Solar abundances

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Why measuring solar abundances?

- **To know the detailed chemical composition of the solar photosphere, considering this as a representative draw of the whole Sun.** This is not the case due to nuclear burning in the solar core, diffusion, Li, Be, B burning in the envelope. But it is not possible to have direct abundance determination of the solar core, and mostly the solar photosphere is not affected by these effects.

- To compare this composition to the meteoritic abundance analysis.

- To test the models
  - **of the solar atmosphere**
  - of the solar interior (helioseismology)

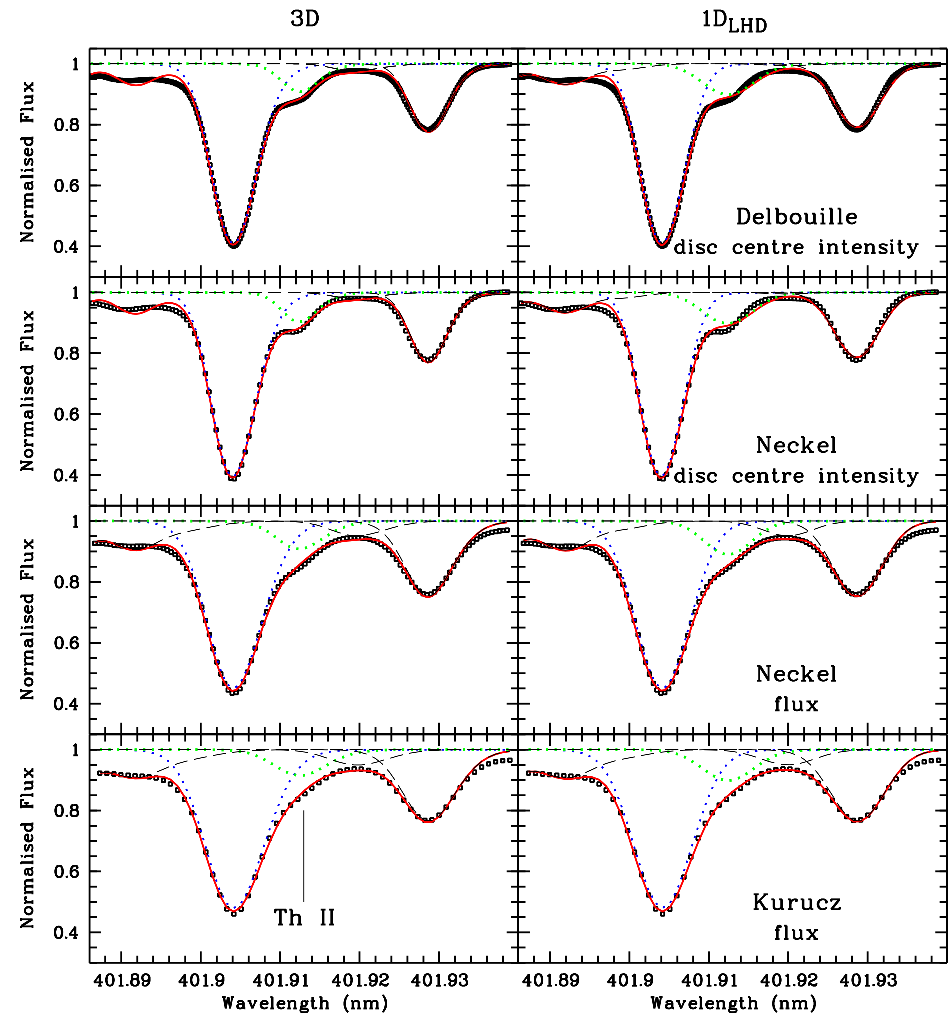
- To determine the oscillator strength of a line from the solar spectrum by assuming a certain abundance.

- **To fix a reference abundance for the chemical analysis of the other stars in the Galaxy and in other galaxies, the inter stellar medium, the external galaxies.**

It seems easy ...

to know the detailed chemical composition of the solar photosphere

- considering that the Sun is our closest stars
  - we have wonderful solar observations
  - we have a deep knowledge on the solar parameters
  - we have new-generation models of the solar photosphere



.... and still there is no absolute consensus on the subject ...

About the solar oxygen abundance

Quote from the book "Oxygen in the Universe" (Stasinska et al. 2011) from the section on the solar photospheric abundance of oxygen:

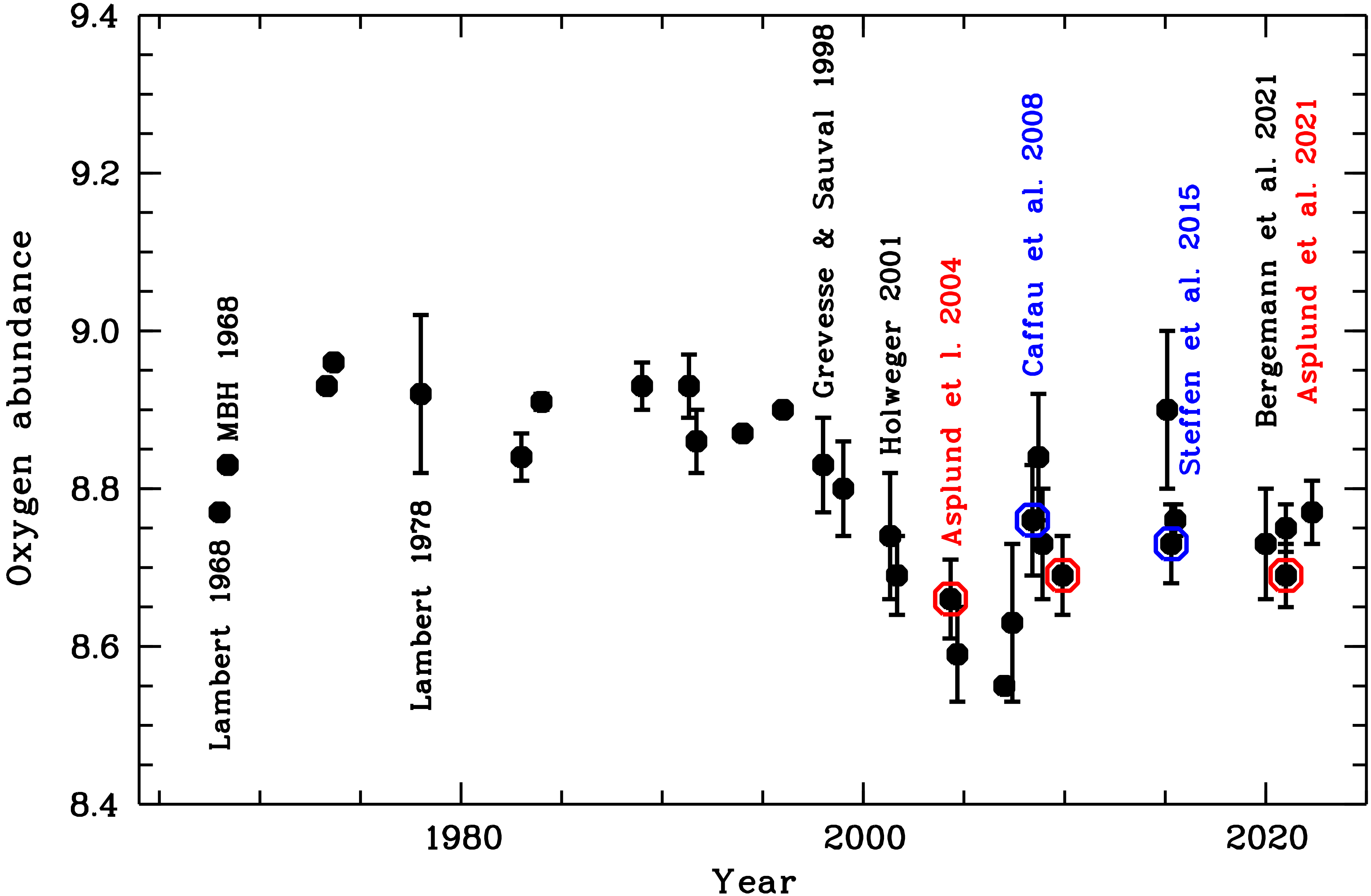
In this section the team of authors ran into the awkward situation that there was no unanimous opinion among the team members about the best procedure of its determination and ultimately best estimate of the oxygen abundance in the solar atmosphere.

Oxygen in the Sun was decreasing in time . . .

- After a stable O abundance for more than 30 years
- O experienced a decrease for almost 10 years
- **. . . but since 2008 A(O) seems quite stable**
- **also according to the most recent investigations**
  - Lodders 2020: $\mathrm{A(O)} = 8.71 \pm 0.04$ dex (3D) and $\mathrm{A(O)} = 8.76 \pm 0.06$ dex (1D)
  - Asplund, Amarsi & Grevesse (2021): $\mathrm{A(O)} = 8.69 \pm 0.04$ dex
  - Bergemann et al. (2021): $\mathrm{A(O)} = 8.75 \pm 0.03$ dex
- **Lodders 2020 suggests:** $\mathrm{A(O)} = 8.73 \pm 0.07$

. . . this makes us hope A(O) is going to be stable so we do not risk to go out of oxygen in the future!

