

# A hands-on lesson on classical spectroscopic methods

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Stellar spectroscopy and Astrophysical parametrisation from Gaia to Large Spectroscopic surveys, 21-23 September 2021



# Outline

- How to create a synthetic spectrum
- How to derive atmospheric parameters with spectral synthesis ( $T_{\text{eff}}$ ,  $\log g$ , [M/H], vmic, vmac, vsini)
- How to derive chemical abundances with spectral synthesis
- How to derive atmospheric parameters from the EW of iron ( $T_{\text{eff}}$ ,  $\log g$ , [Fe/H], vmic)
- Examples



# What's on the market?

Synthesis (with EW analysis)	Equivalent Width	Machine Learning
iSpec (Blanco-Cuaresma+ 2014)	FAMA (Magrini+ 2013)	The Cannon (Ness+ 2015)
fasma (Tsantaki+ 2018)	ARES+MOOG (Sousa+ 2008)	The Payne (Ting+ 2019)
SME (Piskunov+ 2017)	GALA (Mucciarelli+ 2013)	NN for RAVE (Guiglion+ 2020)
BACCHUS (Masseron+ 2016)	StePar (Tabernero+ 2019)	ML for APOGEE (Garcia-Dias+ 2018)
...	...	...

There are also hybrid methods: e.g. SP\_Ace (Boeche+ 2016), MATISSE (Recio-Blanco+ 2006)

Differences on:

- analysis methods
- model atmosphere physics
- time consumption
- atomic line data
- a few publicly available (and fewer user friendly)
- many, many more ...

Choose your package depending on the specific problem  
(e.g. spectral type, rotation, resolution)



# 1. How to create a synthetic spectrum



# 1. How to get the flux at the top of the photosphere



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Ingredients:

- Stellar atmospheric parameters ( $T_{\text{eff}}$ ,  $\log g$ , [M/H],  $\text{vmic}$ )
- Model atmosphere
  - MARCS (LTE, plane parallel/spherical geometry): cool stars
  - Kurucz (LTE, plane parallel): extended grid
  - TLUSTY (non-LTE, plane parallel): hot stars
- Line data: wavelengths, excitation potentials, oscillator strengths, broadening parameters
  - Vienna Atomic Line Database (VALD)
  - National Institute of Standards & Technology (NIST) Database
- Radiative solver
  - MOOG
  - Turbospectrum
- Convolution with rotation kernels ( $\text{vmac}$ ,  $\text{vsini}$ ) & instrumental resolution



# Let's create a Sun!

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Caution: Spectral synthesis is model dependent!

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---

MARCS

Teff= 5777 log g= 4.44

NTAU 72

5.37932065E-04	3784.6	1.511E+01	2.446E+09	2.514E-04	7.508E-02	1.000E+05
7.04358347E-04	3806.3	1.977E+01	3.157E+09	2.912E-04	7.989E-02	1.000E+05
8.97001104E-04	3827.9	2.516E+01	3.968E+09	3.352E-04	8.275E-02	1.000E+05
1.12114053E-03	3851.2	3.142E+01	4.901E+09	3.842E-04	8.394E-02	1.000E+05
1.38277017E-03	3875.6	3.870E+01	5.981E+09	4.386E-04	8.400E-02	1.000E+05
1.68900324E-03	3900.3	4.721E+01	7.234E+09	4.997E-04	8.346E-02	1.000E+05
2.04821557E-03	3925.3	5.719E+01	8.692E+09	5.679E-04	8.253E-02	1.000E+05
2.47003418E-03	3949.9	6.890E+01	1.038E+10	6.458E-04	8.133E-02	1.000E+05
2.96503163E-03	3974.2	8.262E+01	1.236E+10	7.349E-04	8.009E-02	1.000E+05
3.54549590E-03	3998.0	9.867E+01	1.465E+10	8.366E-04	7.892E-02	1.000E+05
4.22616872E-03	4021.5	1.175E+02	1.730E+10	9.519E-04	7.791E-02	1.000E+05
5.02375022E-03	4044.4	1.396E+02	2.040E+10	1.084E-03	7.737E-02	1.000E+05
5.95691999E-03	4067.1	1.654E+02	2.398E+10	1.237E-03	7.732E-02	1.000E+05
7.04850982E-03	4089.7	1.956E+02	2.813E+10	1.410E-03	7.757E-02	1.000E+05
8.32685037E-03	4112.5	2.309E+02	3.296E+10	1.606E-03	7.792E-02	1.000E+05
9.82370118E-03	4135.5	2.722E+02	3.856E+10	1.831E-03	7.845E-02	1.000E+05
1.15754759E-02	4159.1	3.205E+02	4.509E+10	2.086E-03	7.901E-02	1.000E+05
1.36255202E-02	4183.3	3.771E+02	5.267E+10	2.378E-03	7.961E-02	1.000E+05
1.60229445E-02	4208.0	4.433E+02	6.148E+10	2.713E-03	8.042E-02	1.000E+05
1.88238605E-02	4233.4	5.205E+02	7.172E+10	3.098E-03	8.141E-02	1.000E+05
2.20936211E-02	4259.5	6.108E+02	8.362E+10	3.541E-03	8.256E-02	1.000E+05
2.59125342E-02	4286.4	7.161E+02	9.748E+10	4.041E-03	8.357E-02	1.000E+05
3.03761432E-02	4313.9	8.391E+02	1.136E+11	4.612E-03	8.454E-02	1.000E+05
3.55924653E-02	4342.2	9.830E+02	1.323E+11	5.264E-03	8.543E-02	1.000E+05
4.16892557E-02	4370.9	1.151E+03	1.540E+11	6.005E-03	8.627E-02	1.000E+05
4.88128382E-02	4399.9	1.347E+03	1.794E+11	6.856E-03	8.738E-02	1.000E+05
5.71301126E-02	4429.1	1.577E+03	2.087E+11	7.832E-03	8.883E-02	1.000E+05
6.68354590E-02	4458.4	1.844E+03	2.429E+11	8.953E-03	9.065E-02	1.000E+05
7.81644639E-02	4487.8	2.156E+03	2.824E+11	1.022E-02	9.268E-02	1.000E+05
9.13940125E-02	4517.2	2.521E+03	3.284E+11	1.168E-02	9.520E-02	1.000E+05
1.06839751E-01	4546.4	2.946E+03	3.818E+11	1.334E-02	9.809E-02	1.000E+05
1.24881981E-01	4575.8	3.443E+03	4.437E+11	1.522E-02	1.014E-01	1.000E+05
1.45962545E-01	4604.8	4.025E+03	5.156E+11	1.738E-02	1.056E-01	1.000E+05



