundances decrease core temperature by ~1%

&

^{13}N and ^{15}O fluxes proportional to C and N abundances

⇩

Neutrinos: independent estimate of solar C+N abundances

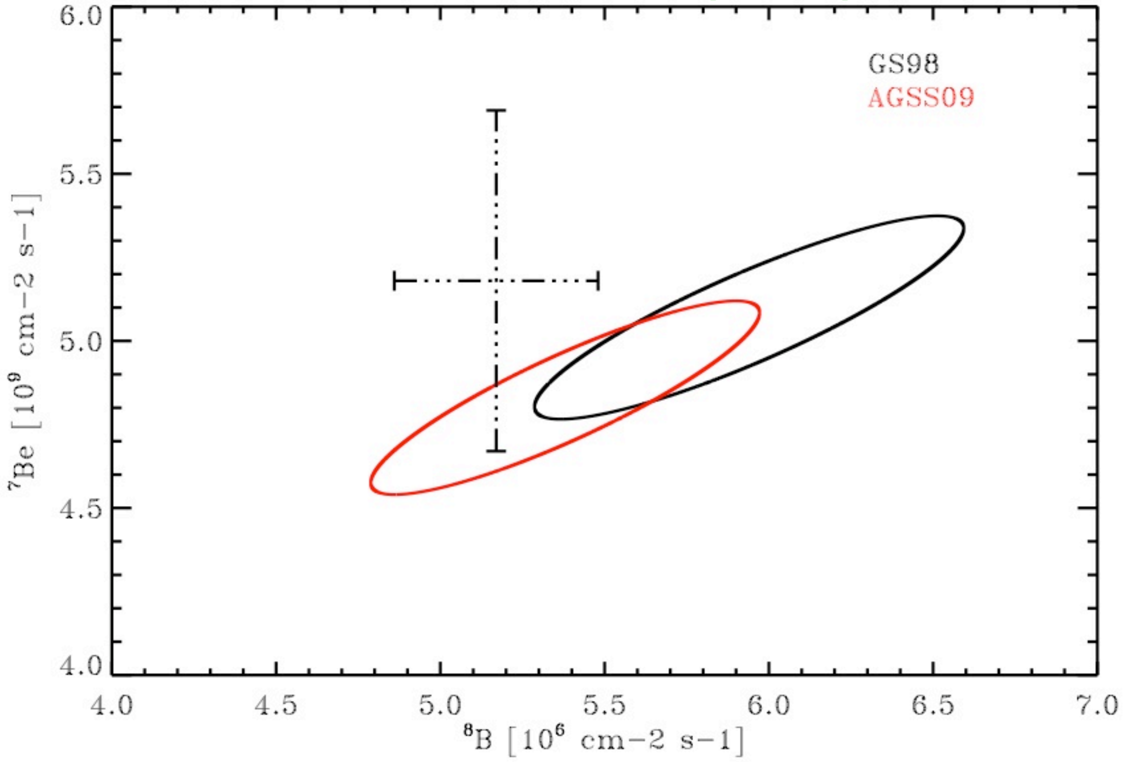
^{7}Be vs ^{8}B fluxes

SNO: $\Phi(^8B)= (5.17\pm0.31)\times10^6$ cm^{-2} s^{-1}

Borexino: $\Phi(^7Be)= (5.18\pm0.51)\times10^9$ cm^{-2} s^{-1}

(Arpesella et al. 2008)

Serenelli et al. (2009):



Note:
Predicted ^{8}B and ^{7}Be fluxes highly correlated

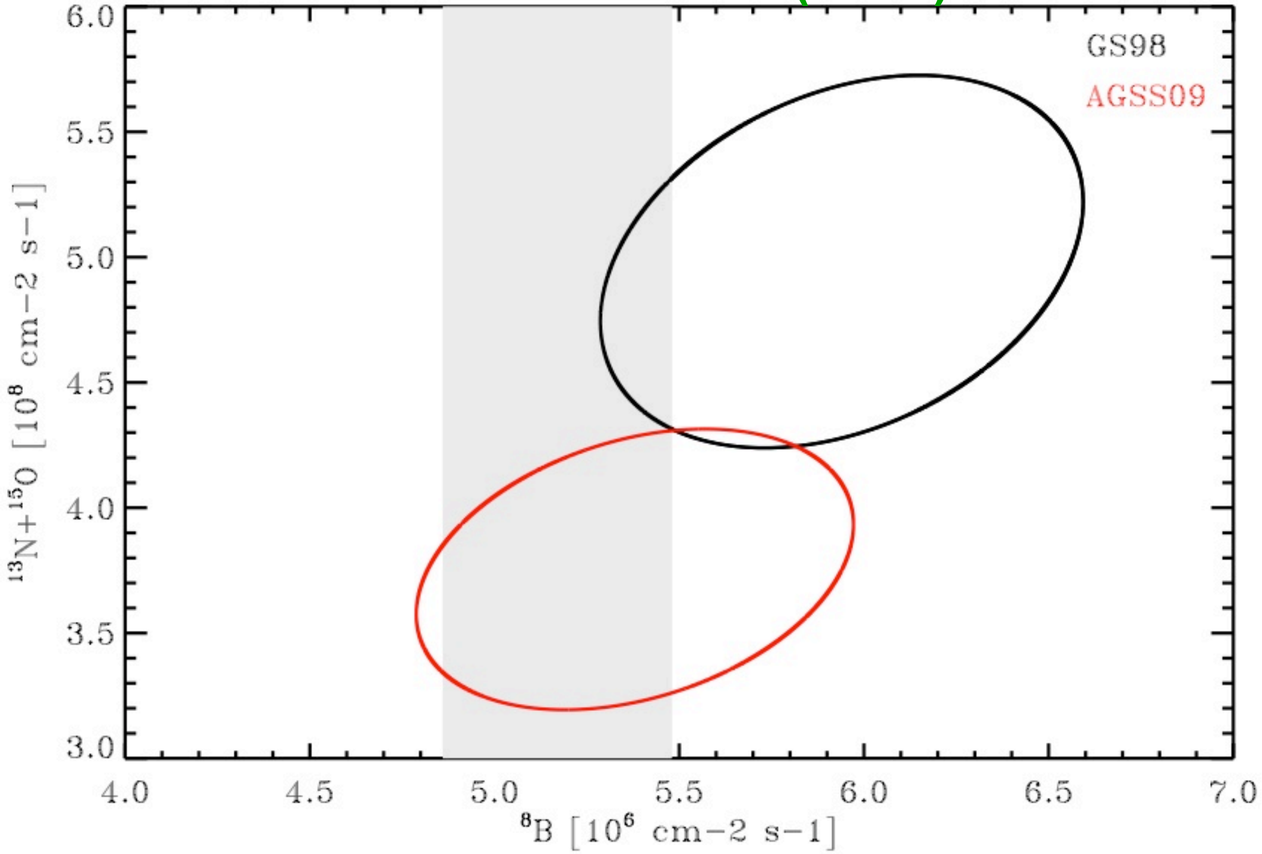
^{8}B vs ^{13}N+^{15}O

Better prospect of discriminating between solar chemical compositions with ^{13}N and ^{15}O neutrinos

Borexino: expect 10% uncertainty ⇒ 2-3σ result

(Improved p+^{14}N from LUNA experiment will also help)

Serenelli et al. (2009):



Summary

Lecture 1: Solar/stellar spectroscopy

- 3D stellar atmospheres highly realistic
- 3D/non-LTE spectral line formation possible

Lecture 2: Solar chemical composition

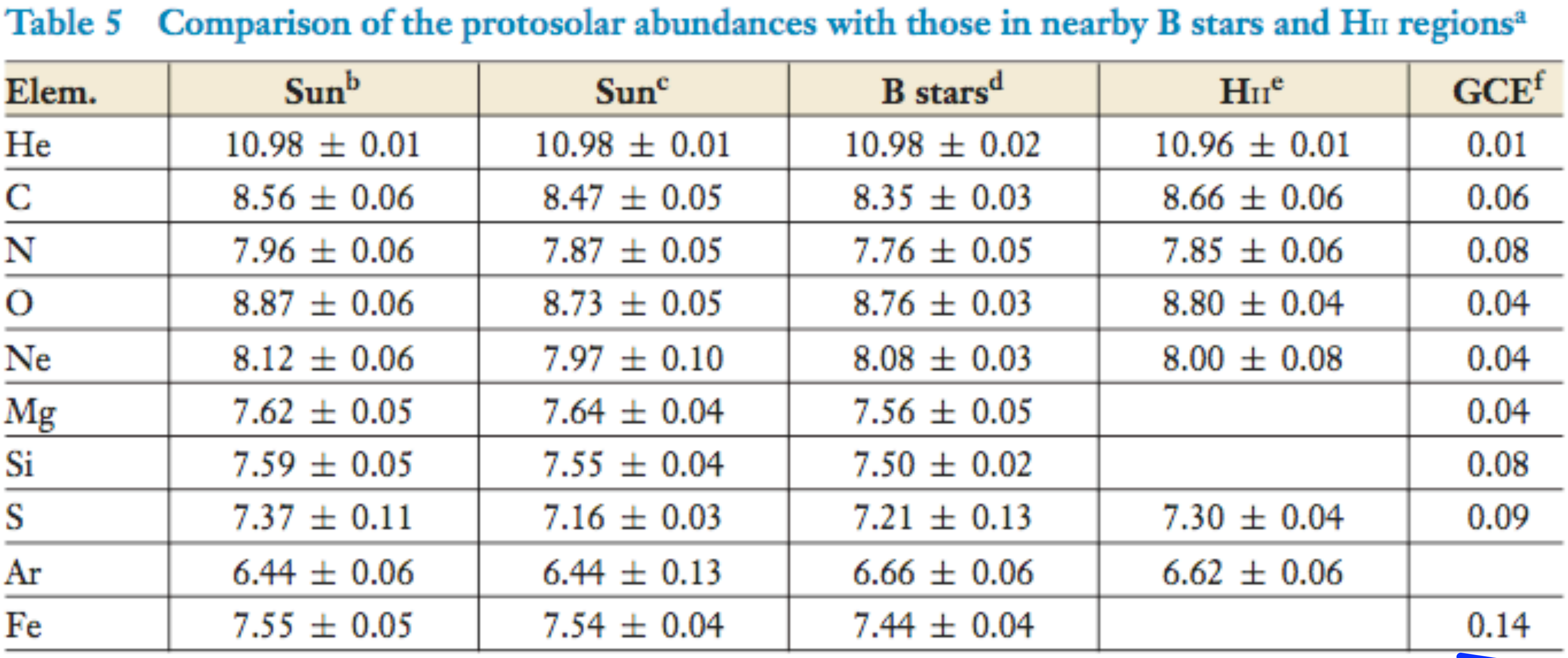
- New low solar C, N, O, Ne abundances
- Conflict with solar interior models

Lecture 3: Is the Sun unusual?

Solar neighborhood

Asplund et al. (2009):

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



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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)

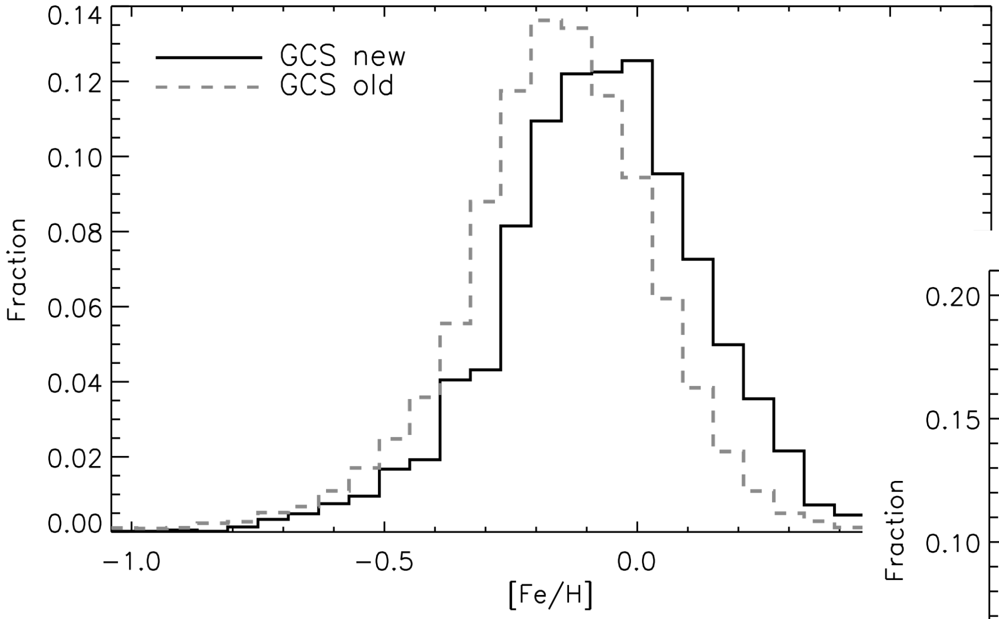
Galactic chemical
evolution over 4.5Gyr
(Chiappini et al. 2003)

Sun vs Galactic disk stars: [Fe/H]

Casagrande et al. 2010:

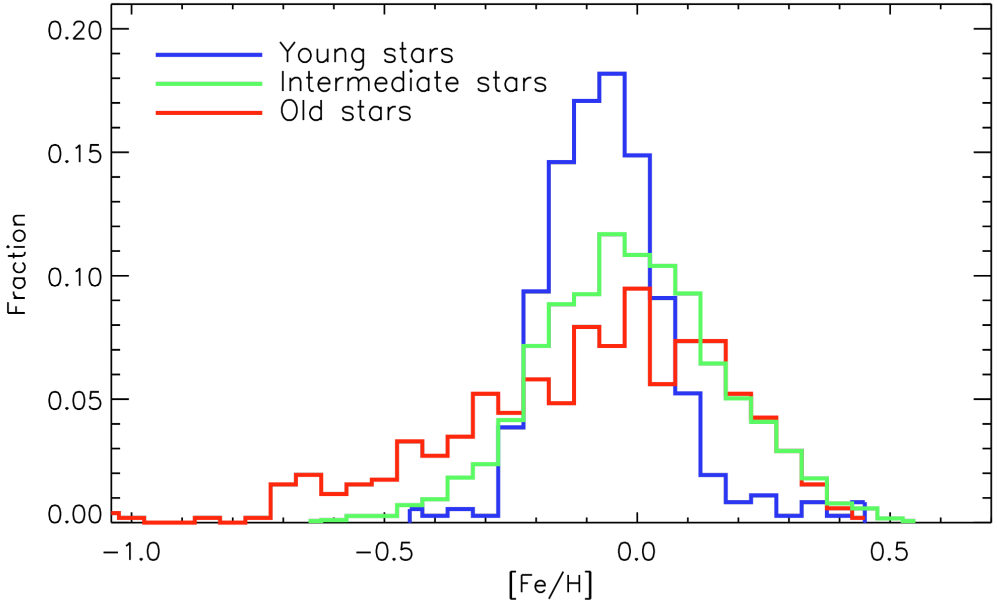
Revision of Geneva Copenhagen Survey of ~14000 stars in solar neighborhood (Nordström et al. 2004)

New T_{eff}, [Fe/H] and ages



Sun quite normal

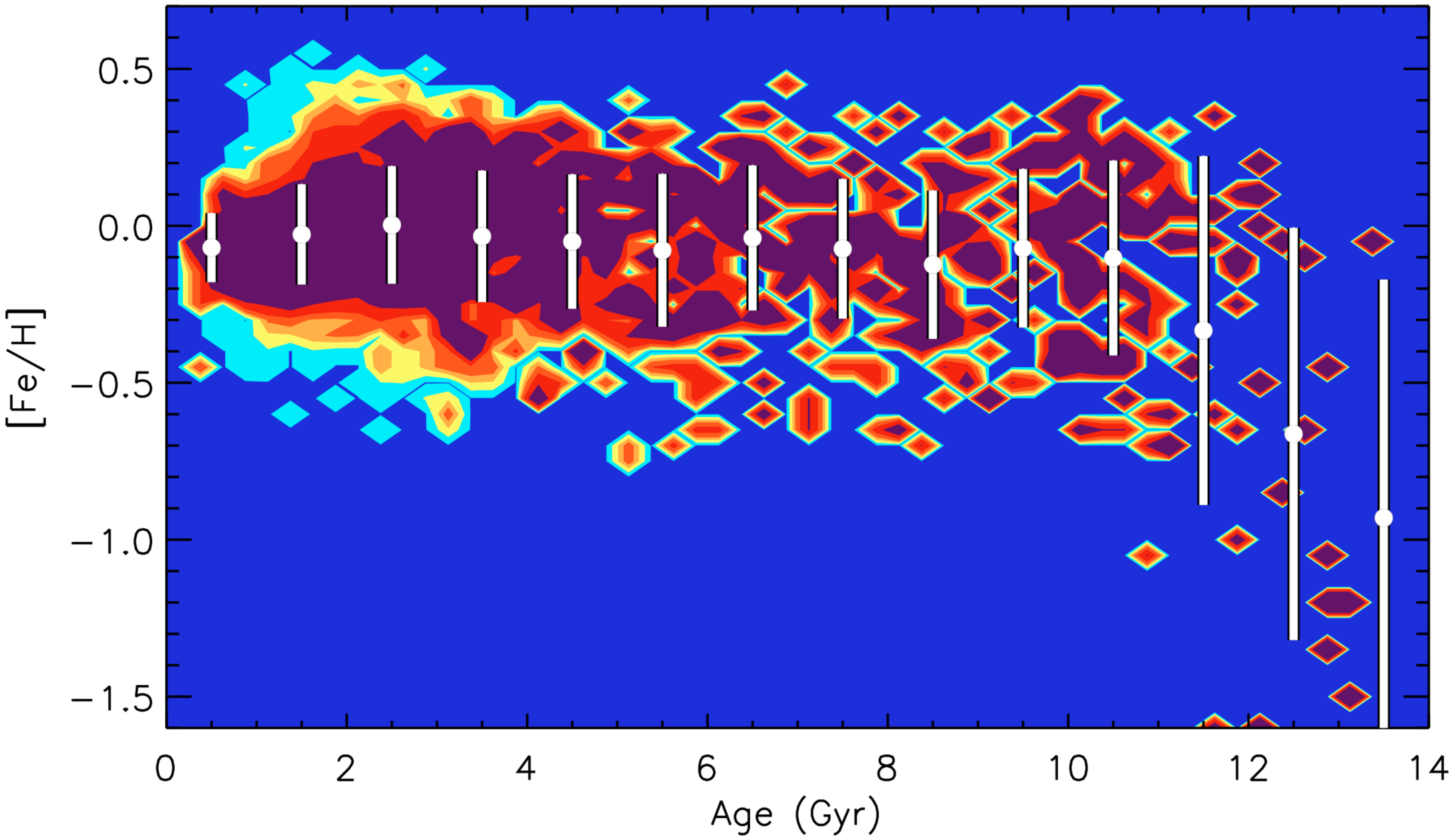
Age dependence of [Fe/H] distribution supports radial migration of stars