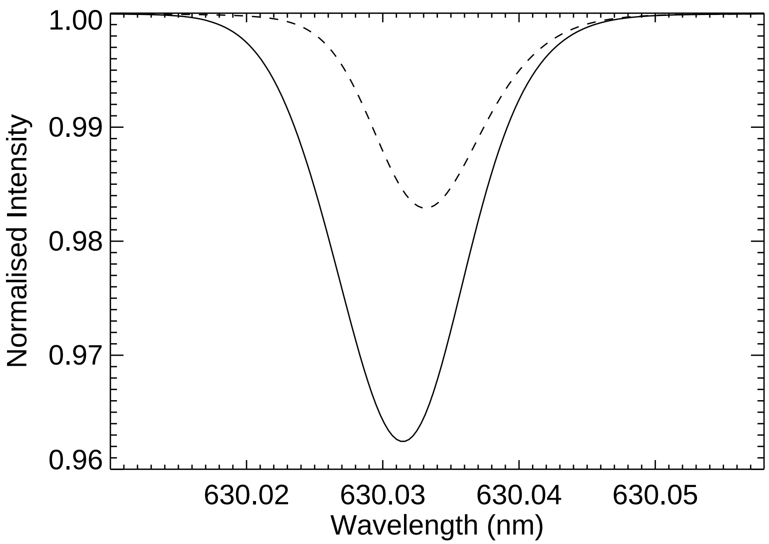
Solar oxygen decreased in time

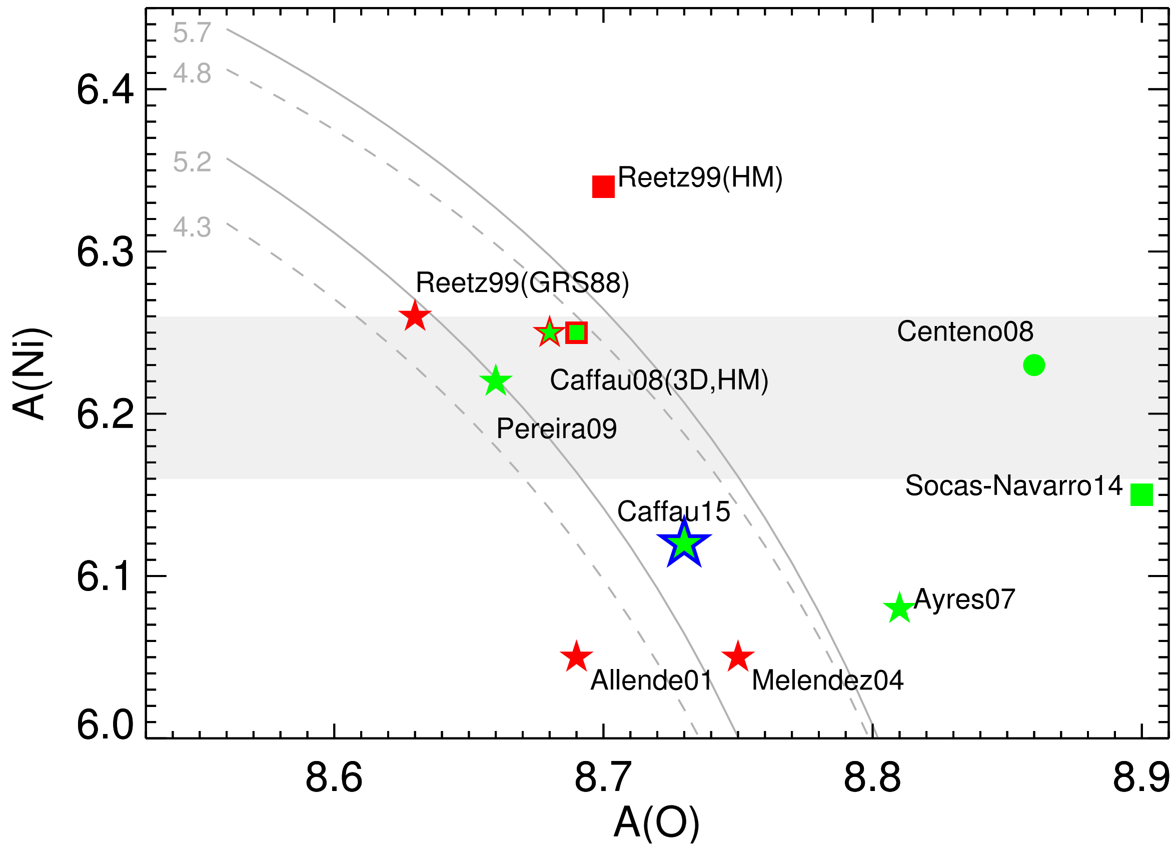


Oxygen

- The differences from the different investigations are not only due to
  - choice on the lines
  - observations
  - solar models
  - NLTE
  - . . .
- It is often something simpler
- and sometmes this brings the largest difference

Oxygen from the forbidden [OI] 630 nm line



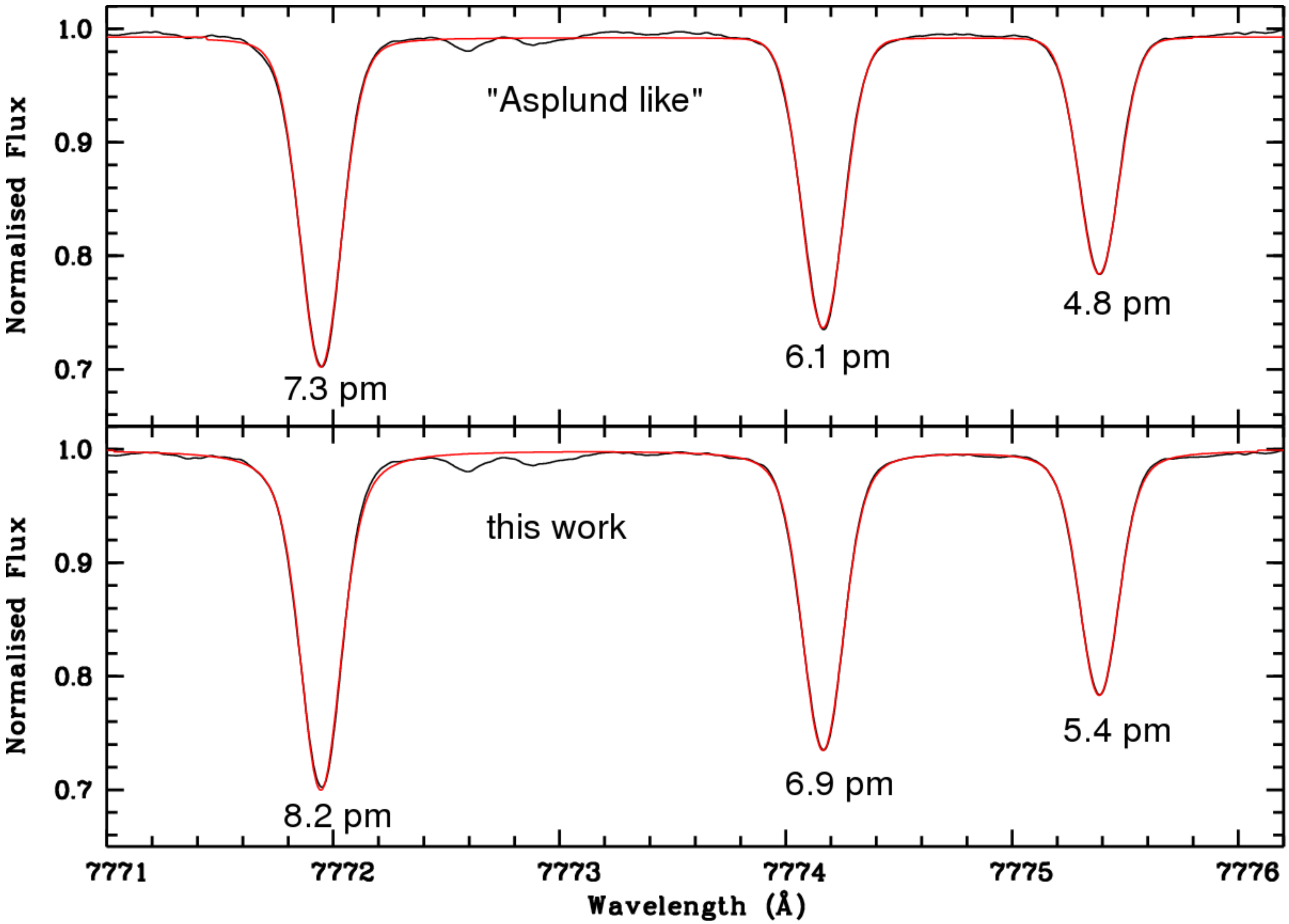


(dashed/green: disk-centre, solid/red: disk-integrated; star: 3D, square: 1D model; grey bar: Ni range)

NLTE of Ni line would reduce its EW (Bergemann et al. 2021)