# Let's create a Sun!

Caution: Spectral synthesis is model dependent!

- Stellar atmospheric parameters (5777, 4.44, 0.0, 1.0)
- Model atmosphere
  - MARCS (LTE, plane parallel/spherical geometry): cool stars
- + optical depth at standard wavelengths
- + temperature in K
- + number density of free electrons
- + number density of all other particles
- = Calculate the radiative transfer equation → Flux

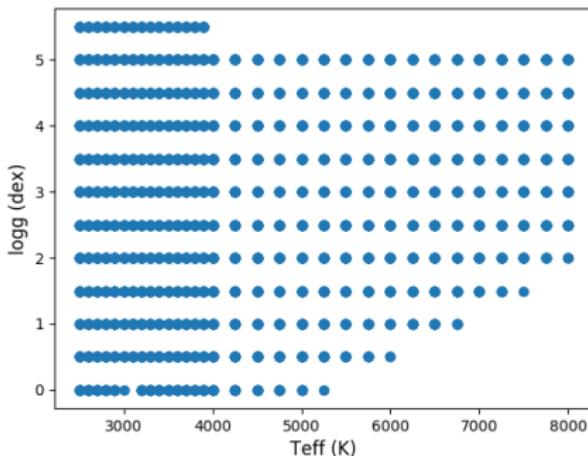
MARCS	Teff= 5777	log g= 4.44	NTAU	72
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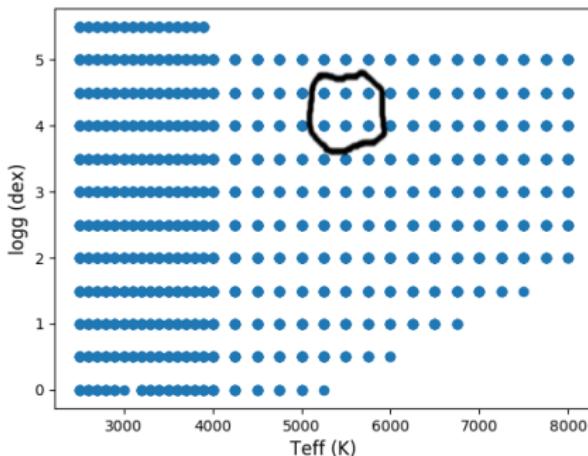
Interpolation within the grids is needed  
(e.g. `scipy.interpolate.griddata`)



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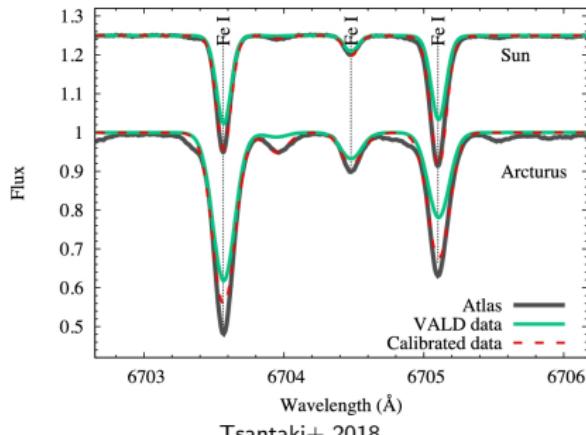
#	Wavelength	ele	EP	loggf	vdwaals	Do
	5339.188	20.1	8.44	-0.075	-7.196	nan
	5339.416	26.0	4.43	-2.146	-7.51	nan
	5339.526	27.0	4.23	-0.377	-7.51	nan
	5339.937	26.0	3.27	-0.609	-7.221	nan
	5340.189	26.0	4.29	-2.229	-7.52	nan
	5340.447	24.0	3.44	-0.724	-7.262	nan
	5340.666	22.0	0.82	-3.174	-7.65	nan
	5341.033	26.0	1.61	-1.717	-7.68	nan
	5341.053	25.0	2.11	-5.671	-7.74	nan
	5341.070	21.0	1.94	3.341	0	nan
	5341.327	27.0	4.15	-0.424	-7.51	nan
	5341.489	22.0	3.06	-0.760	-7.58	nan
	5341.524	58.1	0.67	-5.088	0	nan
	5342.701	27.0	4.02	0.578	-7.51	nan
	5342.958	21.0	0.00	-2.439	-6.11	nan
	5342.969	19.0	1.61	-1.795	0	nan
	5343.380	27.0	4.03	0.024	-7.51	nan
	5343.438	26.0	4.37	-0.806	-7.51	nan