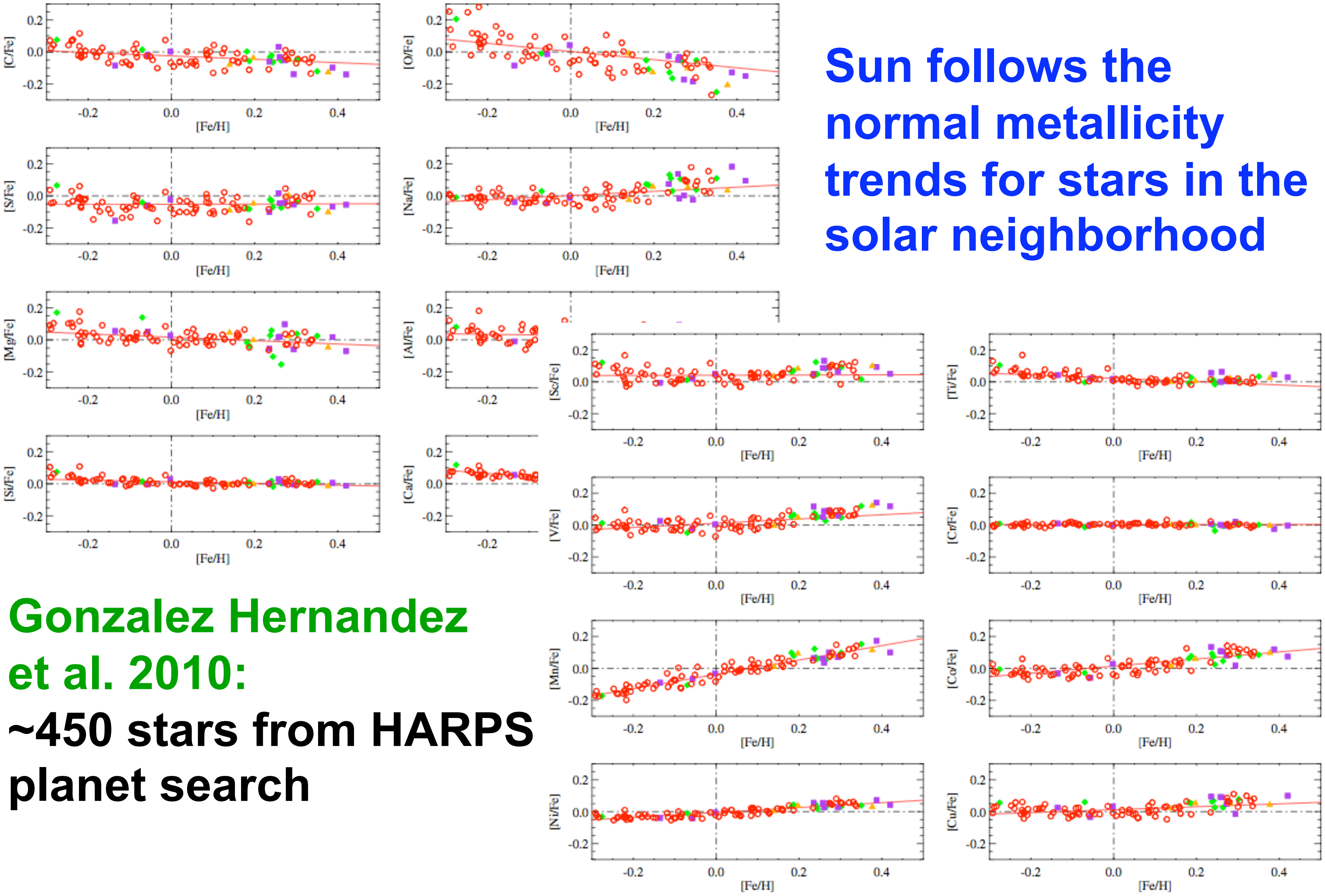
Sun vs Galactic disk stars: age

Casagrande et al. 2010:

(Lack of) Age – metallicity relation: flat with large scatter



Sun vs Galactic disk stars: [X/Fe]



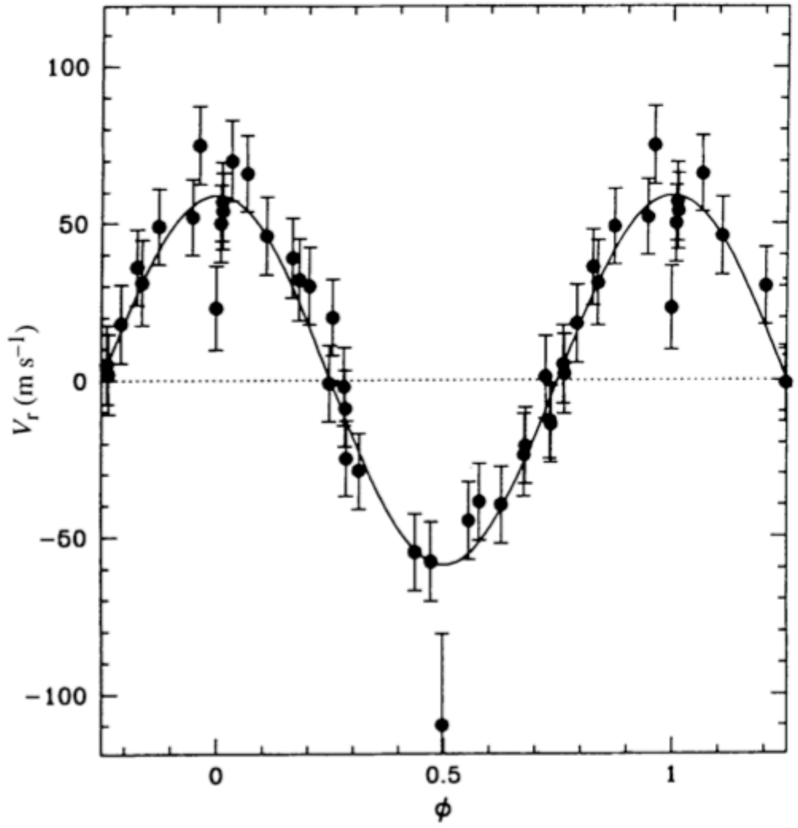
Sun follows the normal metallicity trends for stars in the solar neighborhood

Gonzalez Hernandez et al. 2010:

~450 stars from HARPS planet search

Exoplanets

Mayor & Queloz (1995)

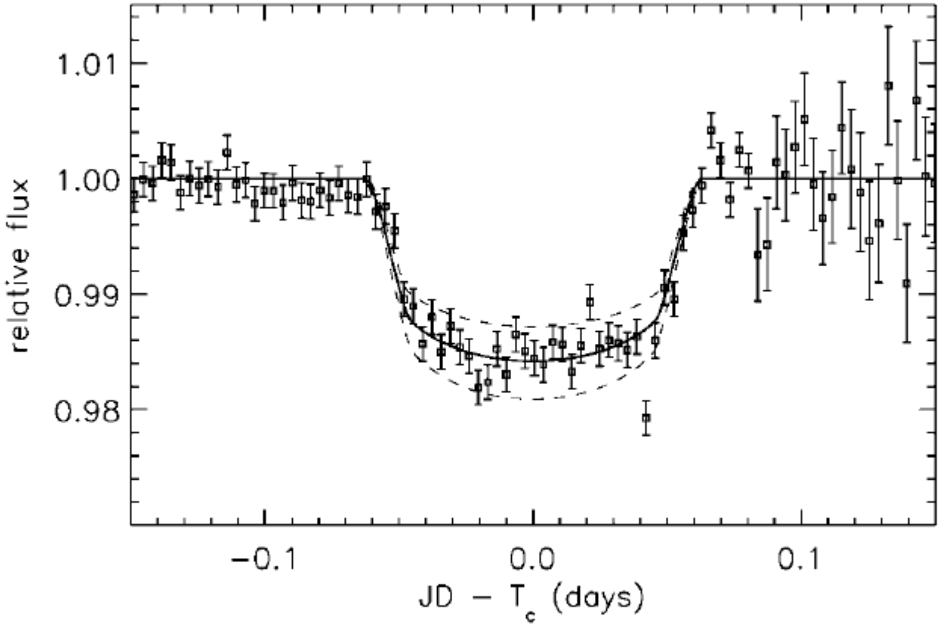


Signatures in chemical compositions due to presence of planets? What about the Sun?

Now >500 exoplanets known:

- Pulsar timing
- Radial velocity
- Transits
- Microlensing
- Direct imaging
- etc

Charbonneau et al. (2000)



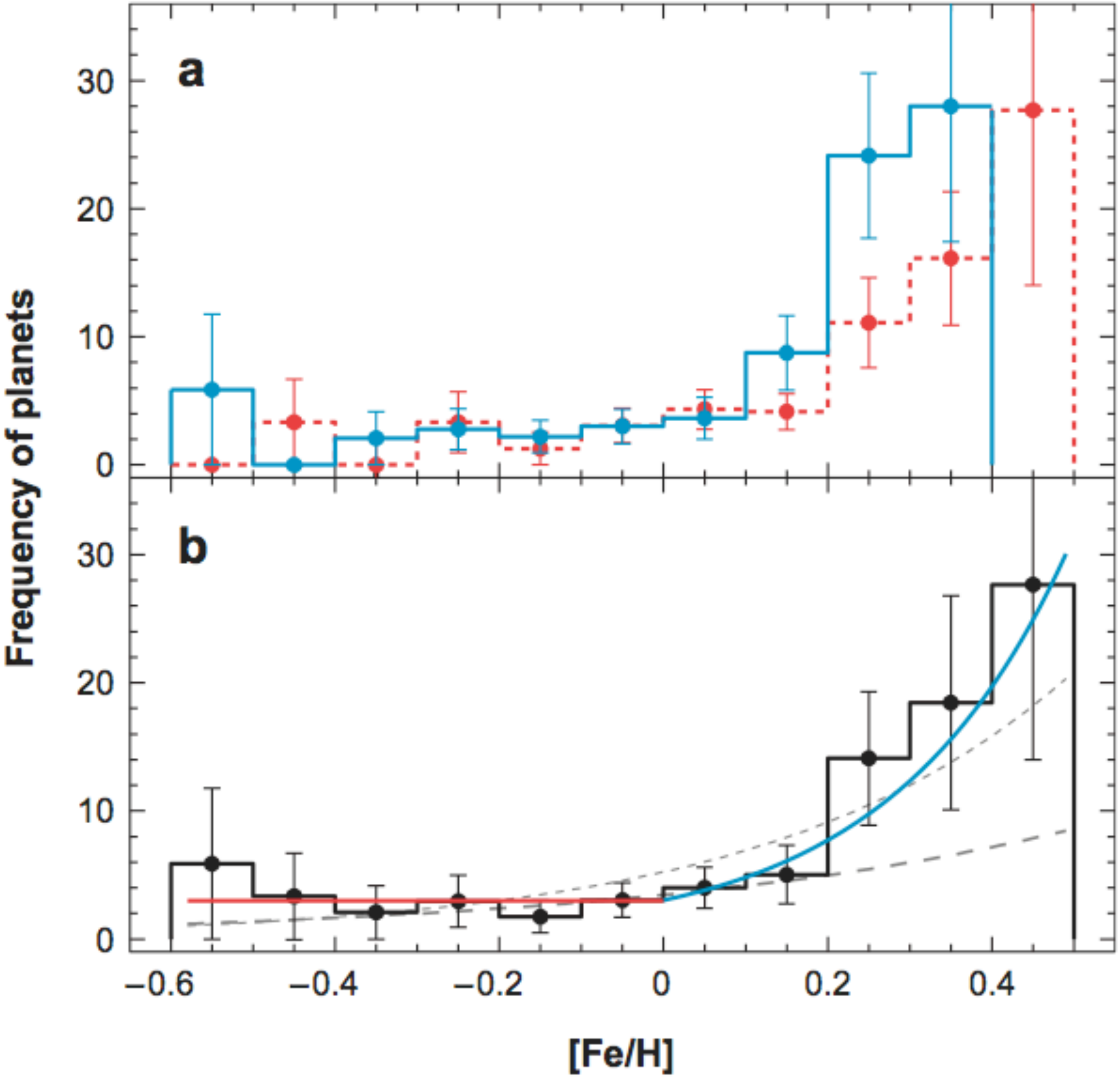
Metallicity dependence

Gonzalez (1997):
Planet hosts are more metal-rich than average

Reasons:
- **Primordial?**
- **Pollution?**

No dependence on size of conv. zone
➔ Primordial

Udry & Santos (2005)



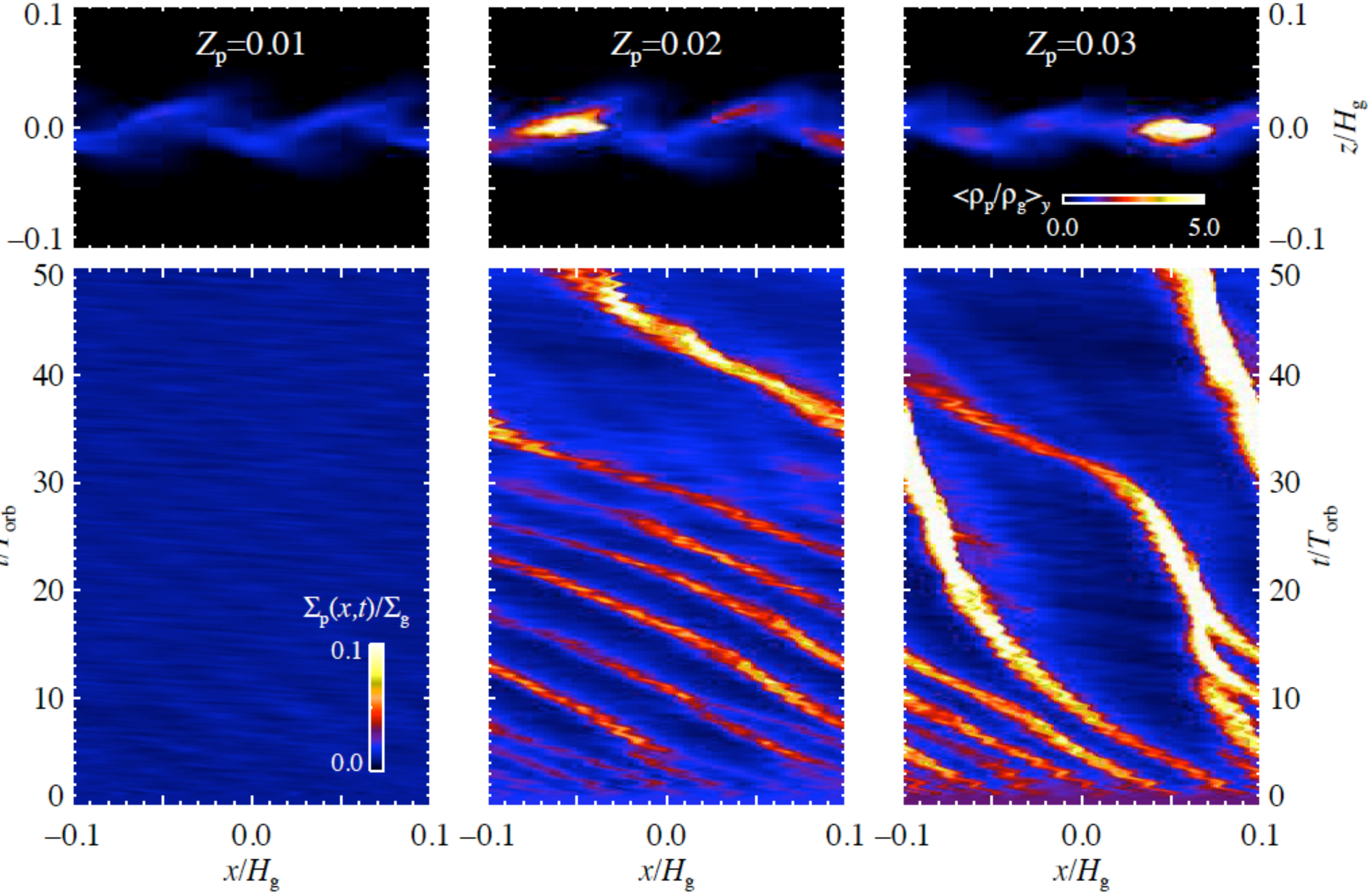
Planet formation scenarios

Two proposed main planet formation scenarios:

- **Core-accretion (Pollack et al. 1996) ➔ [Fe/H] dep.**
- **Gravitational instability (Boss 1997)**

[Fe/H]

Johansen et al. (2009)



Lithium


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


SOLVAY
4492
Copyright © 2003 Theodore W. Gray

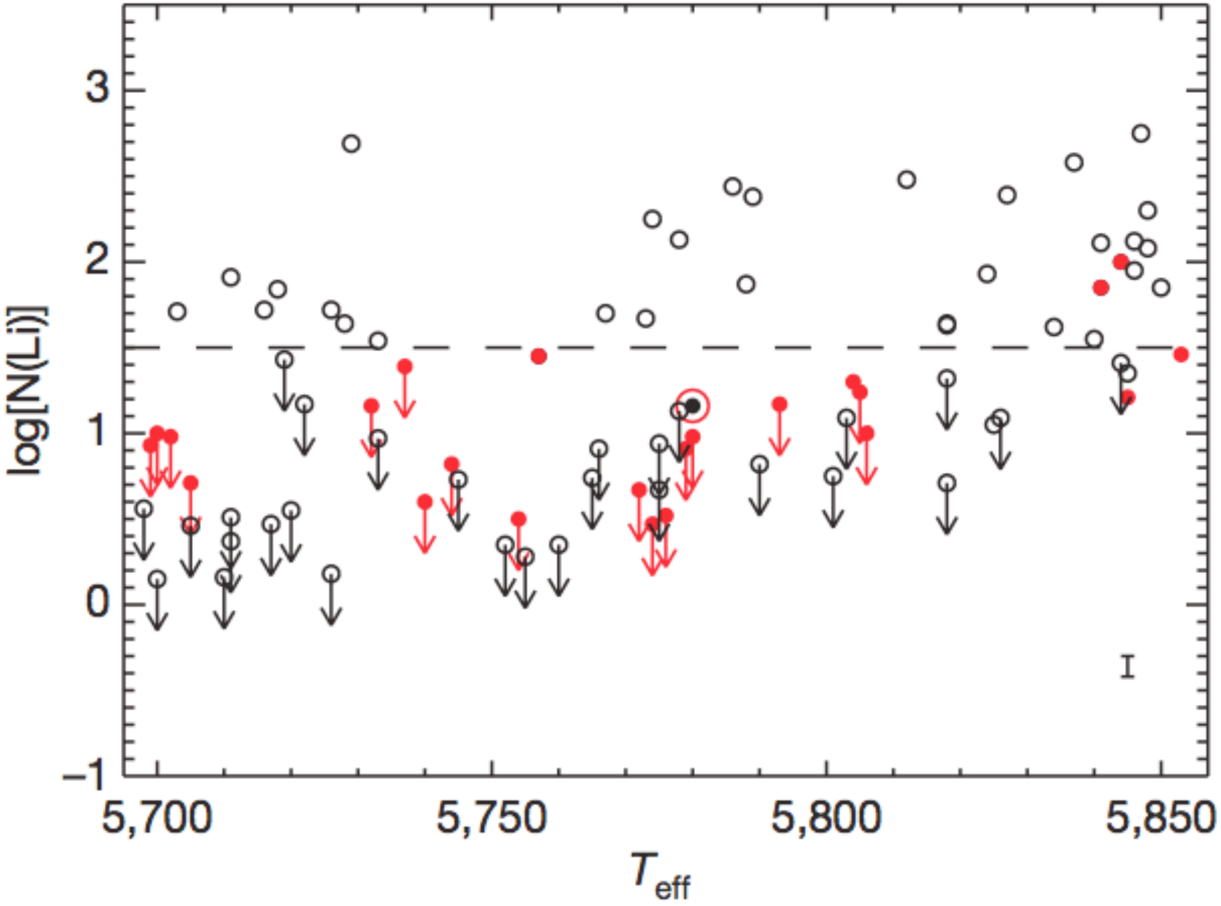
Lithium and planets?

Israelian et al. (2009, Nature):

Solar-like stars with planets tend to have less Li

→Increased Li depletion due to more rotational mixing?

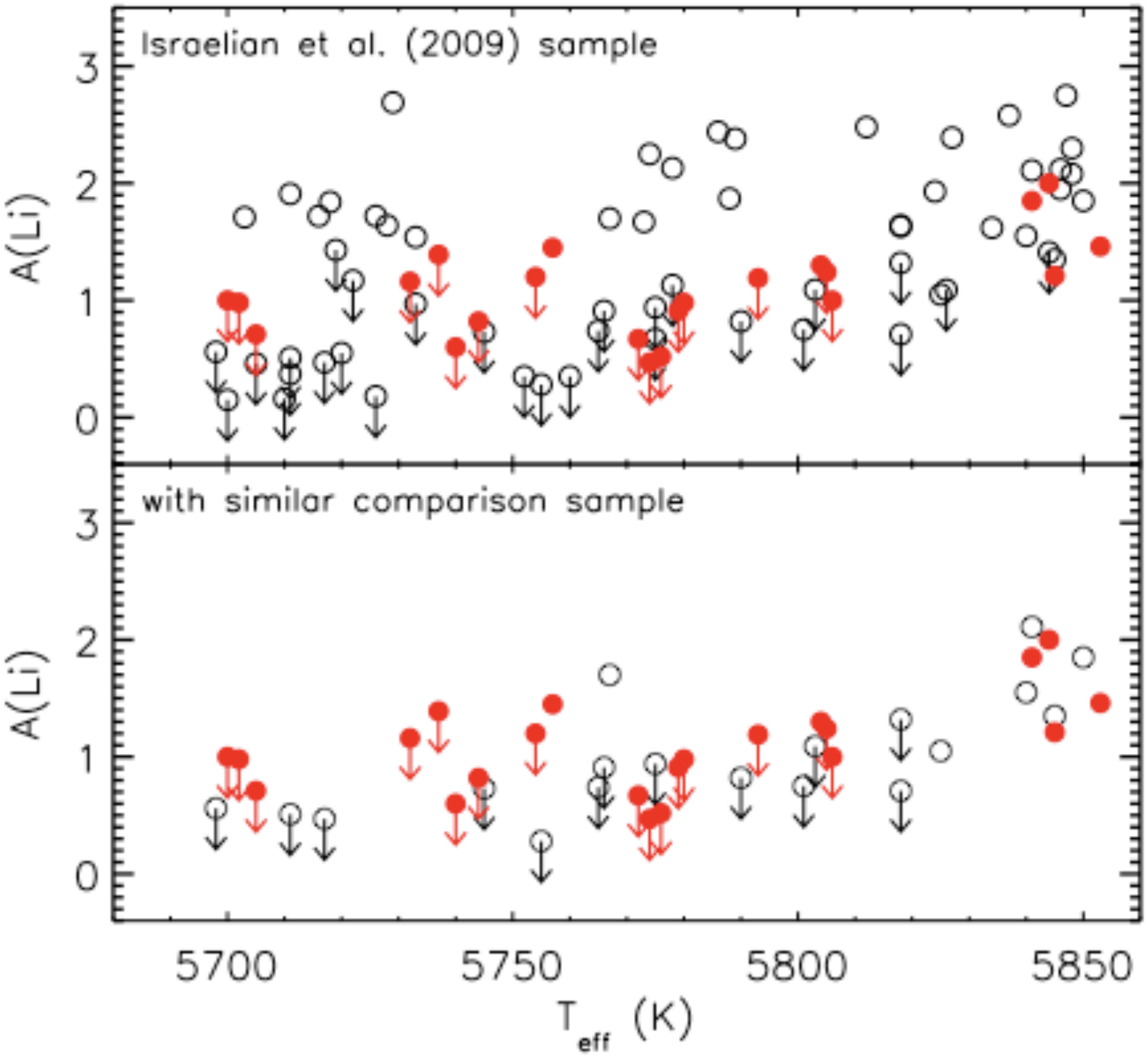
(planet migration? star-disk interactions?)



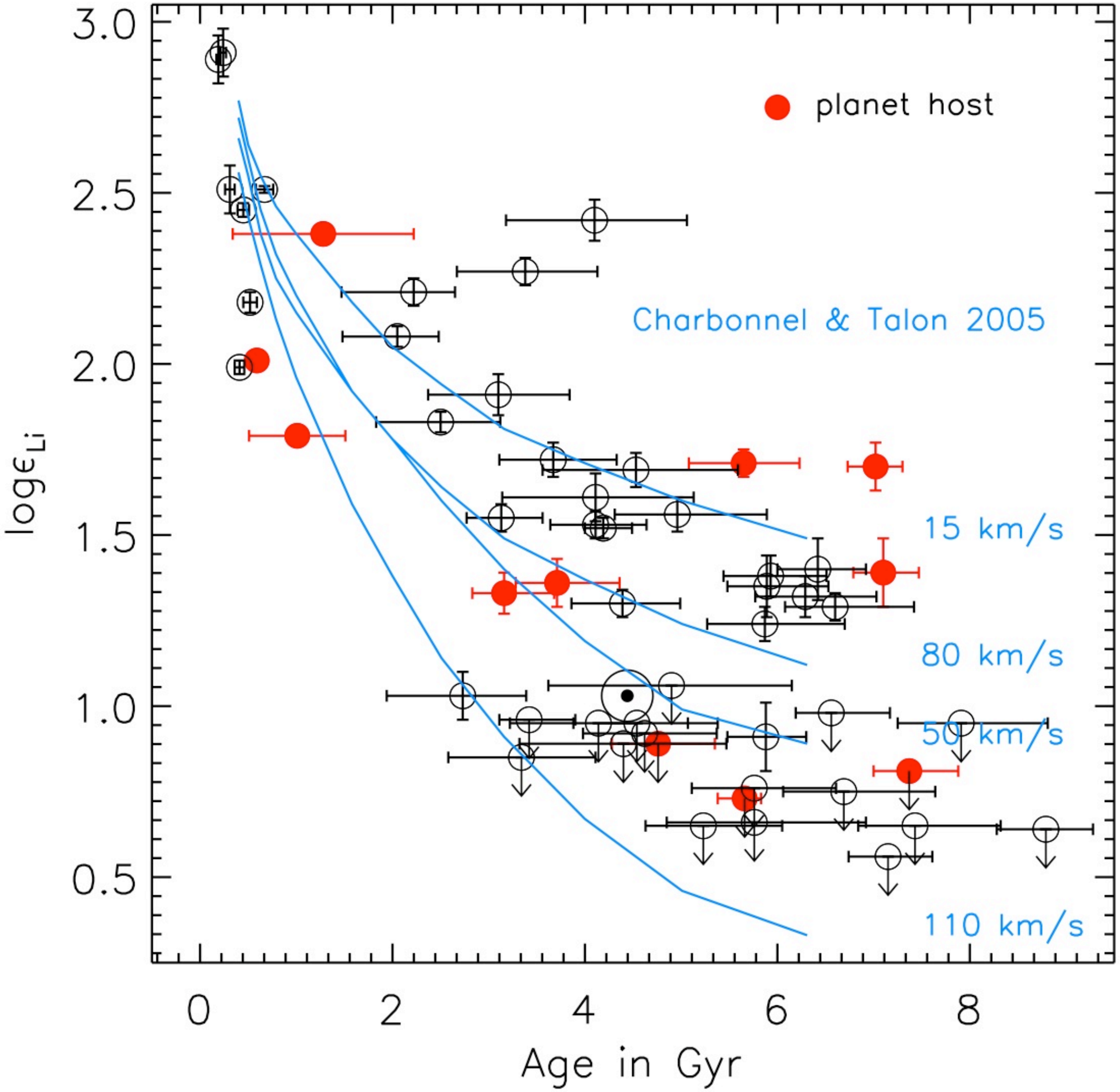
Selection effects

Baumann et al. 2010:

No difference between planet-hosts and single stars



Stellar Li depletion and planets

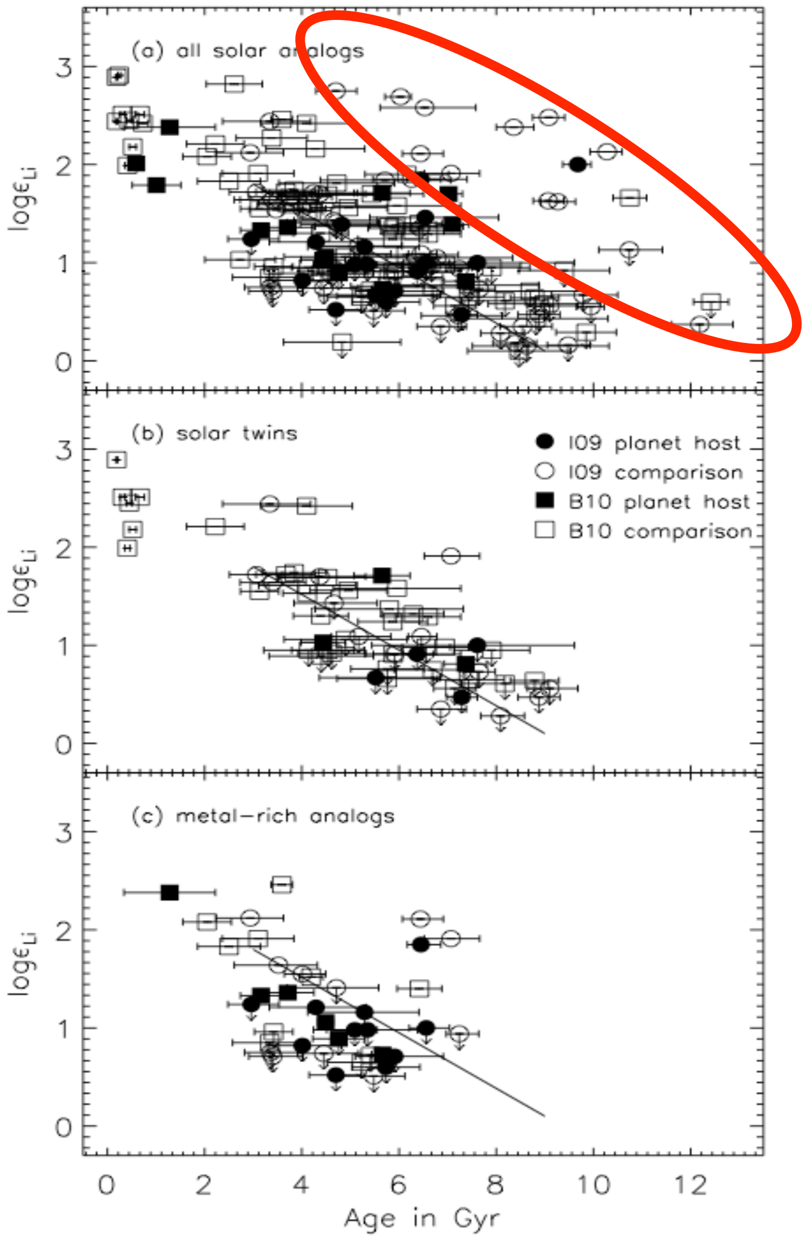


Baumann et al. (2010):

Stellar Li depletion in solar-like stars depends on age but not presence of planets

Sun is normal!

