

ESPECTROSCOPIA DE ESTRELLAS M PARA LA EXPLOTACIÓN CIENTÍFICA DE LA BÚSQUEDA DE EXOPLANETAS CON



*Spectroscopy of M-type stars for the scientific
exploitation of the CARMENES planet-search survey*

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Universidad Complutense de Madrid





Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs★

CARMENES Consortium:

[CAHA] Centro Astronómico Hispano-Alemán

[IAA] Instituto de Astrofísica de Andalucía

[ICE] Institut de Ciències de l'Espai

[IAC] Instituto de Astrofísica de Canarias

[UCM] Universidad Complutense de Madrid

[CAB] Centro de Astrobiología (CSIC-INTA)

[MPIA] Max-Planck-Institut für Astronomie

[LSW] Landessternwarte Königstuhl

[IAG] Institut für Astrophysik Göttingen

[TLS] Thüringer Landessternwarte Tautenburg

[HS] Hamburger Sternwarte

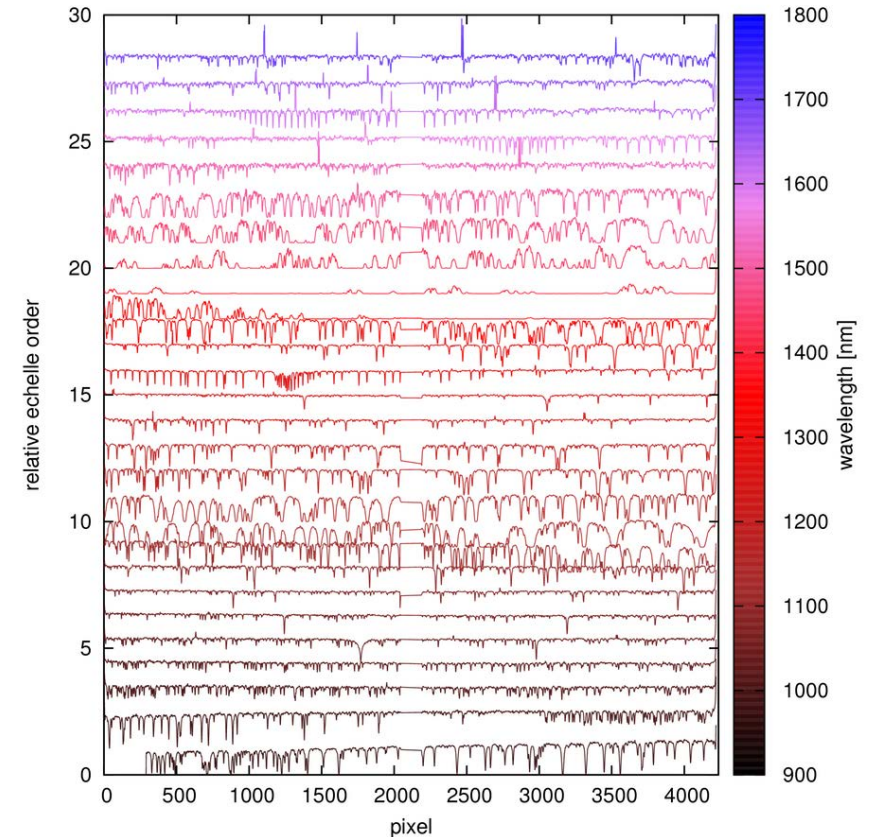
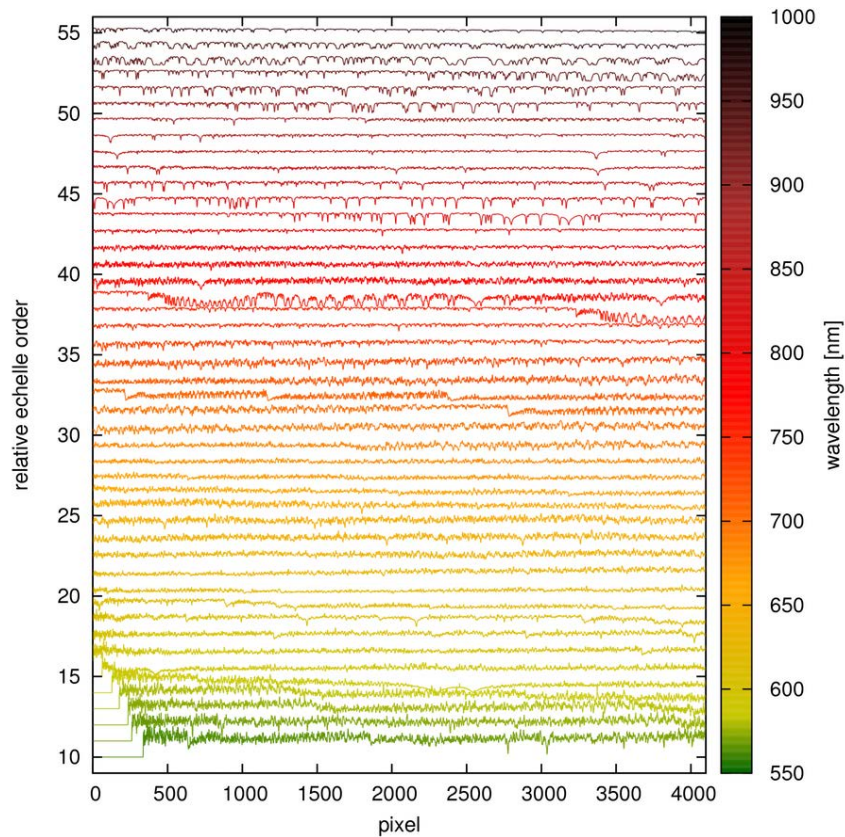
CARMENES science project:

Survey of ~300 M-type main-sequence stars focused on the detection of low-mass planets in their habitable zones

Guaranteed Time Observations (GTO) started on 1th January 2016 and will last for at least three years.

★ <http://carmenes.caha.es>

Wavelength coverage and spectral resolution of CARMENES



Dichroic splits starlight into two beams, one for each channel:

VIS channel: 520-960 nm

61 orders

One CCD 4k x 4k e2v CCD231-84,

R = 94 600

NIR channel: 960-1710 nm

28 orders

Two CCDs 2k x 2k Hawaii-2RG,

R = 80 400

Thesis project

Determination of the **stellar atmospheric parameters** (T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$ and ξ_{macro}) of CARMENES GTO M-type stars.

Prior knowledge of the stellar atmospheric parameters of M stars is crucial for several reasons:

- They make it possible to define the habitable zone around the star.
- They pose major constraints on exoplanetary masses and radii.
- They may show correlations between the stellar atmospheric parameters and the presence of planets.

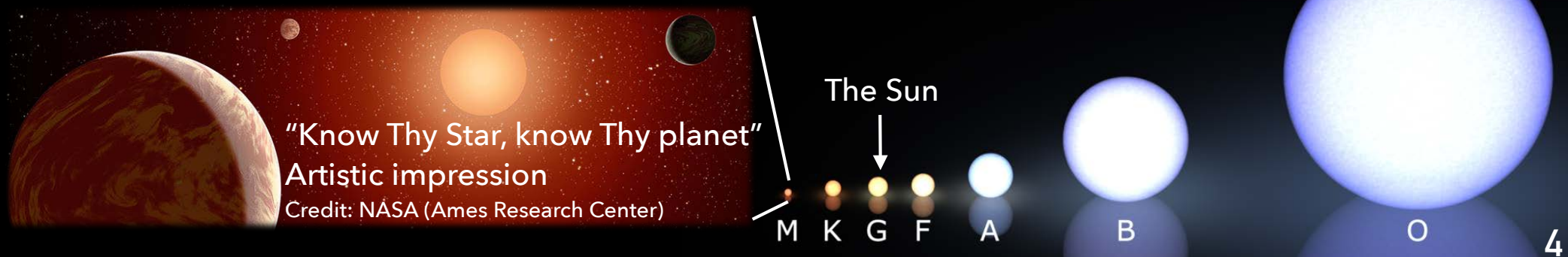
However, this is a long-standing problem, mainly because the stellar atmospheres of M stars are extremely complex to model.

Several methods can be used to derive the stellar atmospheric parameters of a given star. Prime examples of these are the Infrared Flux Method (IRFM), asteroseismology or interferometry, among others.