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Ingredients:

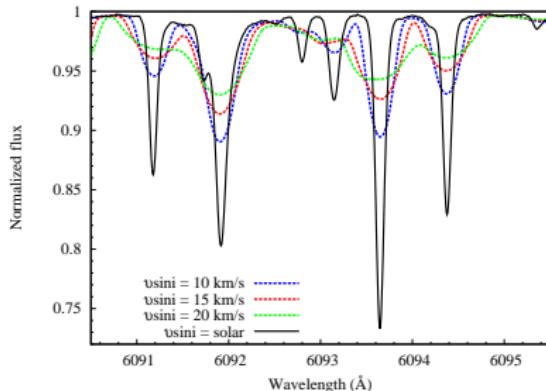
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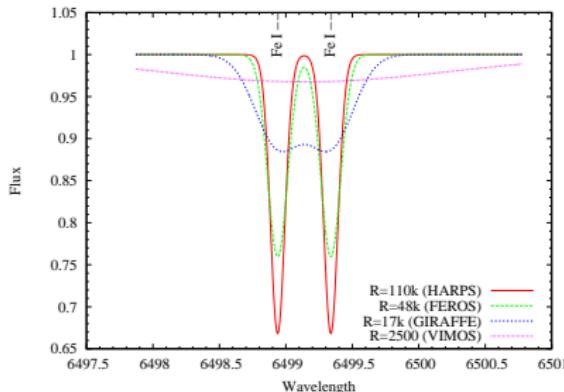
Caution on rotation



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- Convolution with rotation kernels (vmac, vsini) & instrumental resolution  
astropy: `pyasl.rotBroad`, `pyasl.instrBroadGaussFast`



# Let's create a Sun!

Putting everything together



python-based spectral synthesis package:  
[github.com/MariaTsantaki/FASMA-synthesis](https://github.com/MariaTsantaki/FASMA-synthesis)  
yaml configuration file

```
*config1.yml
```

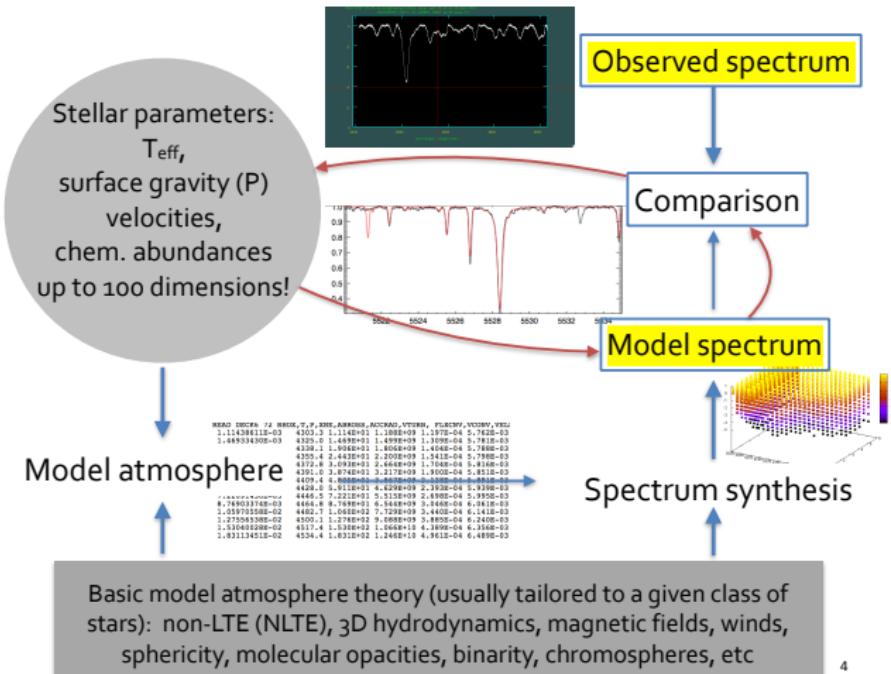
```
1 star1:
2   linelist: FASMA-synthesis/FASMA/rawLinelist/linelist.lst
3   teff: 5777
4   logg: 4.44
5   feh: 0.00
6   vt: 1.0
7   vmac: 3.21
8   vsini: 1.90
9   model: marcs
10  save: False
11  plot: True
12  plot_res: False
13  intervals_file: FASMA-synthesis/FASMA/rawLinelist/intervals.lst
14  snr: null
15  resolution: 115000
16
```



Questions?