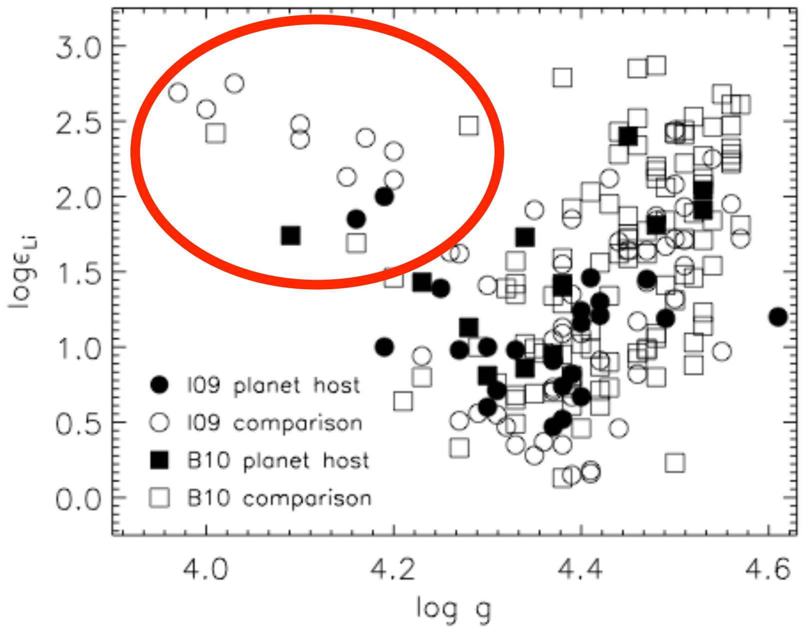
Li in solar twins + analogs



Baumann et al. (2010) & Israelian et al. (2009) stellar parameters, ages and Li are consistent

⇒ Same age-Li trend without planet dependence

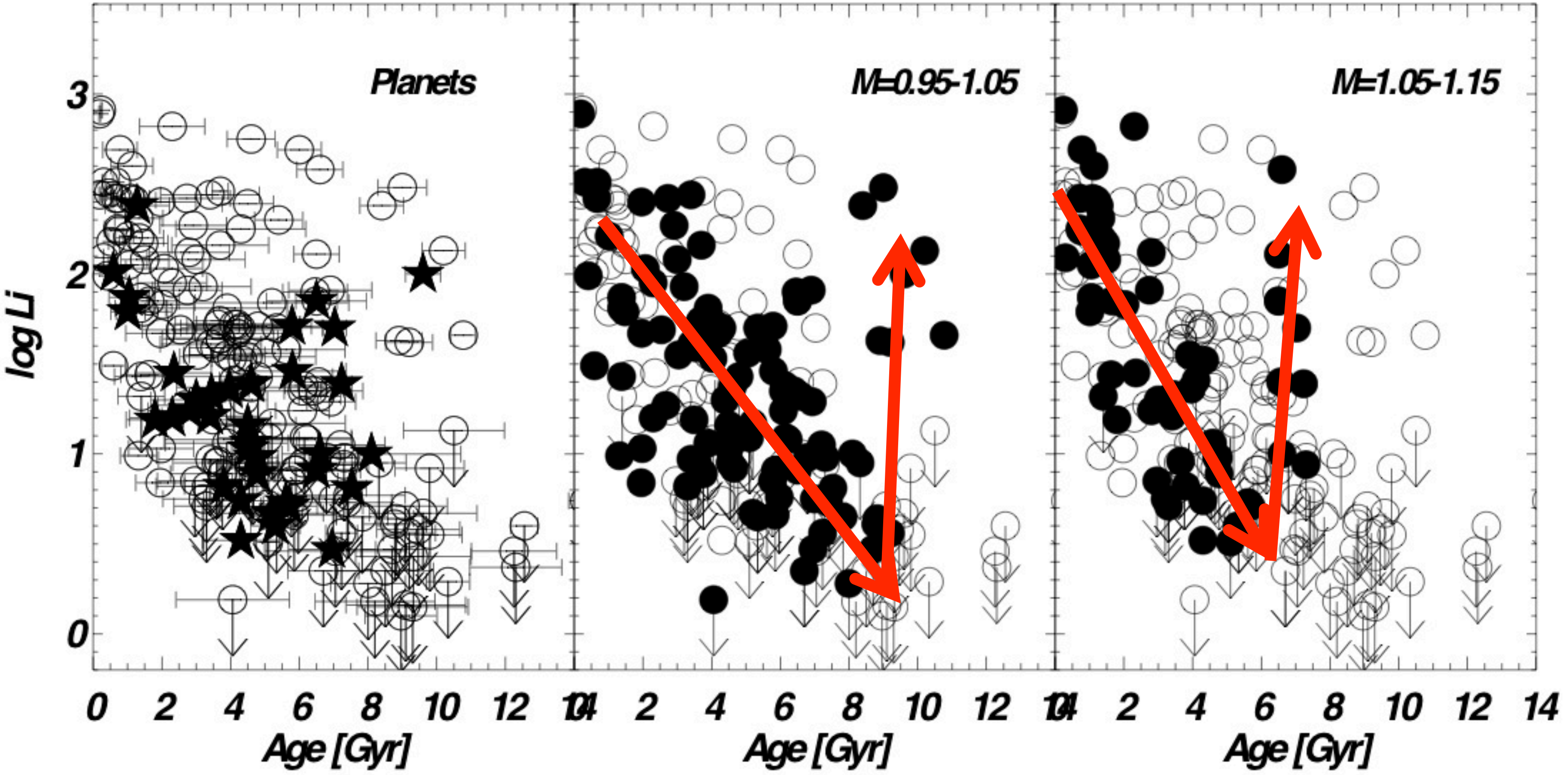
Note few high-Li outliers, which are slightly evolved stars



Mass dependence

For a given mass, Li abundance decreases steadily with age until star leaves the turn-off

Not predicted by standard stellar models



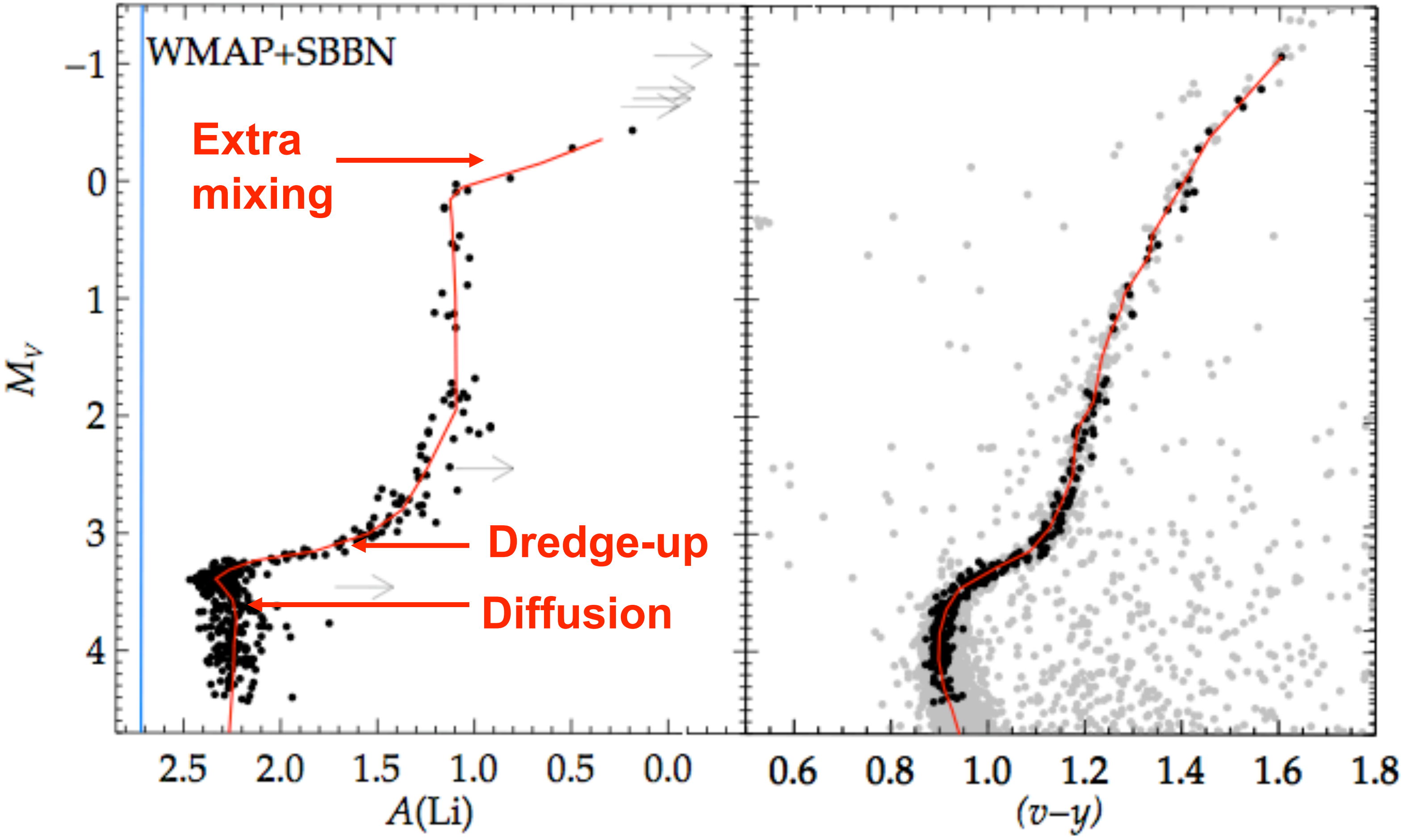
Analogy with metal-poor stars

Li along evolutionary sequence in NGC6397

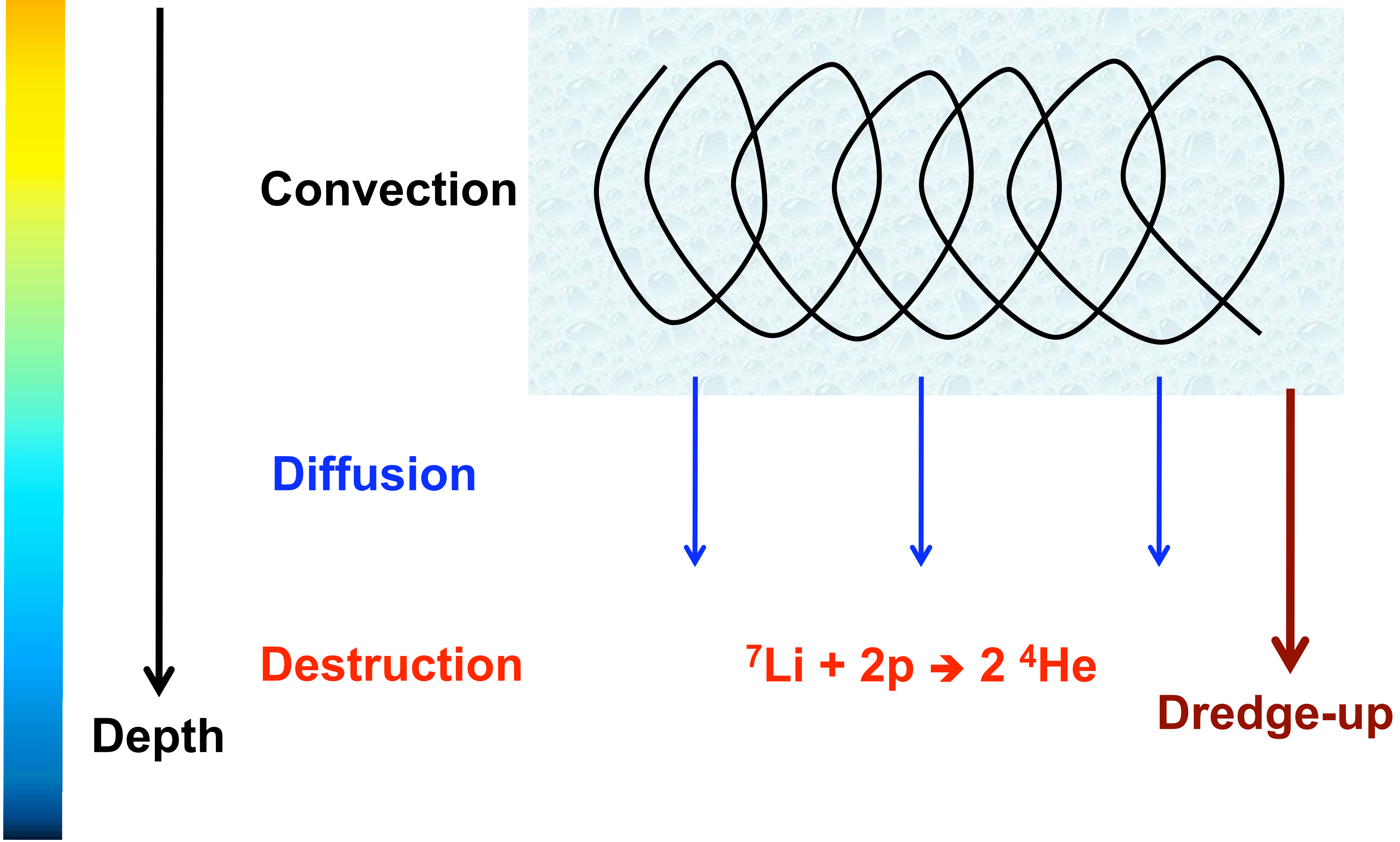
Increase in Li when stars leave turn-off (Korn et al. 2006)

Signature of atomic diffusion + turbulent mixing?

Lind et al. 2009:



Diffusion, dilution, destruction & dredge-up



Convection

Diffusion

Destruction

$^{7}\mathrm{Li} + 2p \rightarrow 2\,^{4}\mathrm{He}$

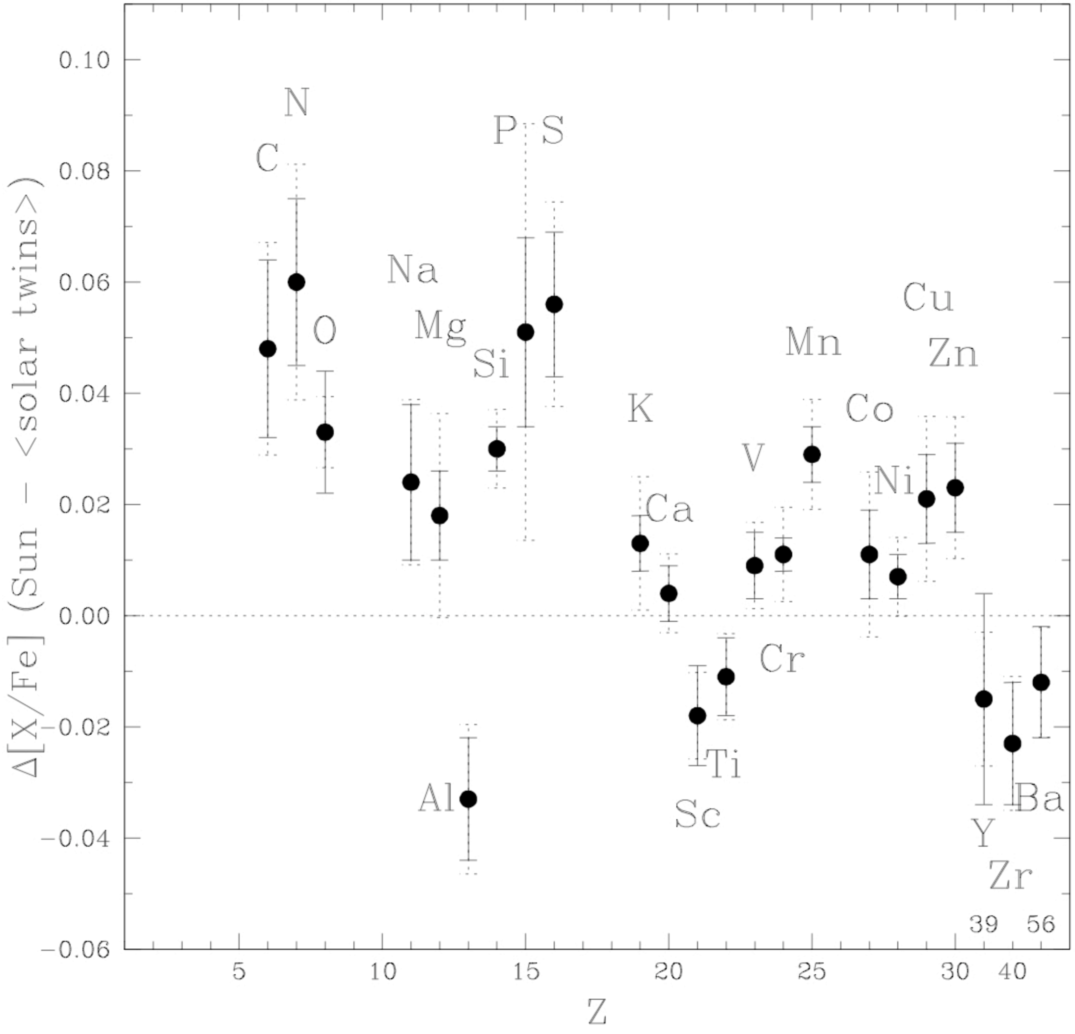
Dredge-up

Depth

Other elements

Melendez et al. 2009,
~~Science~~ ~~Nature~~ ApJL:

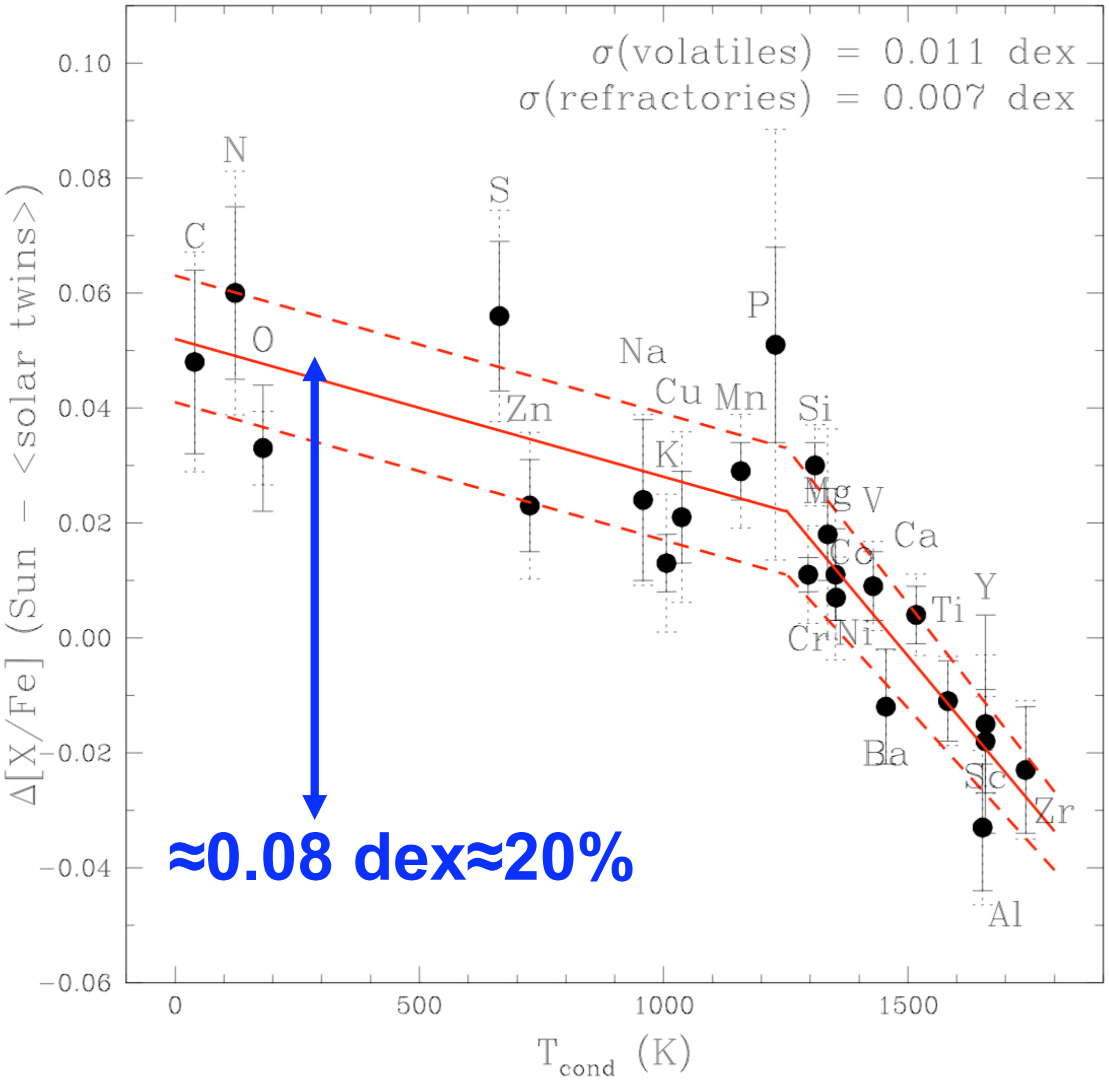
11 solar twins + Sun observed with MIKE on Magellan:



R=65,000
S/N~450
ΔT_{eff}<75K
$\Delta \log g$<0.1
Δ[Fe/H]<0.1

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

Signatures of planet formation



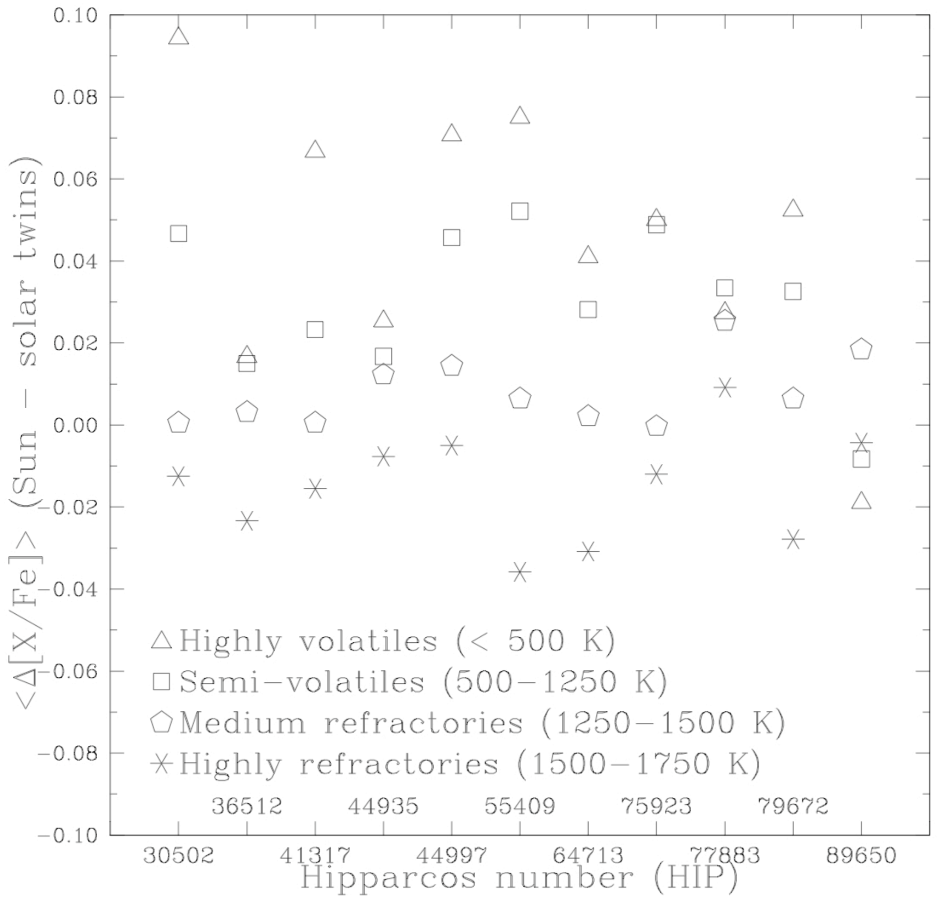
≈0.08 dex≈20%

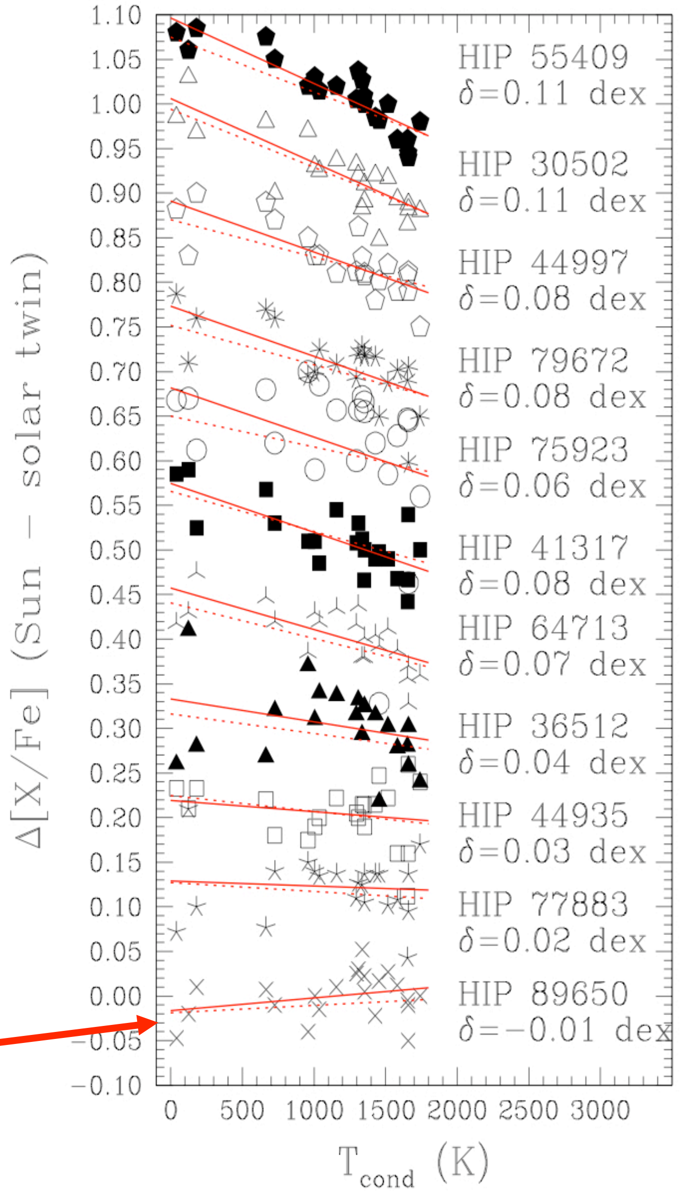
Correlation with condensation temperature highly significant

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

Melendez et al., 2009, ApJ Letters, 704, L66.

The Sun is unusual





Only a minority of our solar twins resemble the Sun

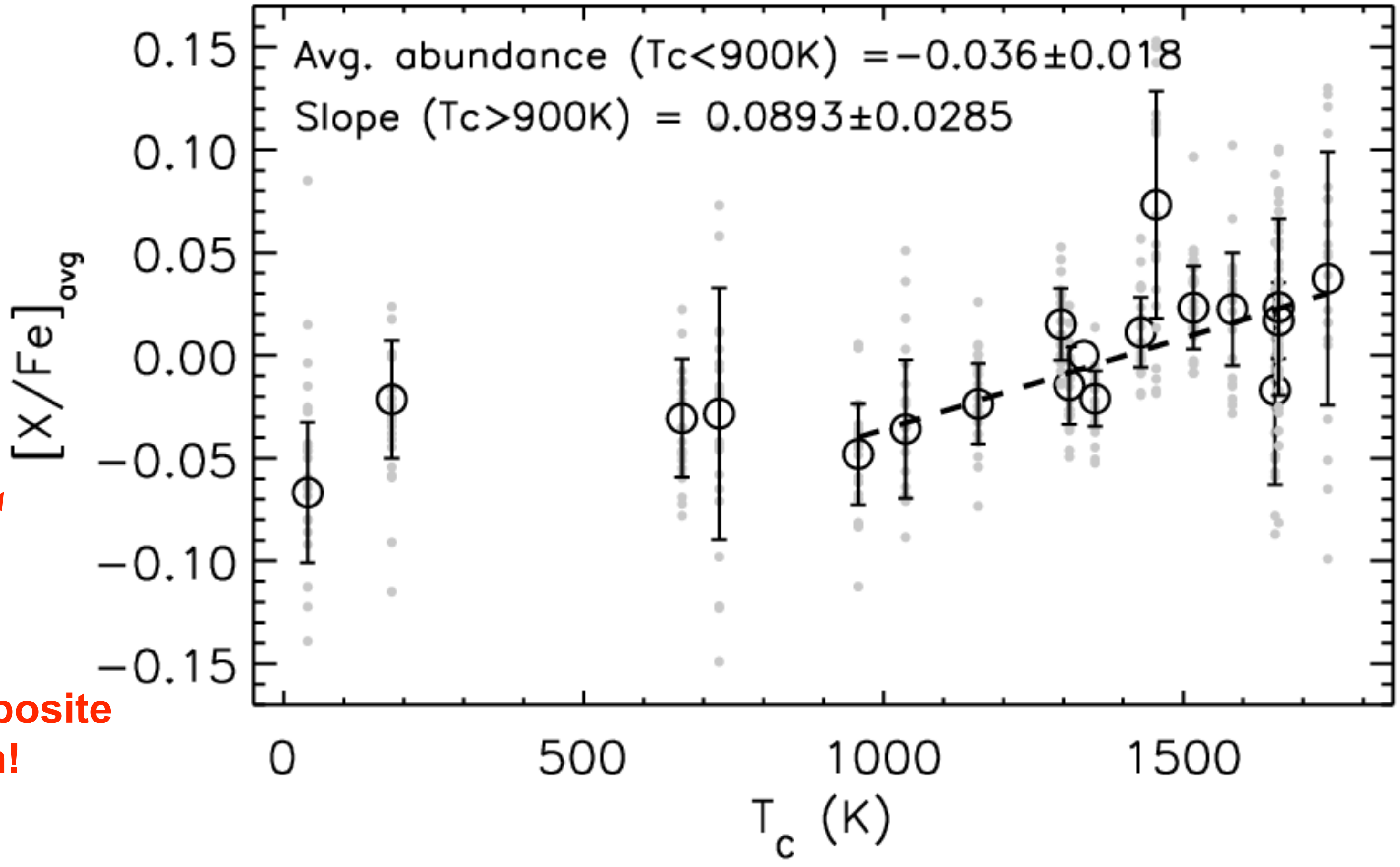
Confirmation of trend

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]



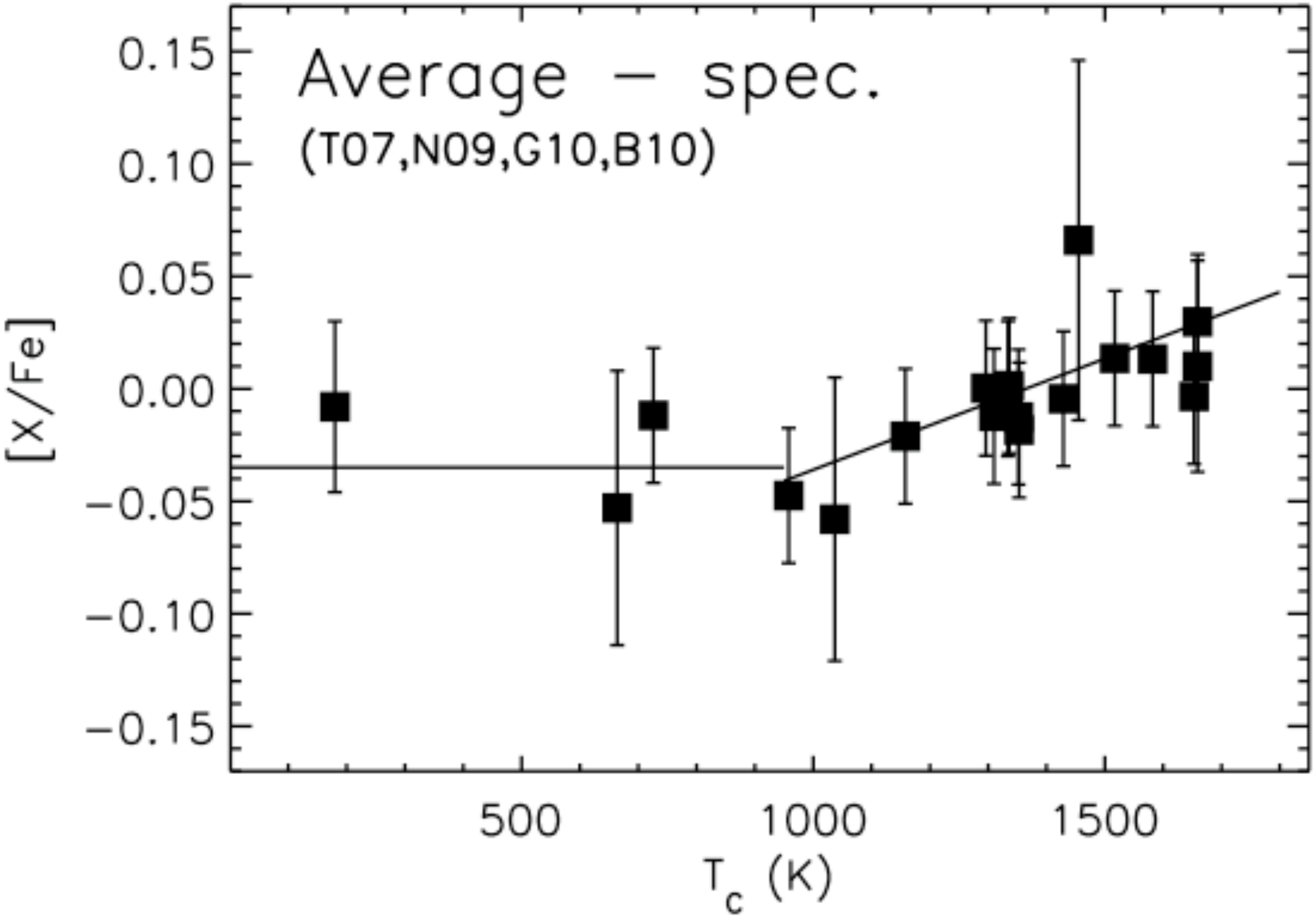
Note: opposite definition!

Re-analyzing previous studies

Why has not the trend been seen in previous studies?