In spectroscopy, two of the most widely-used spectroscopic methods to determine stellar atmospheric parameters are:

➔ **The Equivalent Width (EW) method** (see e. g. Sousa et al. 2008)

➔ **The Spectral Synthesis method** (see e. g. Valenti & Fisher 2005)



The CARMENES stellar library

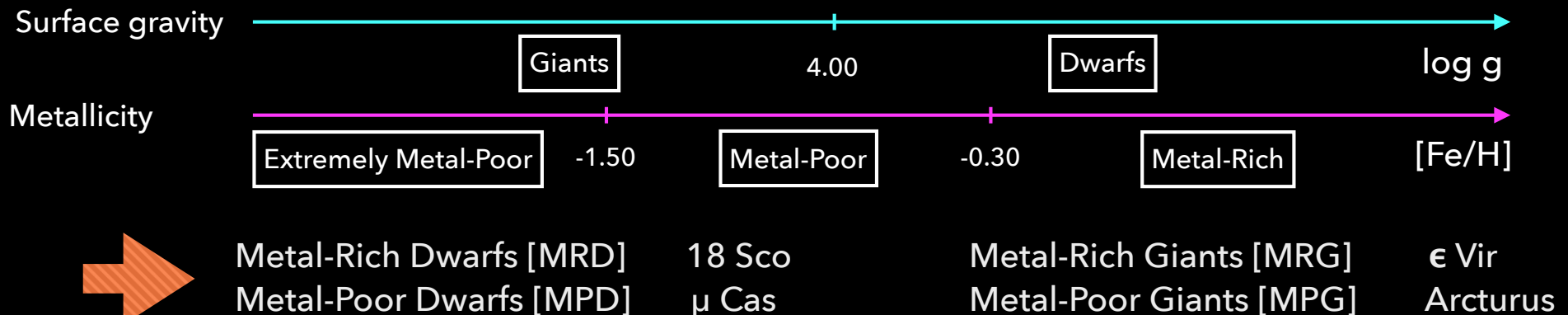
(Caballero et al. A&A, in prep.)

In order to be able to apply the Synthesis Method on the spectra of M stars, it is essential to select the optimal spectral regions used for the comparisons with the synthetic spectra.

So, as a warm-up, we first investigated the spectra of 66 solar-like (FGK-type) stars in the **CARMENES stellar library**, which comprises 139 spectra of O- to M-type stars covering a wide portion of the stellar parameter space (dwarfs and giants, metal-poor and metal-rich).

To simplify the analysis, we first divided the parameter space into four different regions in terms of surface gravity and metallicity (using [Fe/H] as a proxy). We then made a careful selection of Fe I and II lines by means of the visual inspection of the reference spectrum for each of these regions in order to apply the EW method on these stars.

Visual inspection was done using **iSpec** (Blanco-Cuaresma et al. 2014).



Some of the investigated stars are also **Gaia Benchmark Stars** (Jofré et al. 2014, Heiter et al. 2015), which are meant to serve as reference stars of spectroscopic surveys since their parameters have been determined independently from spectroscopy. This in turn will help us assess and validate our own method.

Selected spectral lines along with their atomic parameters come from **VALD3 database** (Ryabchikova et al. 2015)

The CARMENES stellar library

Infrared calcium II triplet
($\lambda = 8498 \text{ \AA}$, 8542 \AA , 8662 \AA)

HD 46223 (O4 V)

HD 36619 (O7.5 V)

ϵ Ori (B1 V)

β Sex (B6 V)