## 2. How to derive stellar parameters



Credit to M. Bergemann



## 2. How to derive stellar parameters

Pre-process the observed spectrum



## 2. How to derive stellar parameters

Pre-process the observed spectrum

- input format (fits, dat)



## 2. How to derive stellar parameters

Pre-process the observed spectrum

- input format (fits, dat)
- cosmetic improvements



## 2. How to derive stellar parameters

Pre-process the observed spectrum

- input format (fits, dat)
- cosmetic improvements
- wavelength re-sampling



## 2. How to derive stellar parameters

Pre-process the observed spectrum

- input format (fits, dat)
- cosmetic improvements
- wavelength re-sampling
- (local) normalization

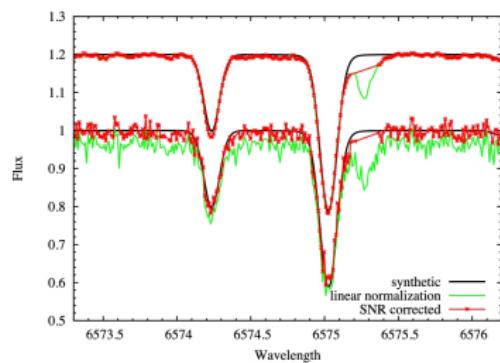


## 2. How to derive stellar parameters

### Pre-process the observed spectrum

- input format (fits, dat)
- cosmetic improvements
- wavelength re-sampling
- (local) normalization

### Minimization process



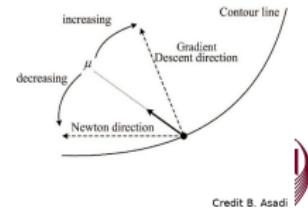
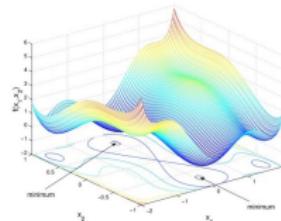
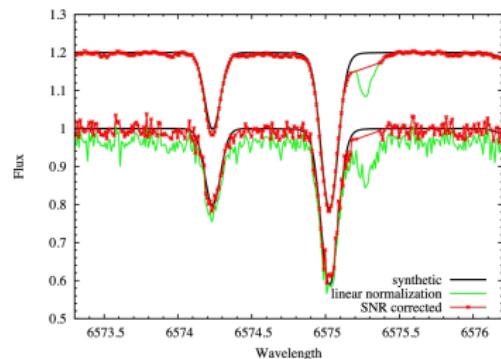
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- cosmetic improvements
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### Minimization process

- $\chi^2$  minimization (`mpfit`, Levenberg-Marquardt)

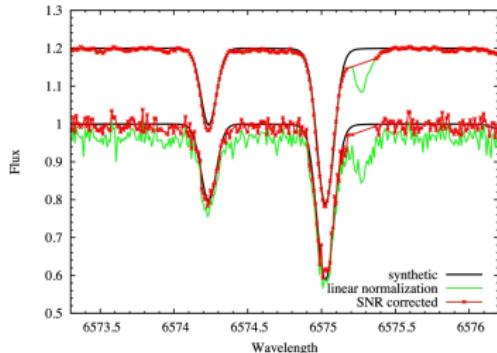


Credit B. Asadi

## 2. How to derive stellar parameters

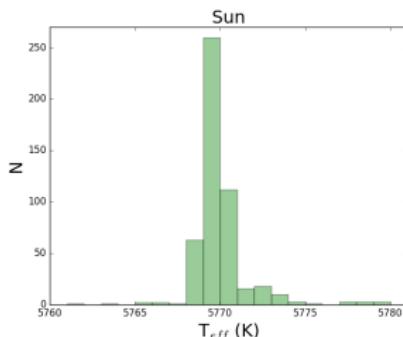
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### Minimization process

- $\chi^2$  minimization (`mpfit`, Levenberg-Marquardt)
- initial conditions



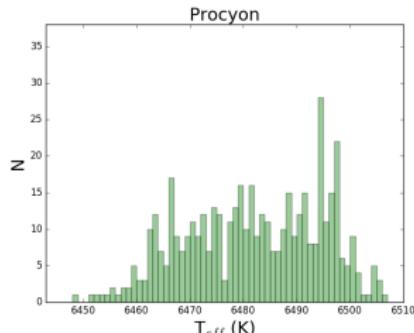
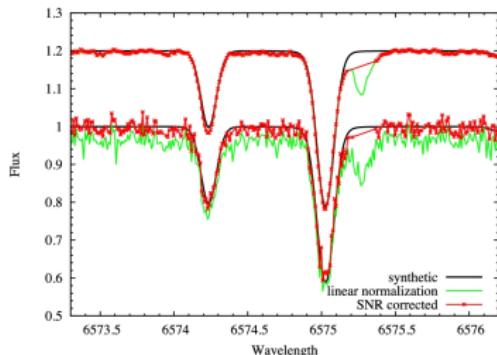
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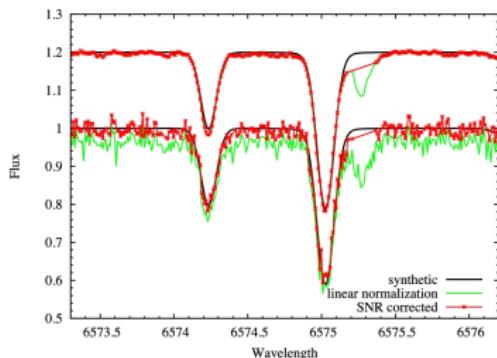
## 2. How to derive stellar parameters

### Pre-process the observed spectrum

- input format (fits, dat)
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- (local) normalization

### Minimization process

- $\chi^2$  minimization (`mpfit`, Levenberg-Marquardt)
- initial conditions
- refine minimization options



- clean for bad/missing lines
- vmic:  $T_{\text{eff}}$ ,  $\log g$ , [Fe/H] (Tsantaki+ 2013, Mortier+ 2013)
- vmac:  $T_{\text{eff}}$  (Valenti+ 2005 MW)