Oxygen from the O I 777 nm triplet

There is some subjectivity in the EW measurements



Solar abundances used in the past decade

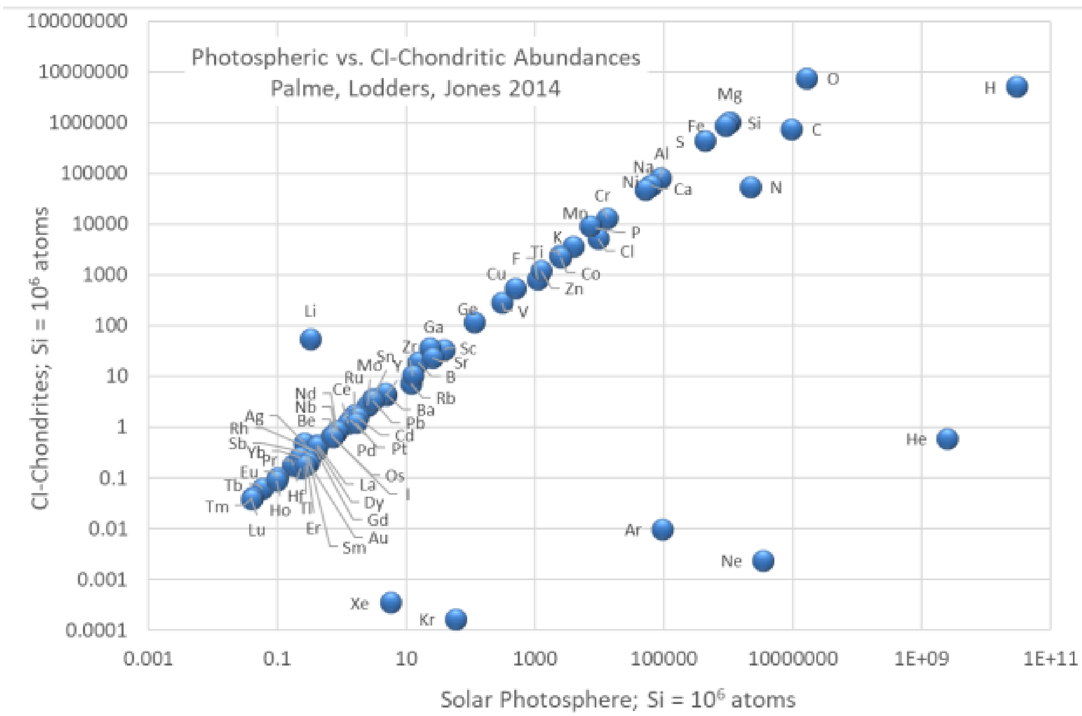
- Anders & Grevesse 1989: all solar abundances
- Holweger 1996: NLTE
- Grevesse & Sauval 1998: all solar abundances
- Lodders 2003: all solar abundances
- Asplund 2005: all solar abundances
- Asplund et al. (2009): all solar abundances
- Lodders et al. (2009): all solar abundances
- Caffau et al. (2011): limited number of elements

What then?

Recent investigations/compilations

Lodders (2020)

- a complete review on solar and solar-system composition
- metheoritic analysis
- review on photospheric results
- recommended values provided (present-day/proto-solar solar system)
- . . .



. . . always a pleasure to read Lodders' papers

Recent investigations/compilations

Asplund, Amarsi & Grevesse (2021)

- based mostly on 3D-NLTE
- solar 3D STAGGER model
- an outstanding, complete analysis
- several high-quality solar observations

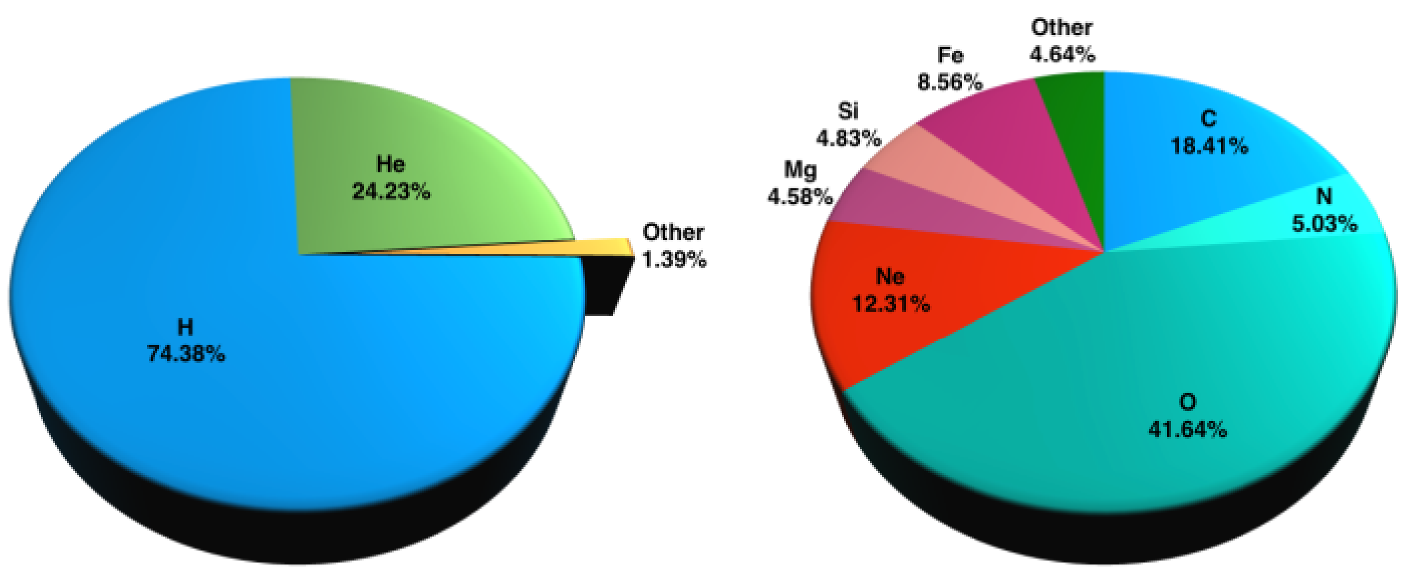
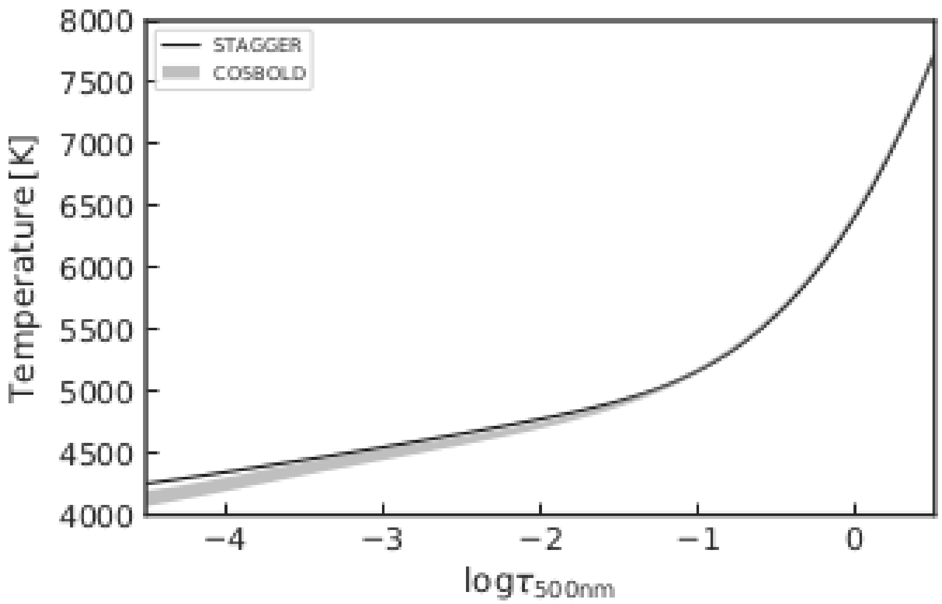