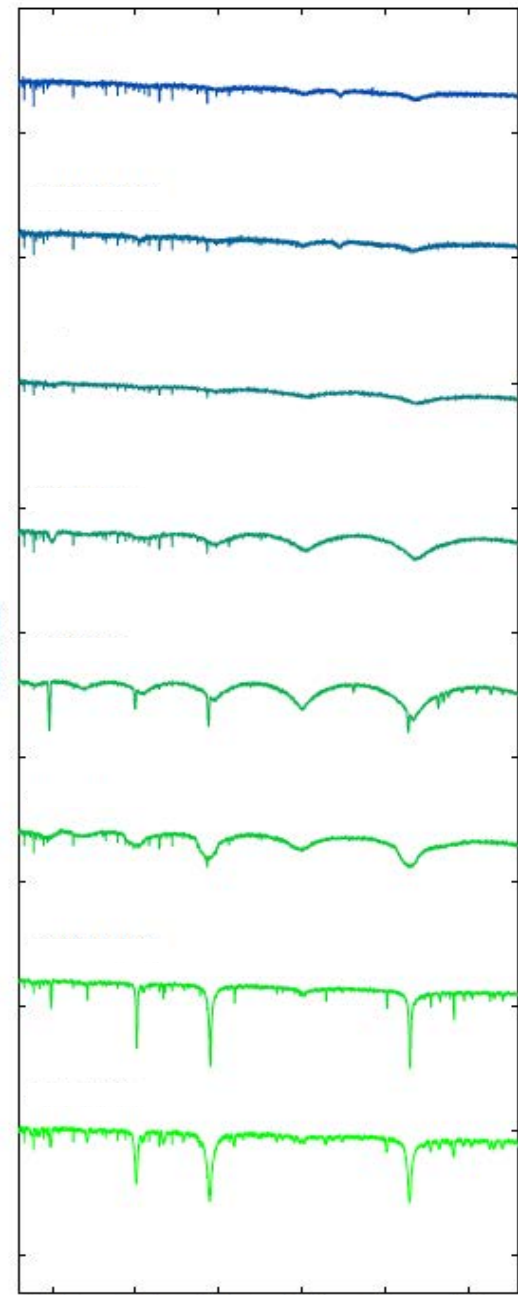
Vega (A0 V)

Altair (A7 V)

HD 49933 A (F2 V)

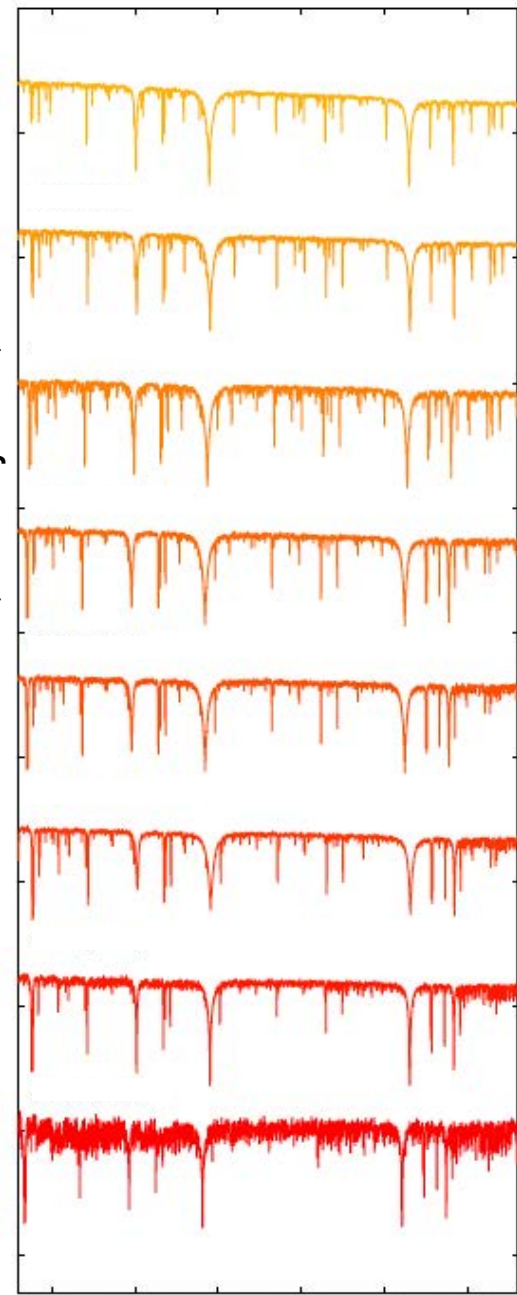
θ Boo (F7 V)

Normalised flux (arbitrary units)



λ (Å)

Normalised flux (arbitrary units)



λ (Å)

18 Sco (G2 V)

Alsafi (G9 V)

HD 219134 (K3 V)