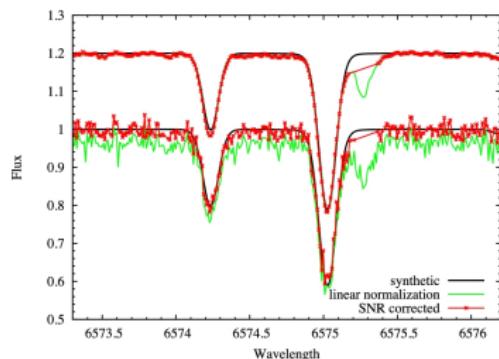
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- initial conditions
- refine minimization options
- fixed parameters

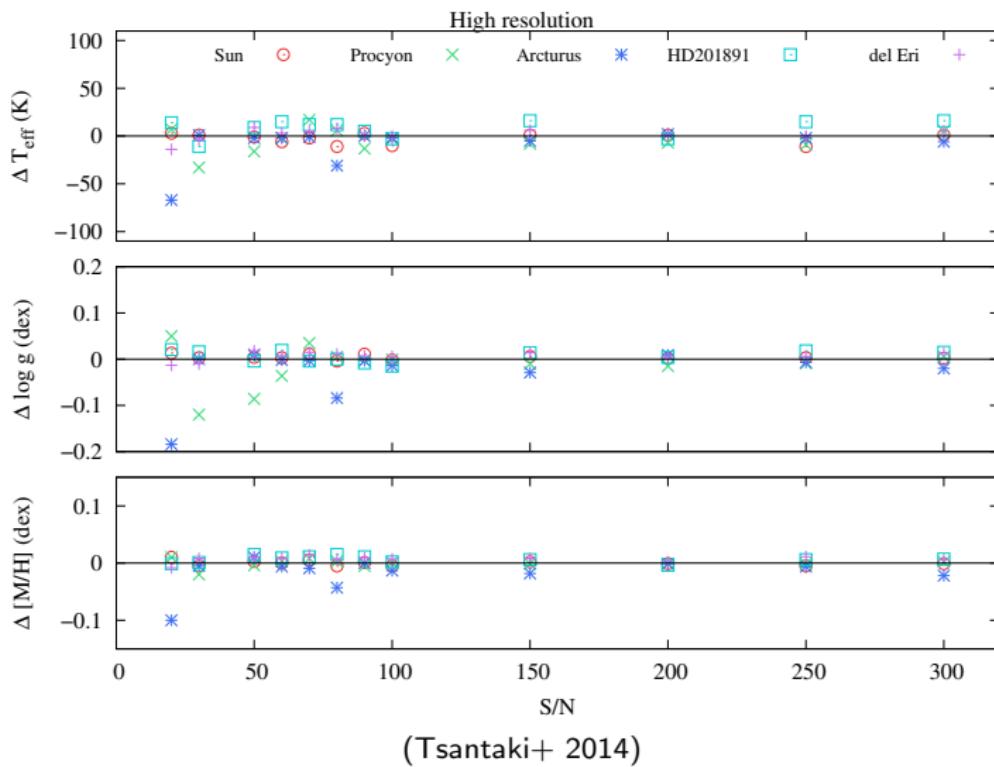


- $\log g$ : seismic, trigonometric
- $\text{vmic}$ :  $T_{\text{eff}}$ ,  $\log g$ , [Fe/H]  
(Tsantaki+ 2013, Mortier+ 2013)
- $\text{vmac}$ :  $T_{\text{eff}}$  (Valenti+ 2005)



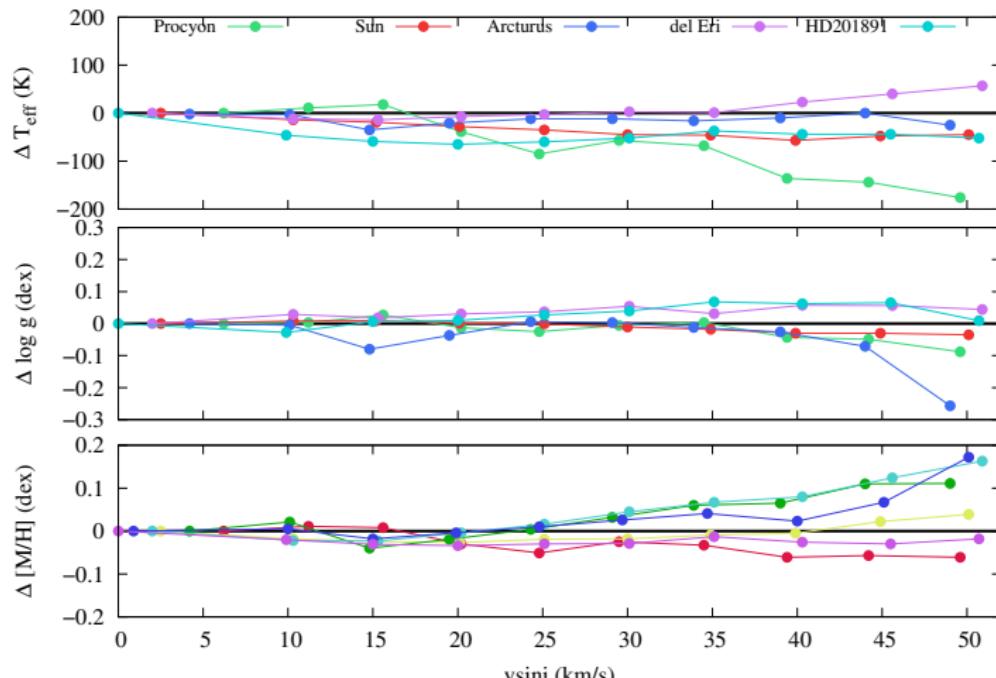
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### Error analysis