Fig. 9. Present-day photospheric mass fractions the most abundant elements. *Left panel:* mass fractions of H, He, and heavy elements. *Right panel:* relative mass fractions of the most abundant heavy elements with the highly volatile C, N, O, and Ne contributing more than 77% of all heavy elements by mass.

Recent investigations

- **Magg et al. (2022)**
  - investigation on several elements: C, N, O, Mg, Si, Ca, Fe, Ni
  - with a 1D and two $\langle 3D \rangle$ models
    - MARCS, STAGGER and CO^{5}BOLD
  - NLTE for O, Si, Mg, Ca, Fe, Ni
  - a really high-quality solar spectrum
    - is it really closer to a now-a-days stellar analysis?

Magg et al. (2022)



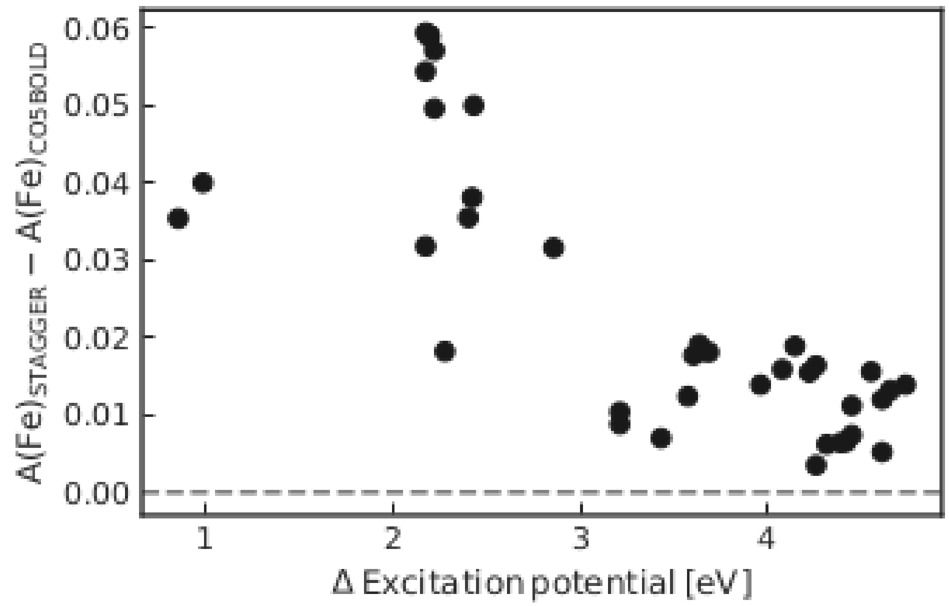


Table 4: Solar photospheric abundances derived in NLTE. See the text for details.

El.	A(El), σ_{tot} 1D[a] NLTE	A(El), σ_{tot} $\langle 3D\rangle$[b] NLTE [c]	$\Delta_{STAGGER-CO5BOLD}$	σ_{stat}
C	8.48 ± 0.08	8.56 ± 0.06	0.016	0.05
N	7.88 ± 0.12	7.98 ± 0.10	−0.011	0.1
O	8.74 ± 0.04	8.77 ± 0.04	0.014	0.02
Mg	7.45 ± 0.08	7.55 ± 0.06	0.020	0.06
Si	7.54 ± 0.07	7.59 ± 0.07	0.005	0.06
Ca	6.34 ± 0.05	6.37 ± 0.05	0.026	0.04
Fe	7.49 ± 0.08	7.51 ± 0.06	0.012	0.08
Ni	6.21 ± 0.04	6.24 ± 0.04	0.001	0.07

Recent detailed investigations

- Mashonkina et al. (2011): solar Fe with 1D-NLTE ($\mathrm{A(Fe)} = 7.56 \pm 0.09$)
- Ayres et al. (2013): isotopic solar CO
- Maiorca et al. (2014): solar F ($\mathrm{A(F)} = 4.40 \pm 0.25$)
- Shi et al. (2014): solar Cu with 1D-NLTE ($\mathrm{A(Cu)} = 4.24 \pm 0.08$)
- Caffau et al. (2015): solar O from [OI] line in 3D ($\mathrm{A(O)} = 8.73 \pm 0.05$)
- Grevesse et al. (2015): solar abbondances from Cu to Th with 3D and when available NLTE corrections
- Scott et al. (2015): solar abbondances from Na to Ca with 3D and when available NLTE corrections
- Scott et al. (2015): solar abbondances from Sc to Ni with 3D and when available NLTE corrections