61 Cyg A (K6 V)

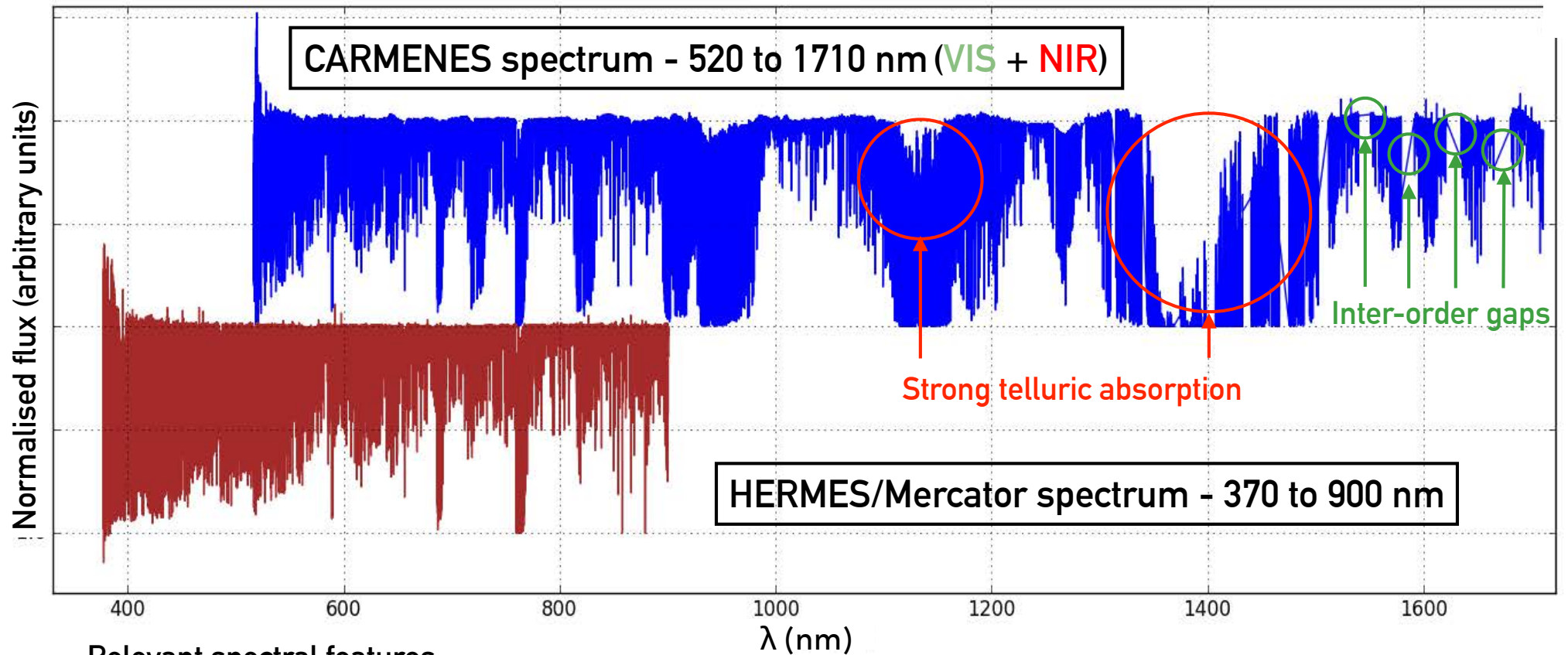
61 Cyg B (K7 V)

HD 79210 (M0.0 V)

GX And (M1.0 V)

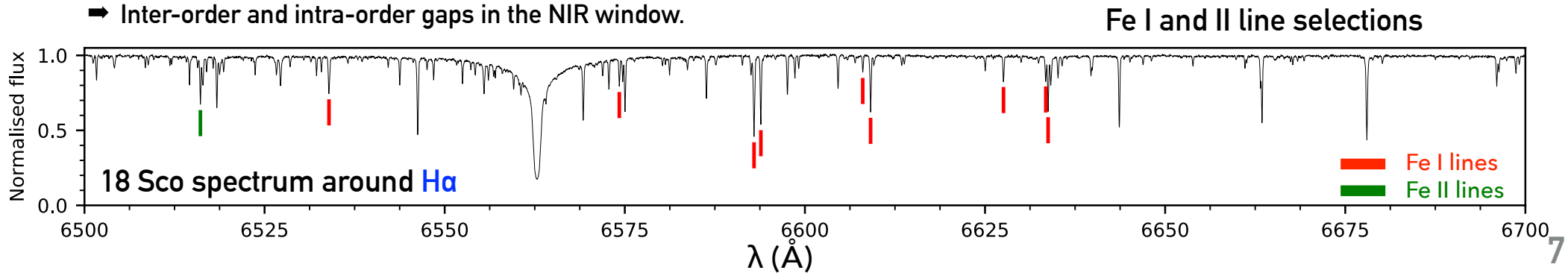
Estrella de Barnard (M3.5 V)