## 2. How to derive stellar parameters

### Error analysis

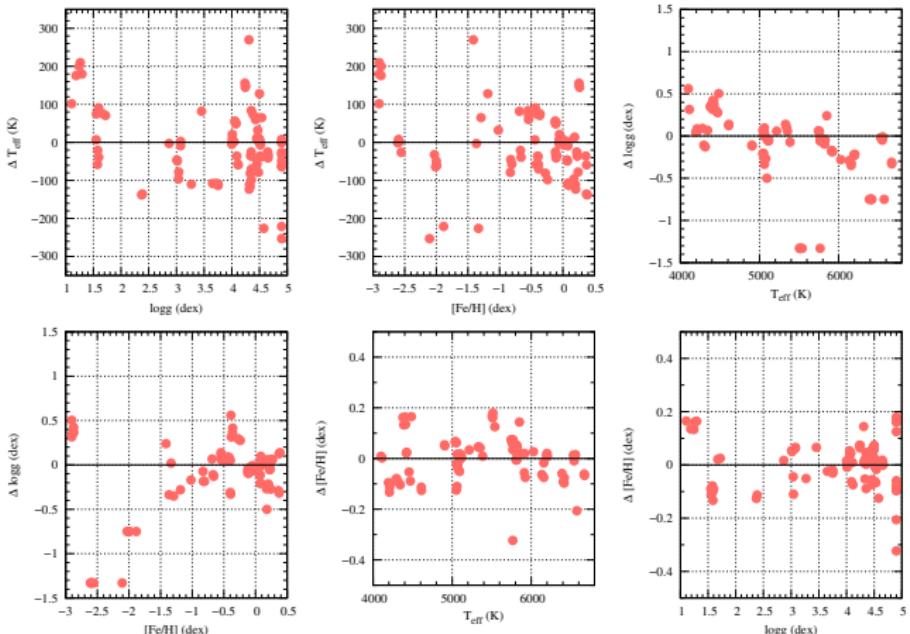


(Tsantaki+ 2014)



## 2. How to derive stellar parameters

### Error analysis



Correlations in parameters with the benchmark values (Tsantaki+ 2014)



## 2. How to derive stellar parameters

Putting everything together!

```
*config2.yml
1 star1:
2   linelist: FASMA-synthesis/FASMA/rawLinelist/linelist.lst
3   teff: 5777
4   logg: 4.44
5   feh: 0.0
6   vt: 1.0
7   vmac: 3.21
8   vsini: 1.90
9   model: marcs
10  save: False
11  element: False
12  fix_teff: False
13  fix_logg: False
14  fix_feh: False
15  fix_vt: True
16  fix_vmac: True
17  fix_vsini: False
18  plot: True
19  plot_res: False
20  damping: 1
21  minimize: True
22  refine: refine
23  observations: FASMA-synthesis/FASMA/spectra/Sun_HARPS.fits
24  intervals_file: FASMA-synthesis/FASMA/rawLinelist/intervals.lst
25  snr: null
26  resolution: 115000
```

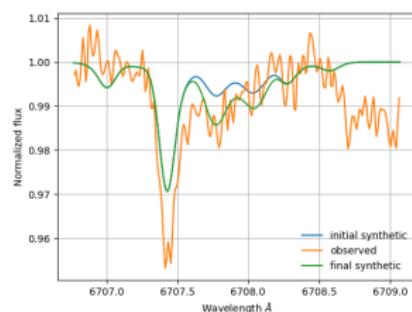


Questions?



### 3. How to derive chemical abundances

- Overall metallicity ( $[M/H]$ ) is derived from all the elements in a region
- Individual chemical abundances ( $[EI/H]$ ) are derived for a specific element
- Create a synthetic spectrum of a known star ( $T_{\text{eff}}$ ,  $\log g$ ,  $[M/H]$ ,  $v_{\text{mic}}$ ,  $v_{\text{mac}}$ ,  $v_{\text{sin}i}$ ) of the specific species
- $[EI/H]$  is the only free parameter
- $\chi^2$  minimization → best-fit value
- Select from: Li, Na, Mg, Al, Si, Ca, Sc, Ti, V, Cr, Mn, and Ni



e.g. Lithium



### 3. How to derive chemical abundances

Putting all together!

```
1 star1:  
2     linelist: FASMA-synthesis/FASMA/rawLinelist/linelist_elements.lst  
3     teff: 5777  
4     logg: 4.44  
5     feh: 0.0  
6     vt: 1.0  
7     vmac: 3.21  
8     vsini: 1.90  
9     model: marcs  
10    save: False  
11    element: Li  
12    plot: True  
13    plot_res: False  
14    damping: 1  
15    minimize: True  
16    observations: FASMA-synthesis/FASMA/spectra/Sun_HARPS.fits  
17    intervals_file: FASMA-synthesis/FASMA/rawLinelist/intervals_elements.lst  
18    snr: null  
19    resolution: 115000
```



Questions?