Recent detailed investigations

- Steffen et al. (2015): solar O with 3D-NLTE ($\mathrm{A(O)} = 8.76 \pm 0.02$)
- Pehlivan Rhodin et al. (2017): solar Sc with revised log(gf)
- Amarsi & Asplund (2017): solar Si with 3D-NLTE ($\mathrm{A(Si)} = 7.51 \pm 0.03$)
- Cubas Armas et al. (2017): solar O from [OI] line with empirical 3D model ($\mathrm{A(O)} = 8.86 \pm 0.04$)
- Amarsi et al. (2018): O+H collisions and 3D-NLTE A(O) from 777 nm triplet ($\mathrm{A(O)} = 8.69 \pm 0.03$)
- Amarsi et al. (2019): solar C abundance from atomic line with 3D-NLTE ($\mathrm{A(C)} = 8.44 \pm 0.02$)
- Amarsi et al. (2020): solar N abundance from atomic lines with 3D-NLTE ($\mathrm{A(N)} = 7.77 \pm 0.05$)

Recent detailed investigations

- Cubas Armas et al. (2020): solar O from [OI] line in solar granules ($\mathrm{A(O)} = 8.83 \pm 0.02$) and intergranules ($\mathrm{A(O)} = 8.76 \pm 0.02$)
- Gallagher et al. (2020): solar Ba with 3D-NLTE ($\mathrm{A(Ba)} = 2.27 \pm 0.01$)
- Amarsi et al. (2021): CNO abundances from molecular lines in 3D-LTE ($\mathrm{A(C)} = 8.47 \pm 0.02 \quad \mathrm{A(N)} = 7.98 \pm 0.04 \quad \mathrm{A(O)} = 8.70 \pm 0.04$)
- Bergemann et al. (2021): solar O with 1D/3D-NLTE ($\mathrm{A(O)} = 8.75 \pm 0.05$)
- Korotin & Kuĉinskas (2022): solar Be with 1D-NLTE ($\mathrm{A(Be)} = 1.32 \pm 0.05$)

To improve solar abundance determinations

- Improvement on NLTE collisions
  - Barklem et al. (2010, 2012, 2017, 2021)
  - Yakovelva et al. (2018)

- New atomic data
  - Lawler et al. (2013) for Ti
  - Ruffoni et al. (2013) for Fe I
  - Lawler et al. (2014) for V I
  - Liu et al. (2014) for Cu
  - Lawler et al. (2015) for Co
  - Holmes et al. (2016) for V
  - Holmes et al. (2017) for Cr II
  - Pehlivan Rhodin et al. (2017) for Mg
  - Lawler et al. (2019) for Sc
  - Li et al. (2020) for Ti II

To improve solar abundance determinations

- Effort on solar observations
  - Doerr et al. (2016): comparison of widely used Delbouille and Neckel intensity
  - Reiner et al. (2016): IAG solar flux atlas
- Opacities
  - Mondet et al. (2015)
- Investigations on magnetic field
  - Fabbian et al. (2010): effects of magnetic field on solar abundances
  - Shuchukina et al. (2014): effects of magnetic field on solar CNO abundances

Solar abundances, summary

- **We have several high-quality solar-abundance investigations**
- Mainly the abundances from the various investigations agree within uncertainties
- Still some minor problems
  - Differences among (3D) models still non-negligible
  - room for improvement on 3D models
  - 3D-NLTE avaliable for many elements but not all
  - What about things missing or needing improvements?
    - opacities
    - turbulence
    - magnetic field
    - ...

Solar abundances: work in progress

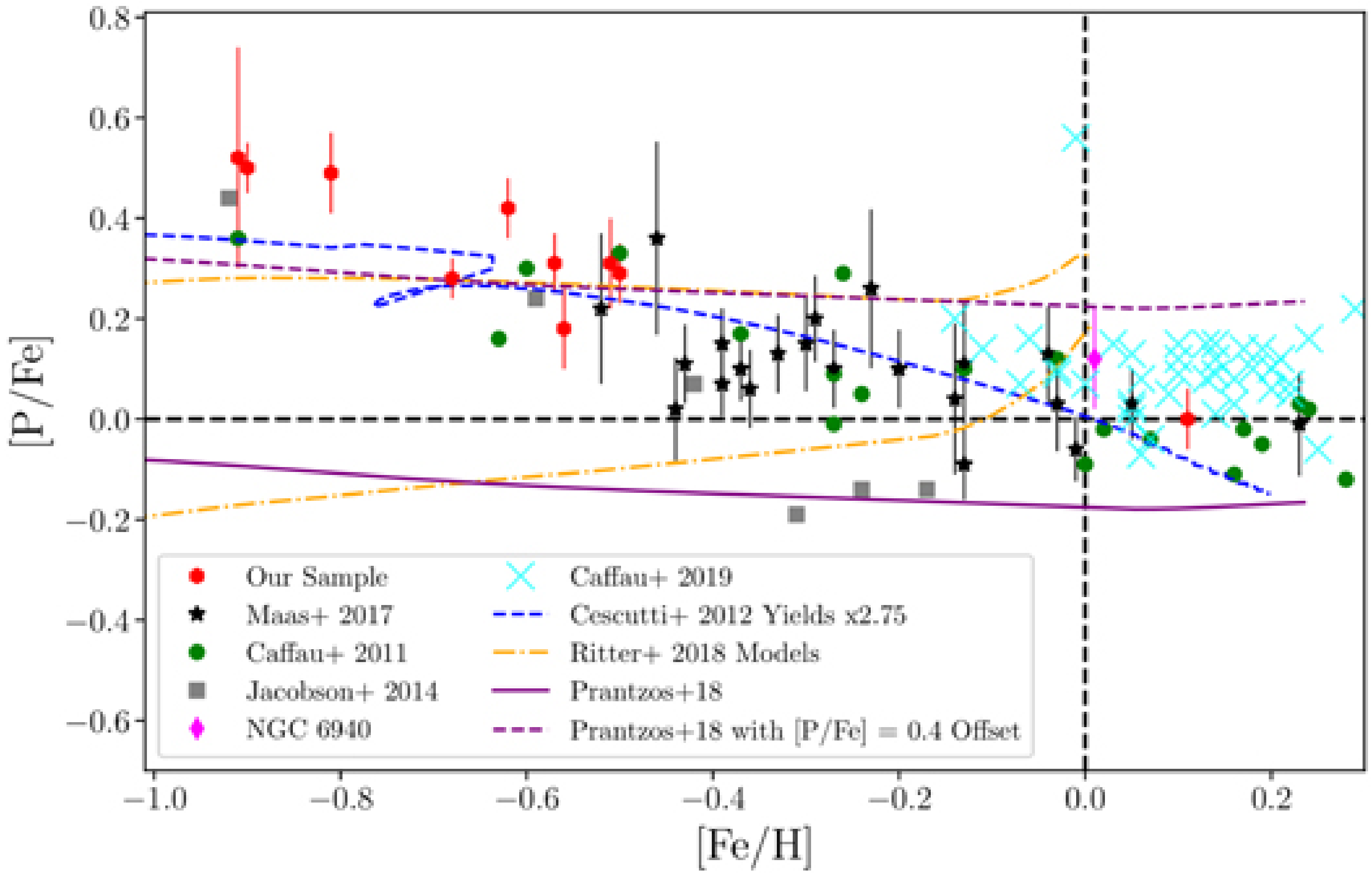
- **The investigation of the solar photosphere is always work in progress**