More diverse samples ➔ too large uncertainties

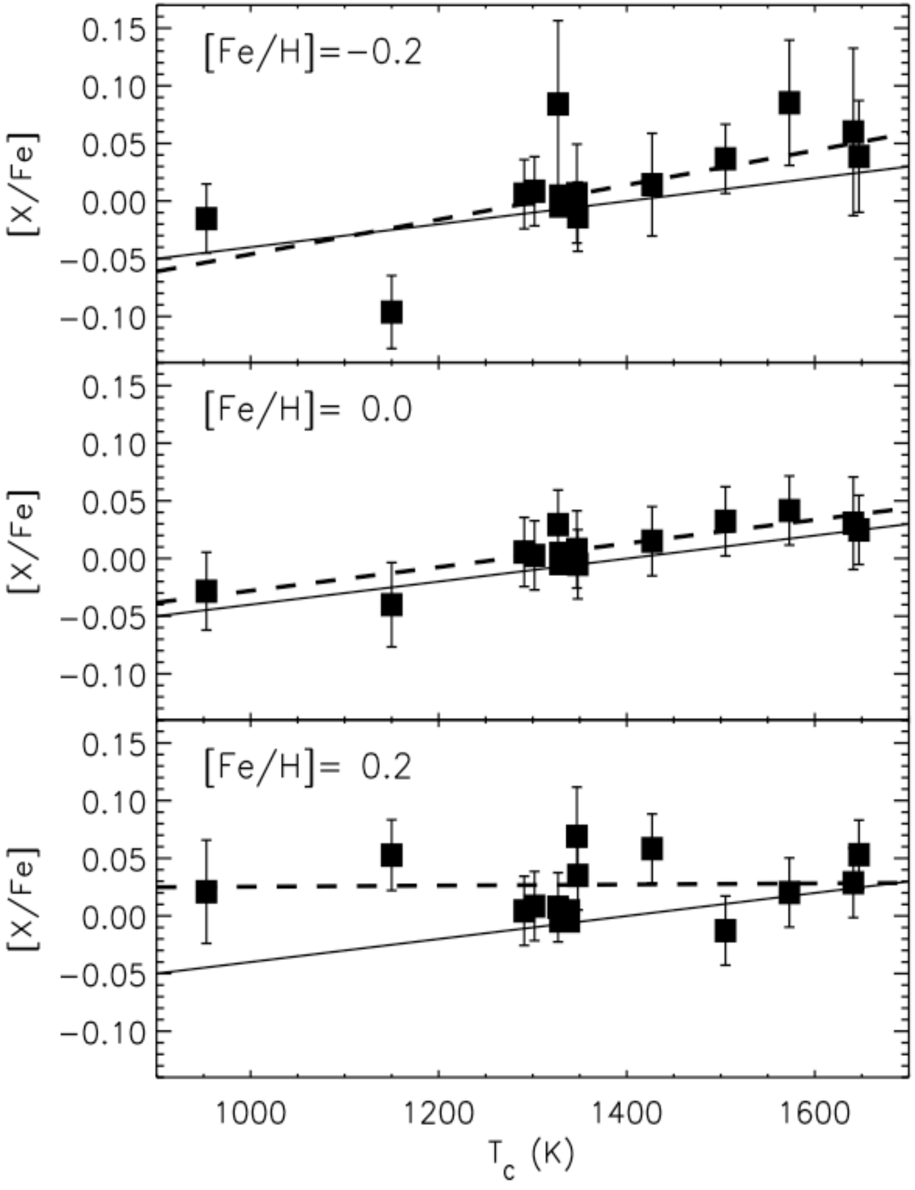
Ramirez et al. (2010): Solar analogs from literature



Data from:
Takeda et al. 2007
Neves et al. 2009
Gonzalez et al. 2010
Bensby et al. 2010

Metallicity dependence

Data from Neves et al. 2009



Ramirez et al. (2010):

Signature exists also in previous stellar samples but disappears at high [Fe/H]

⇒ Metallicity-dependence of planet formation:

At low [Fe/H] only minority has planets but at high [Fe/H] most do?

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

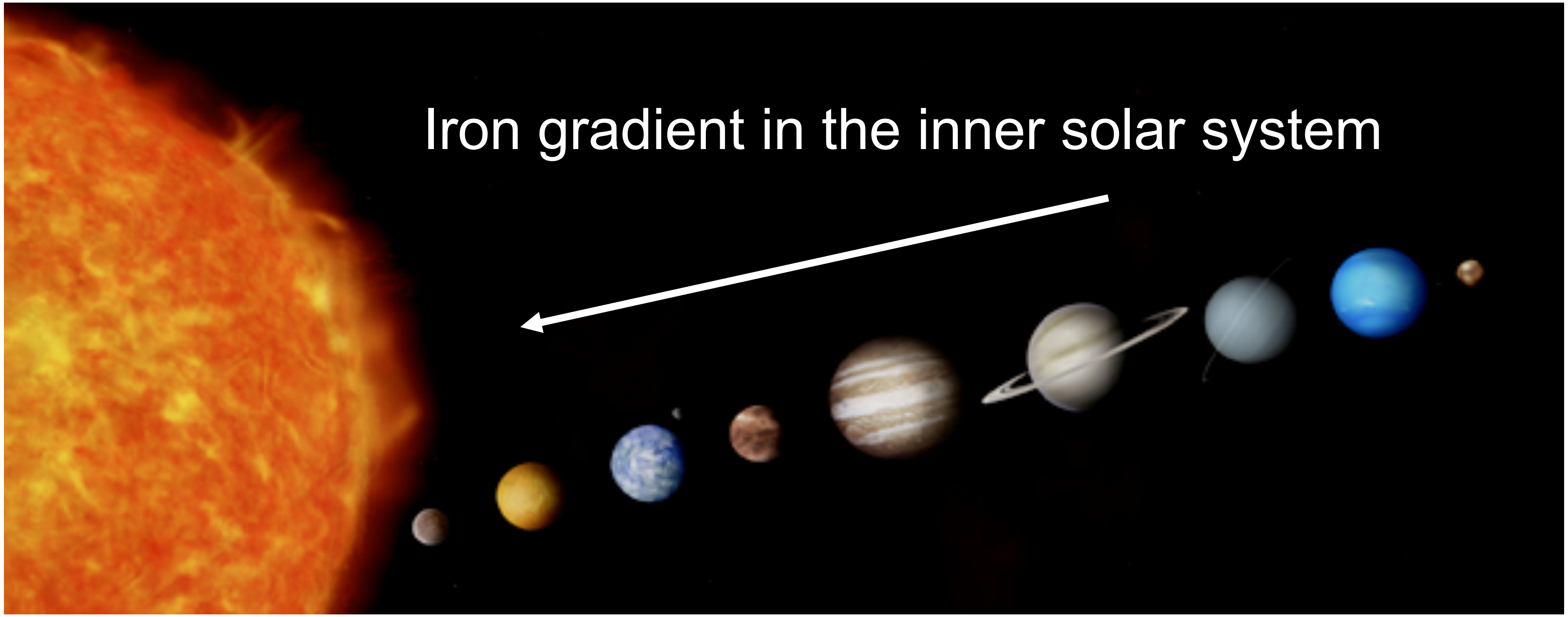
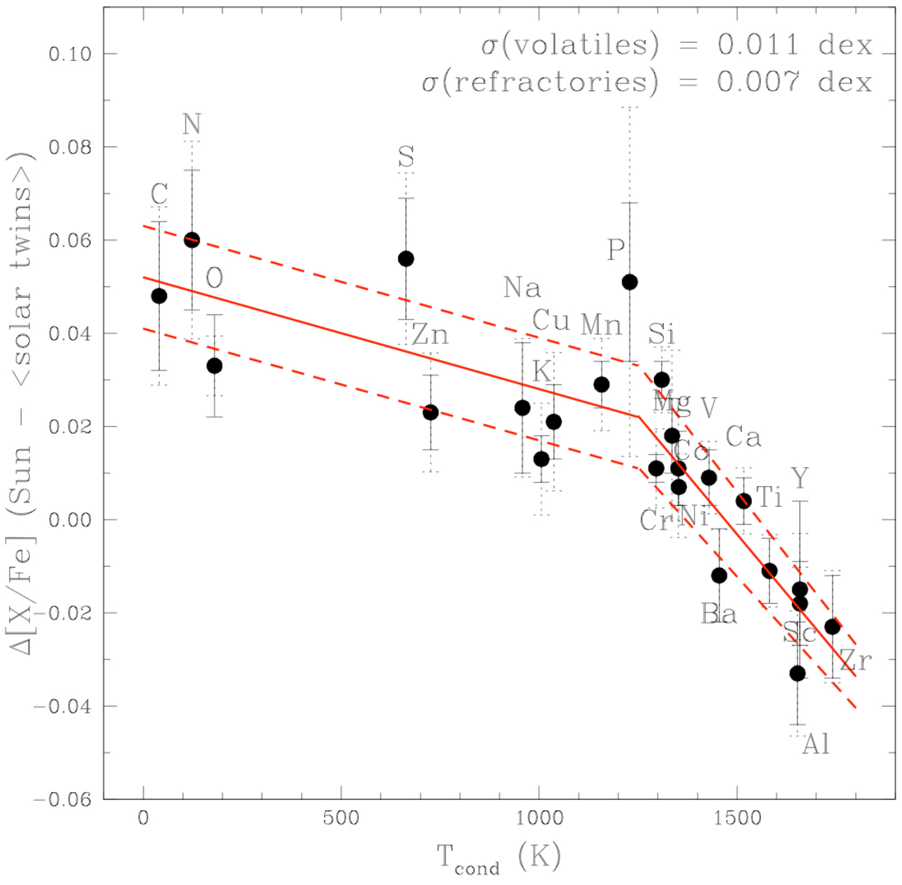


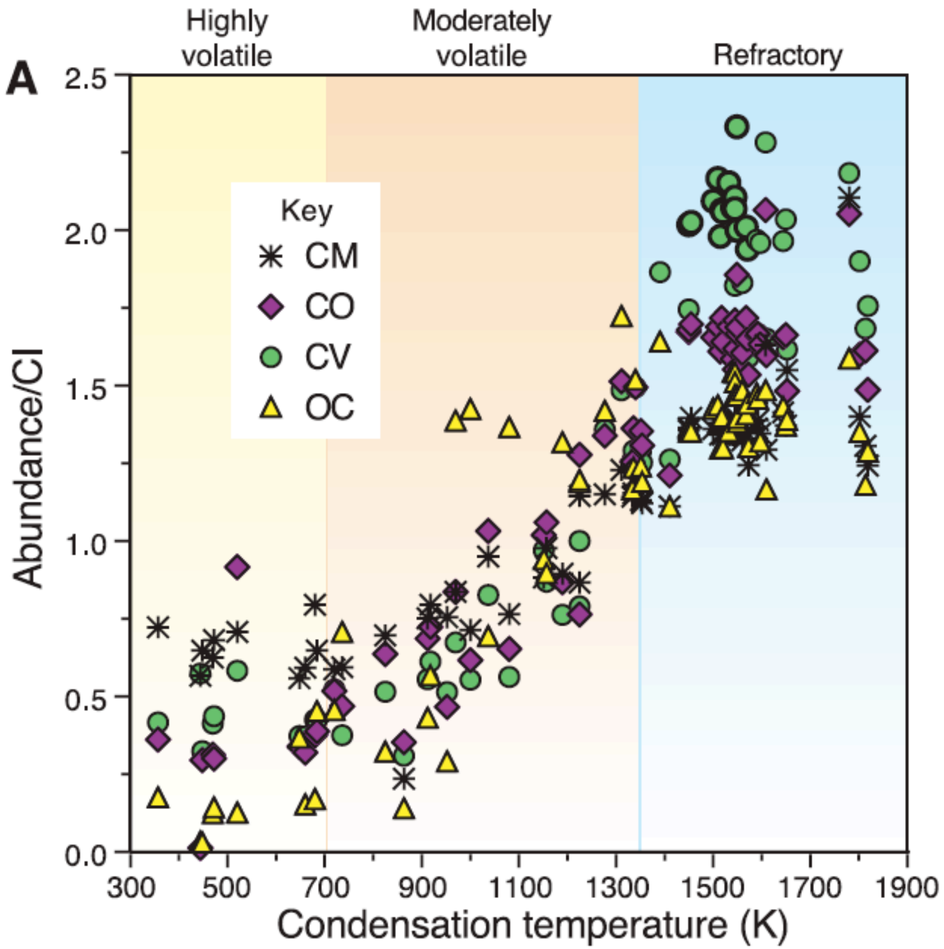
image are adopted from http://universtoday.com/

Meteorites

Similarities with trend seen for chondrites

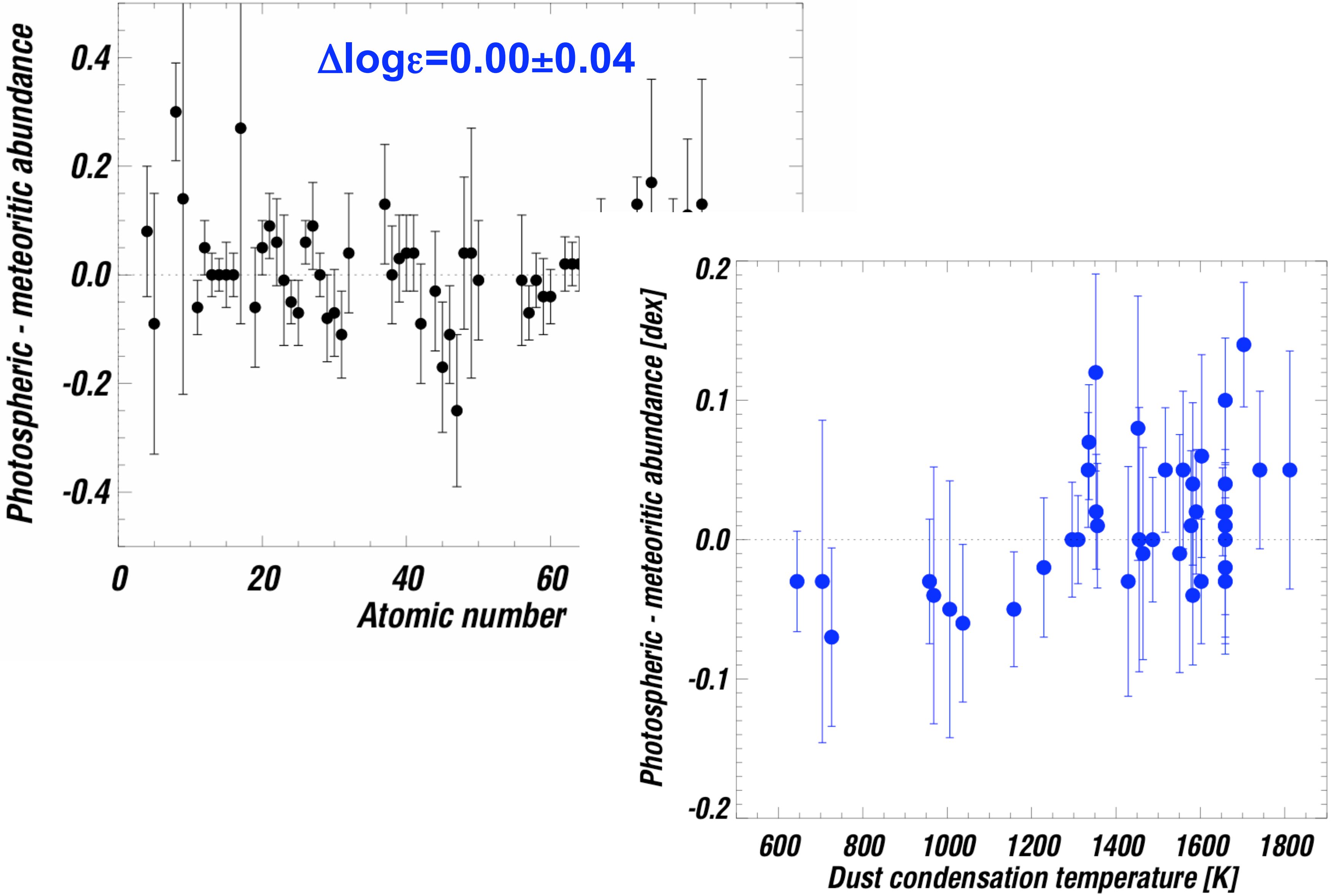


Melendez et al., 2009, ApJ Letters, 704, L66.



Alexander et al. (2001)

Sun vs CI chondrites



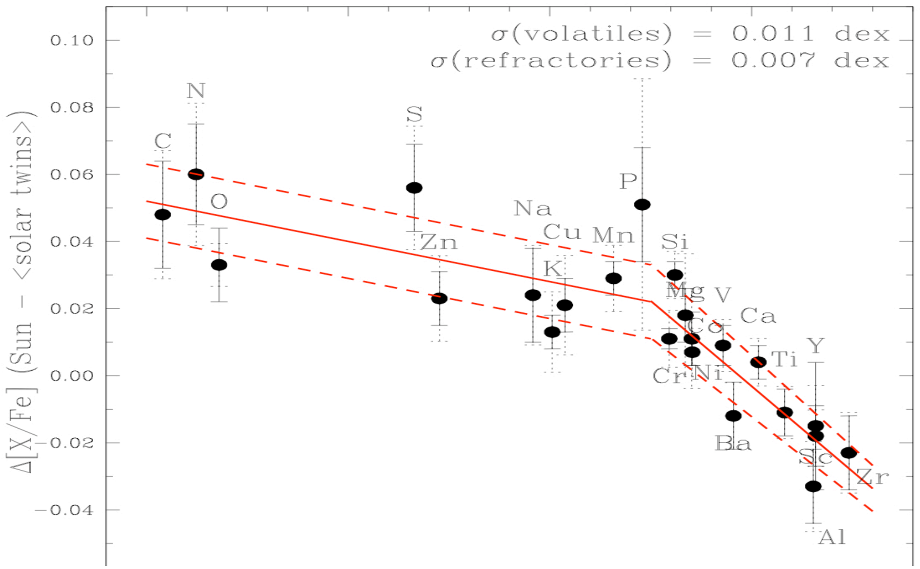
Terrestrial or giant planets?