## 5. The Equivalent Width method

Ingredients:

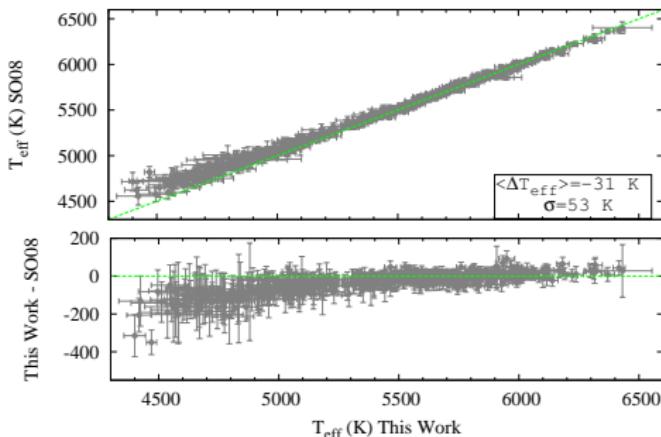
- Line list of neutral (Fel) and ionized species (Fell)
- EW measurements (IRAF, daospec, ARES)
- Calculate [Fe/H] from the curve of growth
- Model atmospheres (MARCS, Kurucz)
- *excitation* balance of Fel lines  $\rightarrow T_{\text{eff}}$   
*ionization* balance of Fel and Fell lines  $\rightarrow \log g$



## 5. The Equivalent Width method

Ingredients:

- Line list of Fe isolated lines



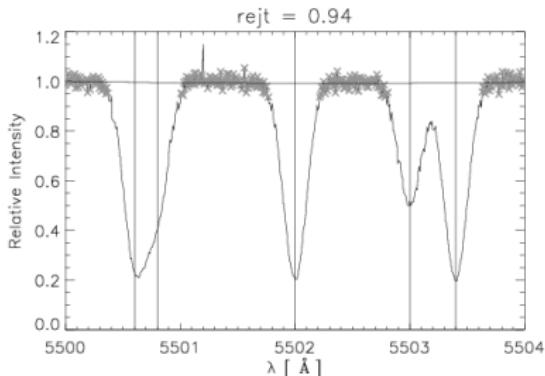
- EW measurements (IRAF, daospec, ARES)
- Calculate  $[\text{Fe}/\text{H}]$  from the curve of growth
- Model atmospheres (MARCS, Kurucz)
- excitation balance of FeI lines  $\rightarrow T_{\text{eff}}$   
ionization balance of FeI and FeII lines  $\rightarrow \log g$



## 5. The Equivalent Width method

Ingredients:

- Line list of Fe isolated lines
- EW measurements with ARES



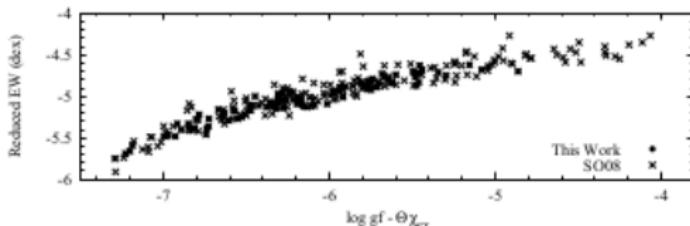
- Calculate  $[Fe/H]$  from the curve of growth
- Model atmospheres (MARCS, Kurucz)
- excitation balance of FeI lines  $\rightarrow T_{\text{eff}}$   
ionization balance of FeI and FeII lines  $\rightarrow \log g$



## 5. The Equivalent Width method

Ingredients:

- Line list of Fe isolated lines
- EW measurements with ARES
- Calculate [Fe/H] from the curve of growth: MOOG+MARCS



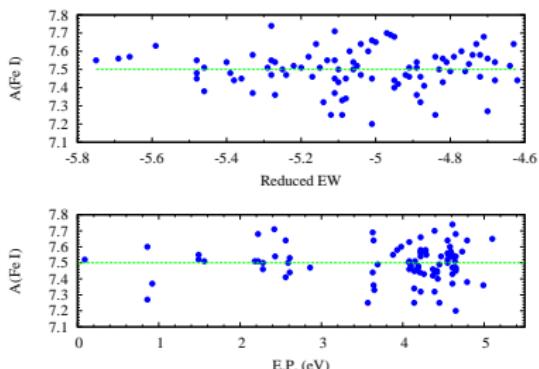
- *excitation* balance of Fel lines  $\rightarrow T_{\text{eff}}$   
*ionization* balance of Fel and Fell lines  $\rightarrow \log g$



## 5. The Equivalent Width method

Ingredients:

- Line list of Fe isolated lines
- EW measurements with ARES
- Calculate [Fe/H] from the curve of growth: MOOG+MARCS
- *excitation balance of FeI lines →  $T_{\text{eff}}$*   
*ionization balance of FeI and FeII lines →  $\log g$*



Fe I = Fe II

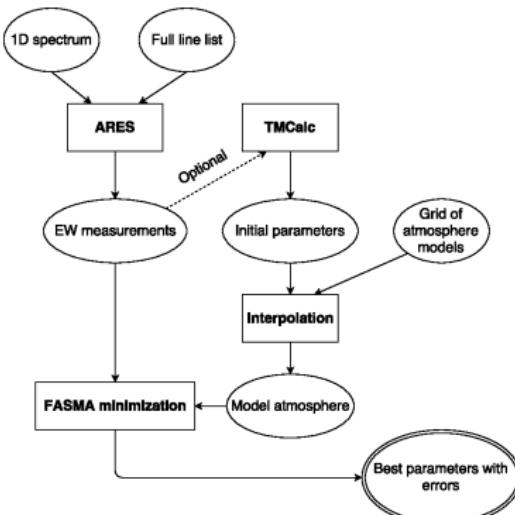
- **Microturbulence:**  
 $A(\text{FeI})$  vs reduced EW ( $= \log EW / \lambda$ )
- **$T_{\text{eff}}$ : Excitation Balance**  
All abundances from Fe should agree for all excitation potentials
- **$\log g$ : Ionization Balance**  
Average  $\log A$  obtained from differing ionization stages must agree