- The outstanding recent investigations (see e.g. Amarsi et al. 2017, 2018, 2019, 2020, 2021) highlight surely a break-through in the field, but we will have in the future:
  - better models
  - metter opacities
  - better atomic data
  - magnetic field
  - . . .
  - perhaps also better observations

- and with better . . . we will always look at the Sun

Solar abundances as a reference

This is the topic many of us are interested in: chemical evolution



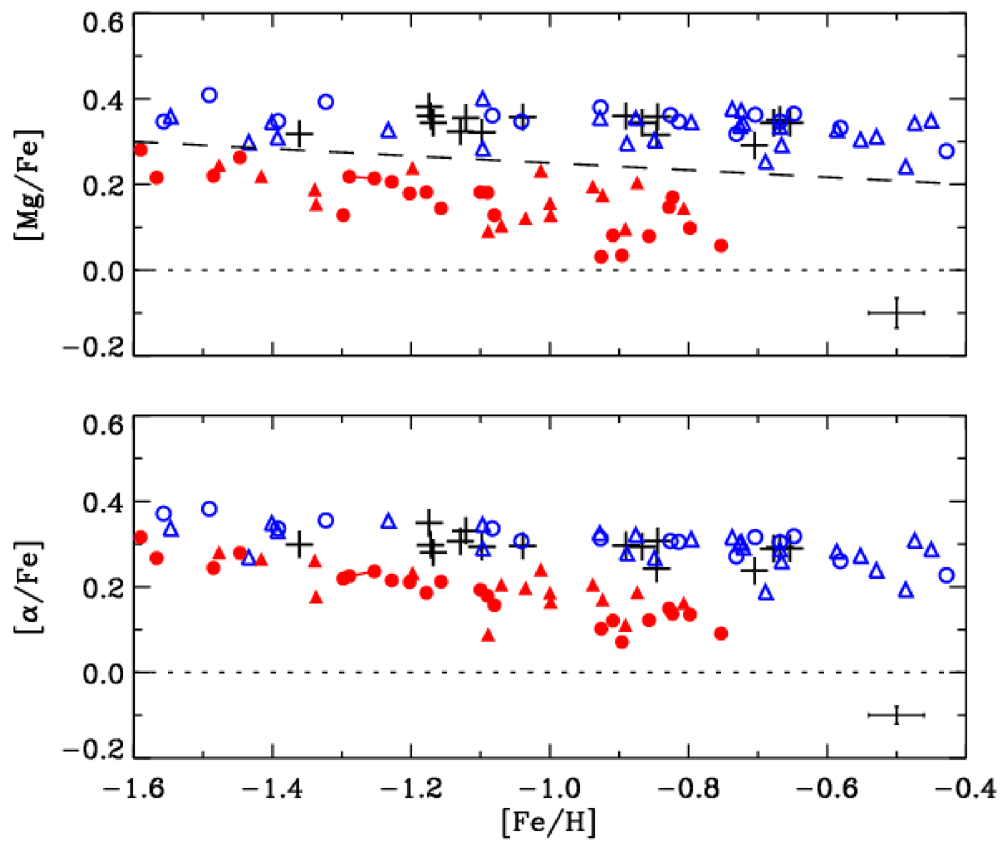
Maas, Cescutti and Pilachowski (2019)

Solar abundances as a reference

- **Majority of the times abundances from different stars are compared the solar abundances are applied**
  - $[\mathrm{X}/\mathrm{Fe}] = (\mathrm{A}(\mathrm{X}) - \mathrm{A}(\mathrm{X})_\odot) - (\mathrm{A}(\mathrm{Fe}) - \mathrm{A}(\mathrm{Fe})_\odot)$
- **The solar abundances are used as a reference, a zero point**
- **But what about is the Sun is not a good zero point**

Solar abundances missing

Unfortunately sometimes [X/Fe] are provided in papers without the solar abundances adopted, making the sample not usable as comparison



Nissed & Schuster (2010)