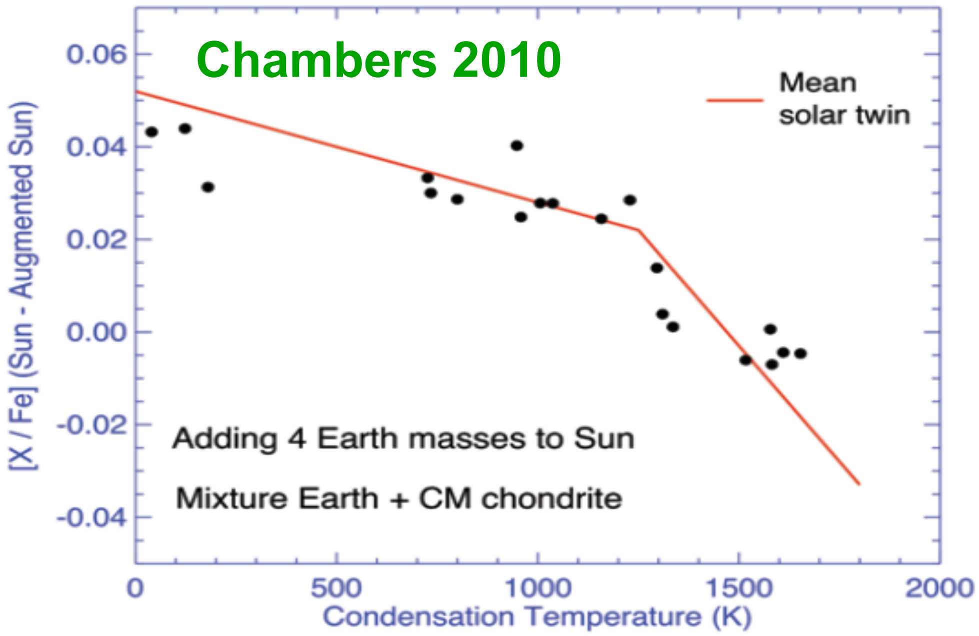
How much dust-cleansed gas accretion is required?

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

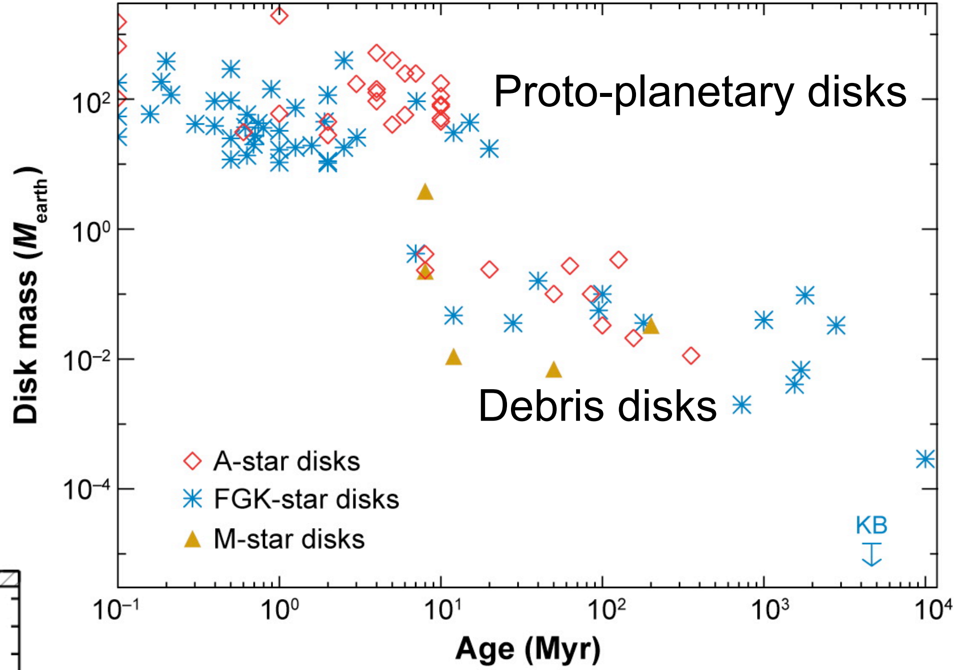




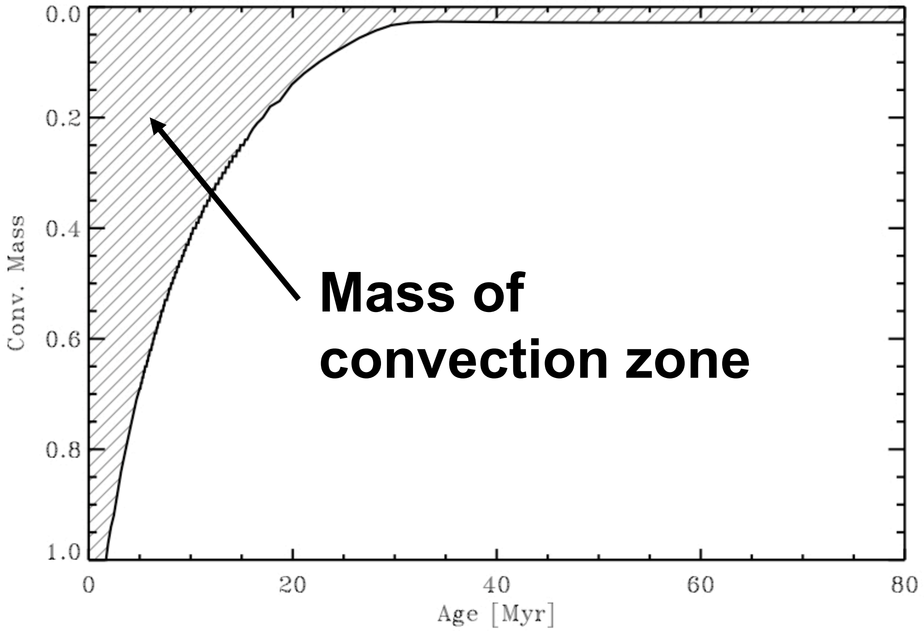
Time-scale problems

Ages of proto-planetary disks typically ≤10 Myr

Wyatt (2008)



Serenelli (2009)



M_{cz} ~0.02 M_o only >30 Myr

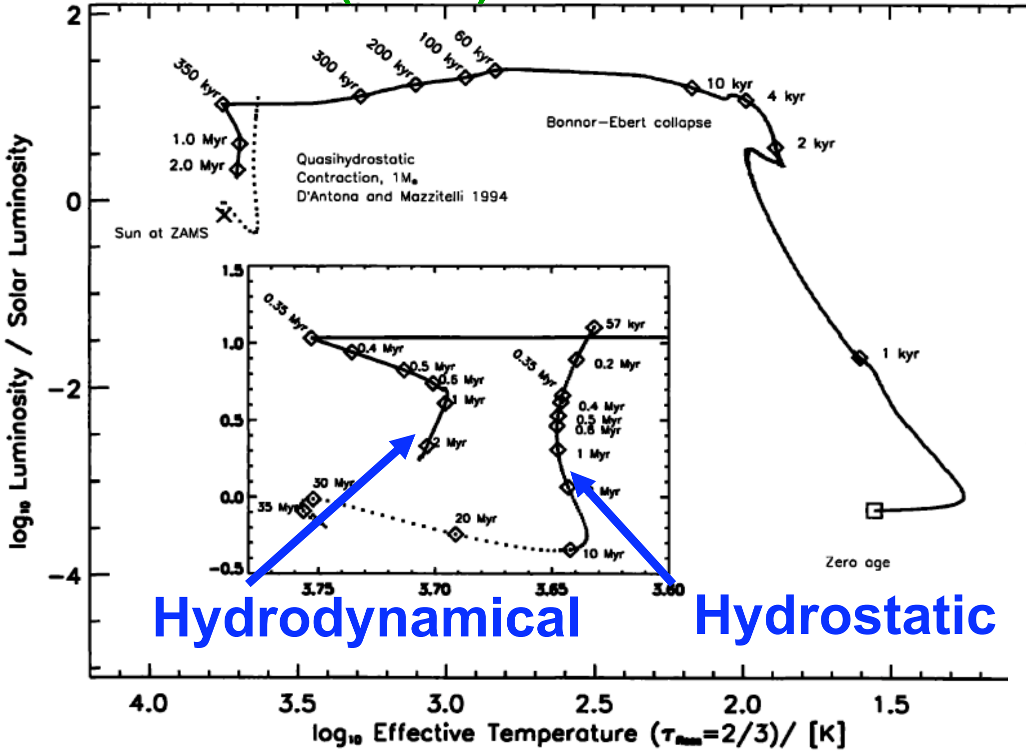
M_{cz} ~0.4 M_o at ~10 Myr

Sun had unusually long-lived disk?

Pre-main sequence

Smaller convection zone in hydrodynamical models?

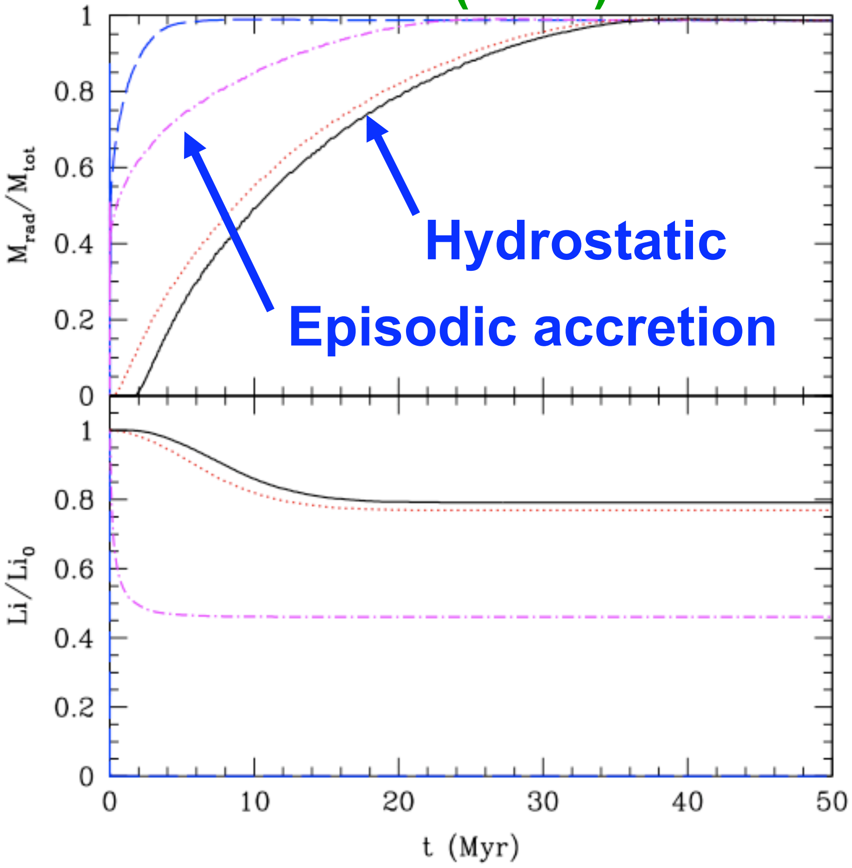
Wuchterl (2004):



Hydrodynamical

Hydrostatic

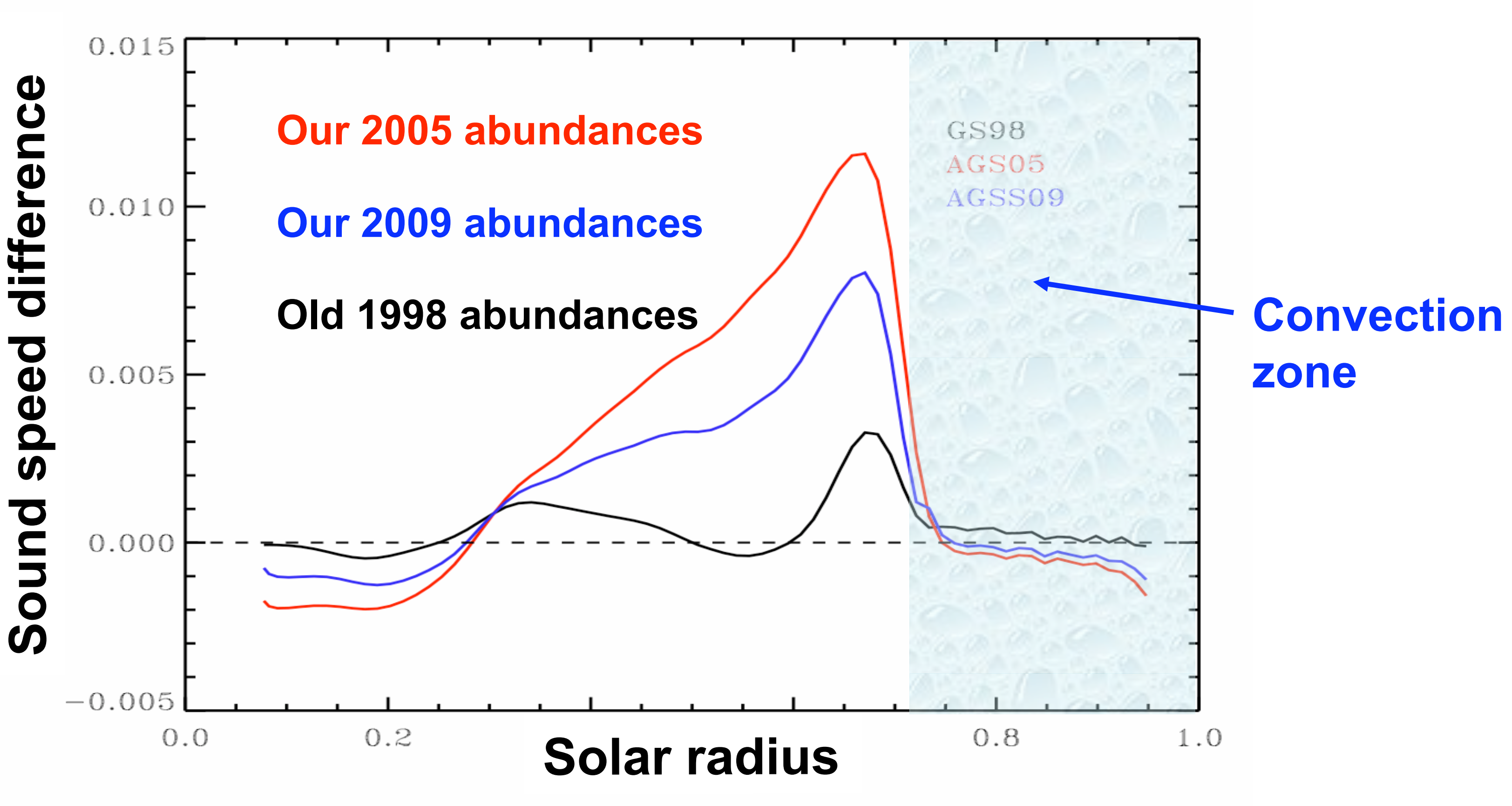
Baraffe et al. (2010):



Hydrostatic

Episodic accretion

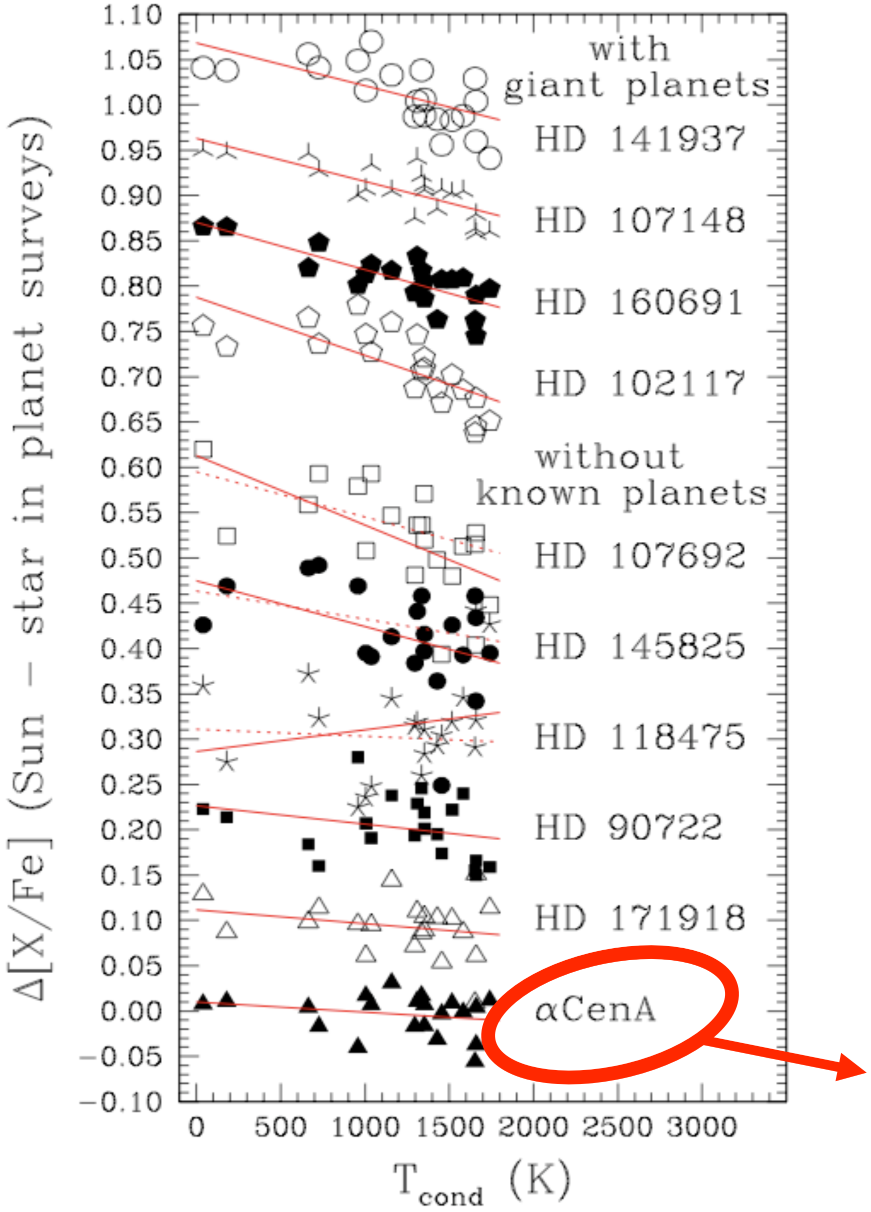
Solution for helioseismology?