## 5. The Equivalent Width method

Ingredients:

- EW measurements with ARES
- Calculate [Fe/H] from the curve of growth: MOOG+MARCS
- *excitation balance of FeI lines →  $T_{\text{eff}}$*   
*ionization balance of FeI and FeII lines →  $\log g$*



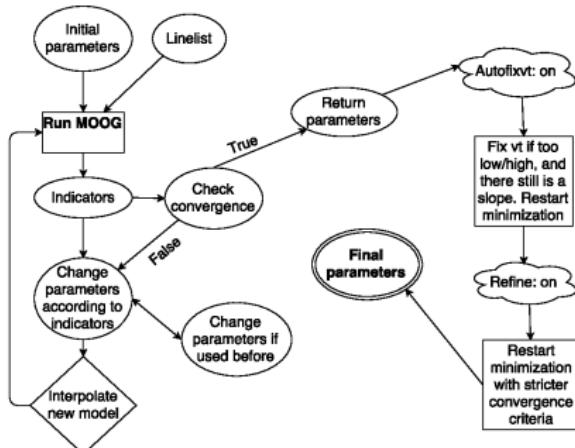
(Andreasen+ 2017)



## 5. The Equivalent Width method

Ingredients:

- EW measurements with ARES
- Calculate [Fe/H] from the curve of growth: MOOG+MARCS
- *excitation balance of FeI lines  $\rightarrow T_{\text{eff}}$*   
*ionization balance of FeI and FeII lines  $\rightarrow \log g$*



(Andreasen+ 2017)



# 5. The Equivalent Width method

The screenshot shows a web browser window with the URL [astro.pt/fasma/](https://astro.pt/fasma/). The page has a green header bar with the FASMA logo and navigation links for Contact, Documentation, and Drivers. The main content area has a dark background with white text. It starts with the title "FASMA" and the subtitle "Fast Analysis of Spectra Made Automatically". Below this, it describes FASMA as a tool to analyze stellar spectra, mentioning papers by Andreasen et al. 2016 and Tsantaki et al. 2017. It encourages users to contact them for questions. The "Drivers" section is expanded, showing three bullet points: "EW" for measuring Equivalent Widths, "EW method" for atmospheric parameters, and "Abundance" for element abundance.

ia FASMA

Not secure | astro.pt/fasma/

FASMA Contact Documentation Drivers

# FASMA

## Fast Analysis of Spectra Made Automatically

FASMA is a tool to analyze stellar spectra as described in [Andreasen et al. 2016](#) and [Tsantaki et al. 2017](#) [in prep. for the synthesis]. FASMA comes with four different drivers to analyze a spectrum, all described below in detail.

Any questions, issues, or suggestions are encouraged. See [contact](#) for details in how to get in touch with us.

### Citation

Please cite the papers mentioned above if you use FASMA in your research. We are also interested in seeing non published research, so we can improve FASMA for a larger group of researchers.

### Drivers

There are four different drivers: *EW*, *EW method*, *synthesis method*, and *abundances* described below. When hovering the mouse over the options, a small description will appear.

- **EW** for measuring EWs from a spectrum. Uses [ARES](#) in the background.
- **EW method** for getting atmospheric parameters from the measured EWs.
- **Abundance** for obtaining abundance of different elements. Atmospheric parameters are needed for this step.

[www.astro.pt/fasma](https://astro.pt/fasma)



# References

- Books
  - The Observation and Analysis of Stellar Photospheres, Gray D., Cambridge University Press, 2015
- Free packages for parameters
  - SME (Valenti+ 1996)
  - GALA (Mucciarelli+ 2013)
  - FAMA (Magrini+ 2013)
  - q2 (Ramirez+ 2014)
  - iSpec (Blanco-Cuaresma+ 2014)
  - fasma (Tsantaki+ 2018)
  - StePar (Tabernero+ 2019)
- Radiative transfer codes
  - MOOG (Sneden+ 1973)
  - SYNTHE (Kurucz+ 1981)
  - SPECTRUM (Gray+ 1992)
  - Turbospectrum (Plez+ 2012)
- Model atmospheres
  - Kurucz (Kurucz+ 1999)
  - PHOENIX (Hauschildt+ 1997)
  - MARCS (Gustafsson+ 2008)
- Atomic data / Line lists
  - NIST (Kramida+ 2020)
  - VALD (Ryabchikova+ 2015)
  - Kurucz (Kurucz 1995)
  - Surveys: Gaia-ESO, APOGEE
  - Specific for K-type (Tsantaki+ 2013)
  - Specific for M-type (Marfil+ 2021)
- Free packages for EWs
  - ARES (Sousa+ 2007)
  - DAOSPEC (Stenson+ 2008)
  - VoigtFit (Krogager+ 2011)



## Finally remarks

Things conveniently neglected:

- Non-LTE
- 3D hydrodynamics
- magnetic fields
- winds
- sphericity
- molecules

Don't use the codes as black boxes. Be patient... astronomers are not programmers.



## 8. Exercise

Your turn!