Suggestion: put always in your paper the solar abbundeances adopted

What to use for the reference solar abundances

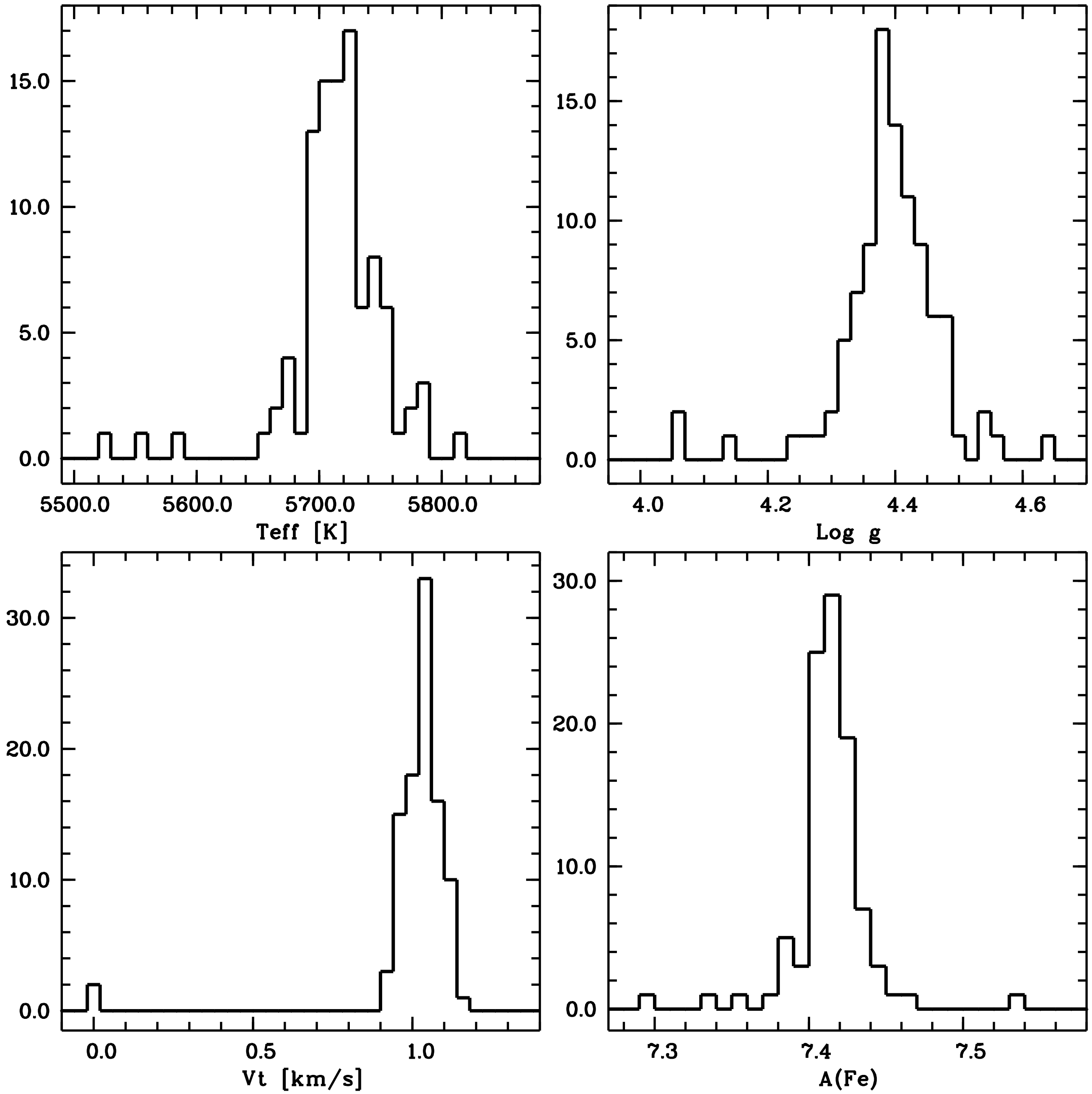
- Several choices are reasonable
  - Take the solar abundances from a complete compilation (e.g. Lodders et al. 2009, Lodders 2020 or Asplund et al. 2021)
  - Choose the abundance of each element from your preferred investigation
  - Derive your own values:
    - from a solar (Moon or asteroid) spectrum observed with the same spectrograph
    - by using the same method used to analysed the other spectra (see e.g. Gratton et al. 2003)

Derive your own Solar abundances

Collected hundred high-quality spectra

- 98 HARPS spectra of Vesta
  - S/N at 500 nm in the range 47 – 98
  - one spectrum with S/N=47
  - six spectra with $60 < \mathrm{S/N} < 72$
  - 91 spectra with $\mathrm{S/N} = 94 \pm 4$
- Analysis in homogeneous way with MyGIsFOS (as done for GES UVES spectra):
  - $\mathrm{T_{eff}} = 5715.6 \pm 39.9$ K, range 5523.8–5812.0
  - $\log g = 4.38 \pm 0.08$ [cgs], range 4.05–4.63
  - $\mathrm{V_t} = 1.01 \pm 0.16$ km/s, range 0.0–1.15
  - $\mathrm{A(Fe)} = 7.42 \pm 0.02$, range 7.30–7.54

Vesta HARPS spectra



Dangers from one single spectrum

And if my solar reference spectrum is one of the outlayers?

As Rolf-Peter Kudritzki said:

“One spectrum no spectrum!”

Of course I can assure more than one observation.

Solar abundances as a reference

- Solar abundance a reference but
  - Too many changes in short time
  - Too many possibilities
  - Often a 3D-NLTE solar abundance as “zero-point” to 1D-LTE analysis
- At the end the solar abundances are often just a zero point for [X/Fe] visualisation
- It is often just needed a solar system reference abundance
  - This is the reason why my preferred choice is Lodders et al. (2009) or now Lodders (2020)

Artificial Sun

- **It could be worthwhile to have, or better to build a solar system reference set of abundances**
  (as suggested to me by Hans-G. Ludwig)
  - **For species with same value in various studies keep it**
  - **For species changing values in time and analysis to be decided what to take**
    - **E.g. A(Pb) of 1.92 ± 0.08 in Grevesse et al. 2014 and 1.75 in Asplund et al. (2009)**

Artificial solar neighbourhood

- **But, is the Sun representative for the investigation on the Galactic evolution?**
  - **Several stars in the solar vicinity and with similar kinematic parameters could be a better reference**
  - **The work done bt Przybilla et al. (2008) with hot youg stars could be extended:**
  - **Select with Gaia stars with kinematic similar to the Sun**
    - **similar age**
    - **different temperature**
    - **different evolution state**
  - **Derive a solar vicinity chemical pattern**

Suggestions

- Provide **ALWAYS** the solar abundances adopted
- Deliver A(X) instead of/with [X/Fe]
- Take into consideration the idea to accept:
  - a solar system reference abundances
  - a solar neighbourhood reference


GRAZIE!