Solar interior composition is not the same as photospheric abundances

Preliminary results: not enough…

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%

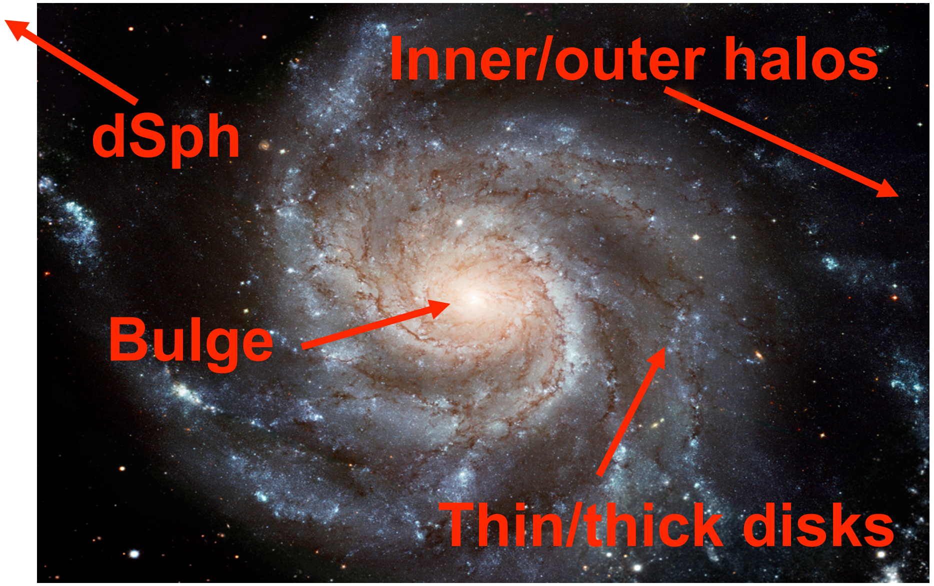
Close-in giant planets prevent long-lived disks and/or formation of terrestrial planets?

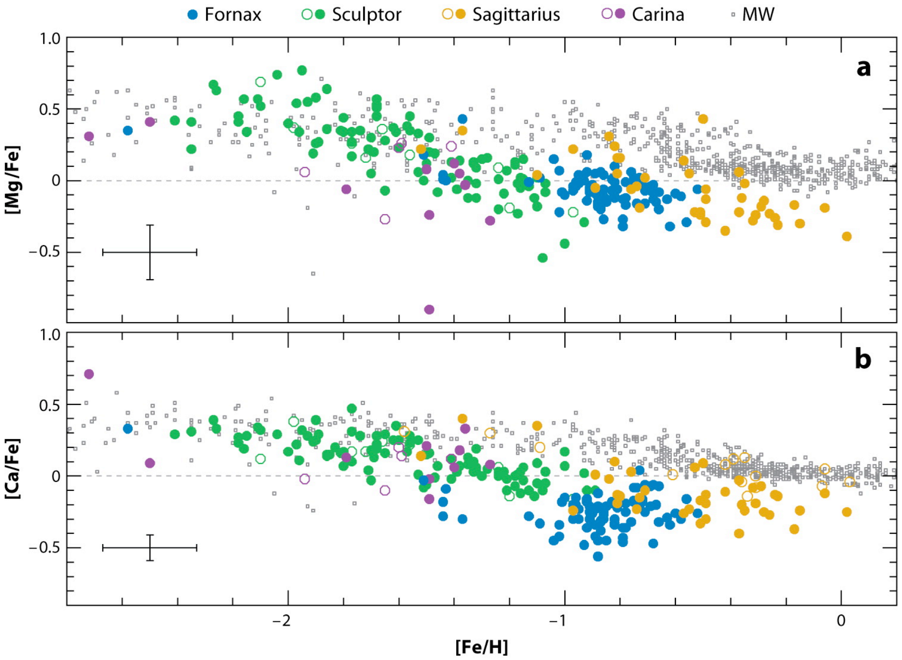
An ideal candidate for terrestrial planet searches

Galactic archaeology

Stellar abundances + kinematics to unravel the history of the Milky Way and its populations:
Nucleosynthesis, IMF, SFR, infall/outflow, migration etc
(see lectures by E. Tolstoy!)

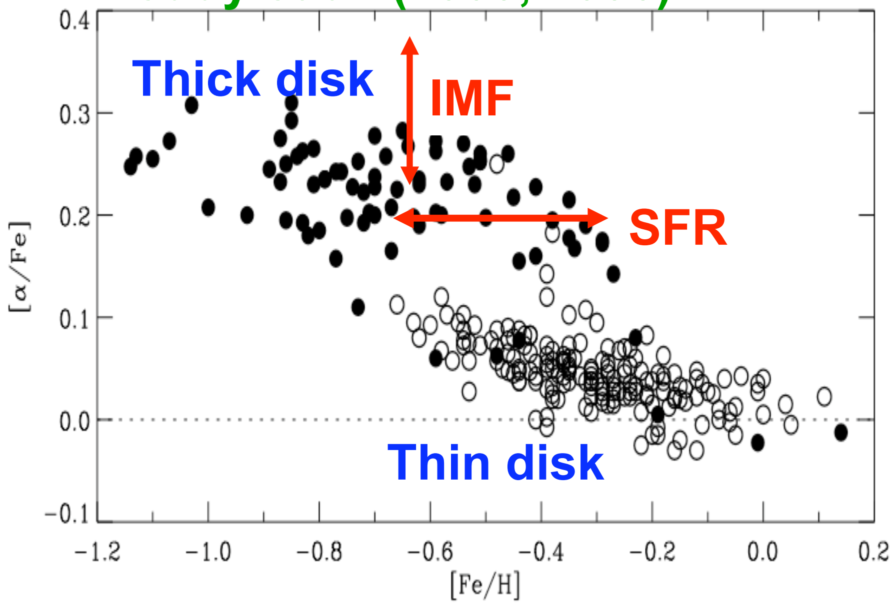
- Nature of the first stars
- Evolution of the bulge
- The disks and their substructure
- Chemical enrichment of globular clusters
- dSph/UFD and MW accretion history





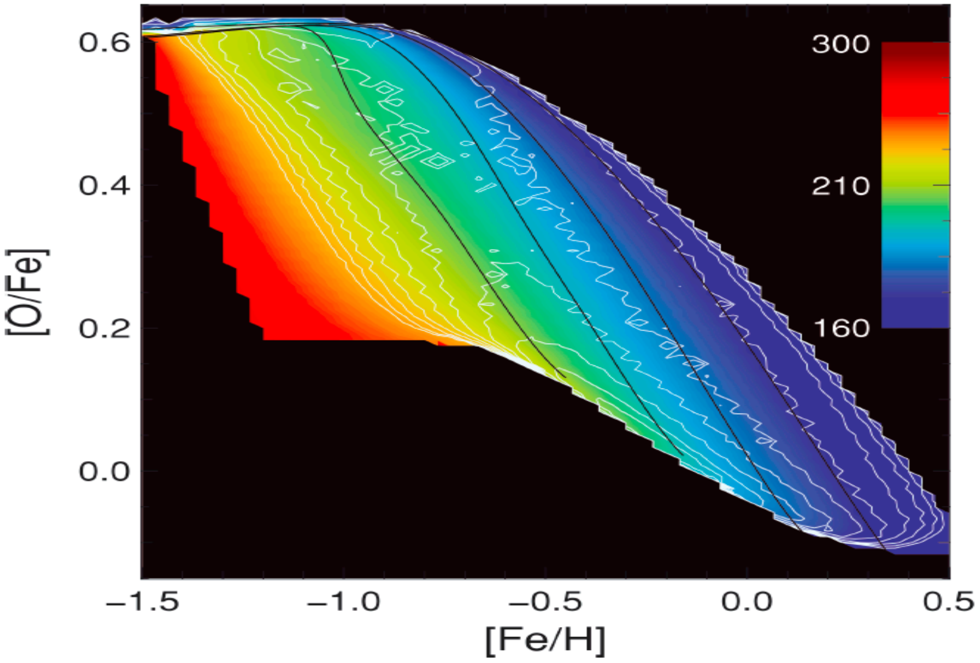
Tolstoy et al. (2009)

Galactic thin/thick disk


Reddy et al. (2003, 2006)

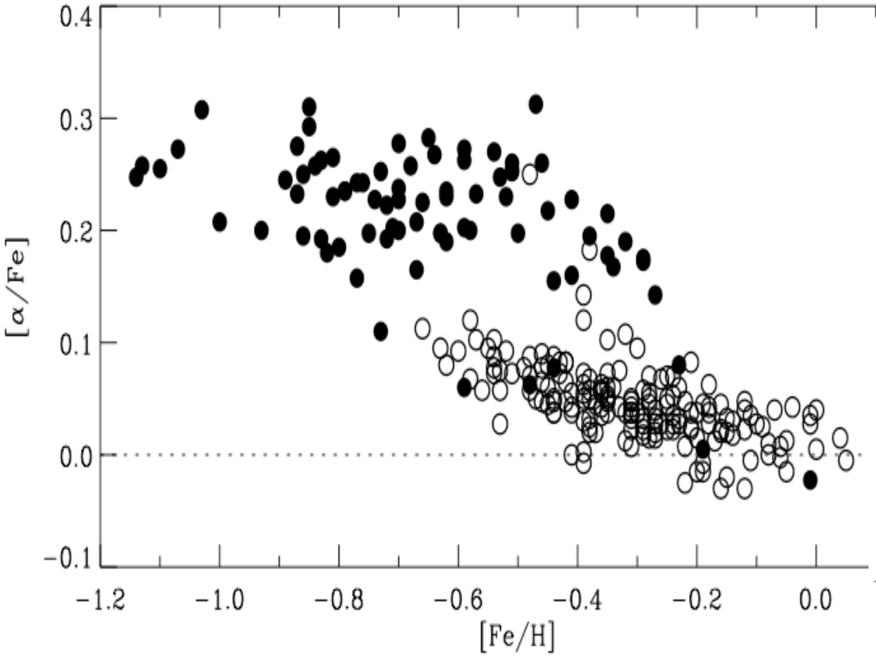
Classical Galactic chemical evolution models:
Merger origin for thick disk?

Galactic chemical evolution models w/ radial migration:
Thick disk natural consequence of old stars from inner disk migrated to solar neighborhood


Schönrich & Binney (2009)

Galactic archeology and planets

Reddy et al. (2006)



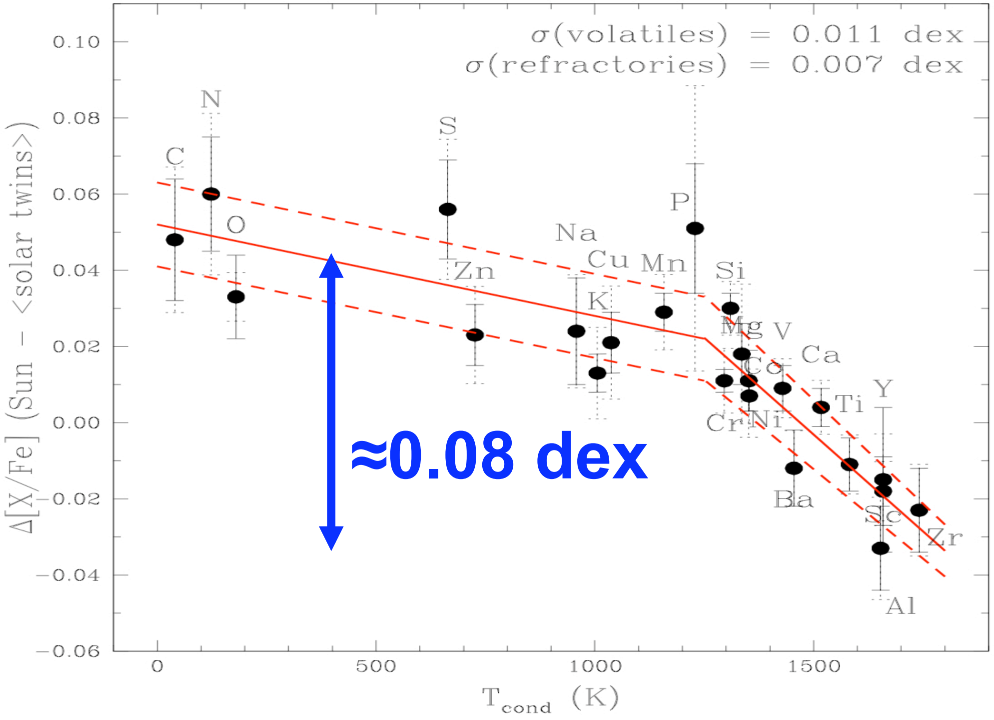
Planet signature larger!

Size of signature will depend on M_{CZ}, i.e. spectral type

Disk substructure and chemical tagging

Δ(Thick-thin) ≈ 0.1 dex

Δ(Thin) ≈ 0.01 dex?



≈0.08 dex

Searching for solar siblings

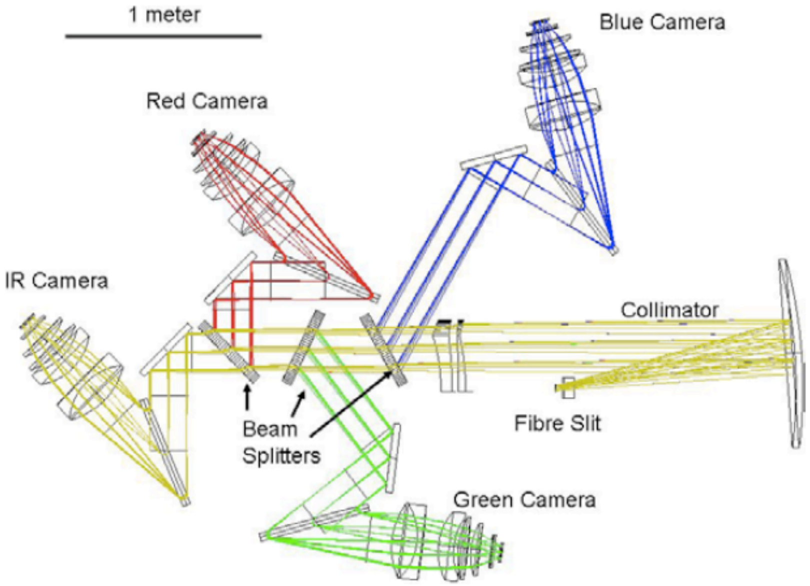


Figure 1: *schematic layout of the four-band HERMES spectrometer, showing the three dichroic beamsplitters, four VPH gratings and four cameras.*

images are adopted from http://www.aao.gov.au/

HERMES @ AAT 4m R=30k & S/N~100 spectra of 10^6 stars for "*chemical tagging*" (2012-2017):

⇒ 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

Lecture 1: Solar/stellar spectroscopy

- 3D stellar atmospheres highly realistic
- 3D/non-LTE spectral line formation possible

Lecture 2: Solar chemical composition

- New low solar C, N, O, Ne abundances
- Conflict with solar interior models

Lecture 3: Is the Sun unusual?

- Planet formation imprinted in abundances
- Complicates Galactic archaeology

Summary

- **Solar chemical composition**
  - New abundances for all 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

Recent publications

Solar chemical composition:

Asplund et al. (2009, ARAA)	3D analysis of all elements
Melendez & Asplund (2008, A&A)	[OI]
Scott et al. (2009, ApJL)	O+Ni
Asplund et al. (2009b, A&A)	C
Sauval et al. (2009, A&A)	N
Asplund et al. (2009c, A&A)	O
Asplund et al. (2009d, A&A)	Na-Ca
Scott et al. (2009, A&A)	Fe-peak
Grevesse et al. (2009, A&A)	Heavy elements

3D solar modelling:

Trampedach et al. (2009, A&A)	New 3D solar model
Hayek et al. (2009, A&A)	New 3D code
Pereira et al. (2009a, A&A)	Testing 3D models
Pereira et al. (2009b, A&A)	Solar granulation
Pereira et al. (2009c, A&A)	Center-to-limb variations

Astrophysical implications

Melendez et al. (2009, ?)	Is the Sun chemically unusual?
Ramirez et al. (2009, A&A)	solar twins
Serenelli et al. (2009, ApJL)	Helioseismology
Nieva et al. (2009, A&A)	Solar neighborhood
Schönrich et al. (2009, MNRAS)	Galactic chemical evolution

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