Spectra of a solar-type star, 18 Sco (G2 V)



Relevant spectral features:

- ➔ Presence of telluric absorption regions, especially in the NIR window.
- ➔ Inter-order and intra-order gaps in the NIR window.



Stellar atmospheric parameters of FGK-type stars from high-resolution optical and near-infrared CARMENES spectra [★]

E. Marfil¹, D. Montes¹, H. M. Tabernero^{2,1}, J. A. Caballero³, J. I. González Hernández^{4,5}, A. Kaminski⁶, E. Nagel⁷,
and the CARMENES consortium

λ_{air} [Å]	Source ^a	χ_1 [eV]	log gf		Golden ^c	Star type ^b			
			VALD3	This work		MRD	MPD	MRG	MPG
16396.306	VALD3	6.28	-0.530			•			
16404.601	And16	6.36	+0.581			•		•	
16407.786	VALD3	6.29	+0.007			•	•		
16436.621	And16	5.92	+0.007			•		•	
16440.394	And16	6.29	-0.241			•		•	
16444.816	And16	5.83	+0.663			•	•	•	
16466.921	And16	6.39	+0.003			•	•	•	•
16471.753	And16	6.37	+0.030			•			•
16474.077	And16	6.02	-0.959			•	•		•
16481.228	VALD3	6.39	-0.162			•			
16486.666	VALD3	5.83	+0.783			•		•	•
16506.293	VALD3	5.95	-0.463					•	
16537.994	VALD3	6.29	-0.867			•			
16539.193	And16	6.34	-0.119			•			
16544.667	And16	6.34	-0.029			•		•	•
16551.994	And16	6.41	+0.338			•		•	•
16557.148	VALD3	6.41	-1.083						•
16559.677	And16	6.40	+0.210						•
16561.764	And16	5.98	+0.243				•		
16586.051	And16	5.62	-0.753					•	•
16612.761	And16	6.40	+0.286			•		•	
16629.836	VALD3	6.57	-0.435			•			
16645.874	And16	5.96	-0.032			•	•	•	•
16807.435	And16	5.83	-1.301					•	
16833.052	And16	5.96	-0.889			•		•	•
16843.228	And16	5.87	-1.321			•			
16865.513	And16	6.41	-0.749						•
16869.950	VALD3	6.41	-0.415					•	
16874.116	And16	6.35	-0.159			•			
16892.384	VALD3	6.31	-0.799			•		•	•
16969.910	VALD3	5.95	-0.069					•	
17005.450	VALD3	6.07	+0.005				•		•
17008.971	VALD3	6.62	-0.301			•		•	
17011.095	VALD3	5.95	+0.102			•			•
17037.787	And16	6.39	-0.852						•

Some lines were already selected and analysed in previous works:

- [VIS] Sousa et al. (2008), Tsantaki et al. (2013)
- [NIR] Andreasen et al. (2016)

New identified lines come from VALD3 database

624 Fe I lines altogether:

- 402 in MRD stars
- 304 in MPD stars
- 319 in MRG stars
- 383 in MPG stars

20 Fe II lines altogether

^a References. Sou08: Sousa et al. (2008); And16: Andreasen et al. (2016); VALD3: VALD3 queries.

^b Star type. MRD: Metal-Rich Dwarf; MPD: Metal-Poor Dwarf; MRG: Metal-Rich Giant; MPG: Metal-Poor Giant.

^c Golden Fe I lines as defined in Jofré et al. (2014).

The Equivalent Width (EW) method

This method relies on the measurements of the equivalent widths of a given selection of spectral lines and derives the stellar parameters of the star under the assumption of local thermodynamic equilibrium (LTE) (Andreasen et al., 2016, A&A 585, A143).

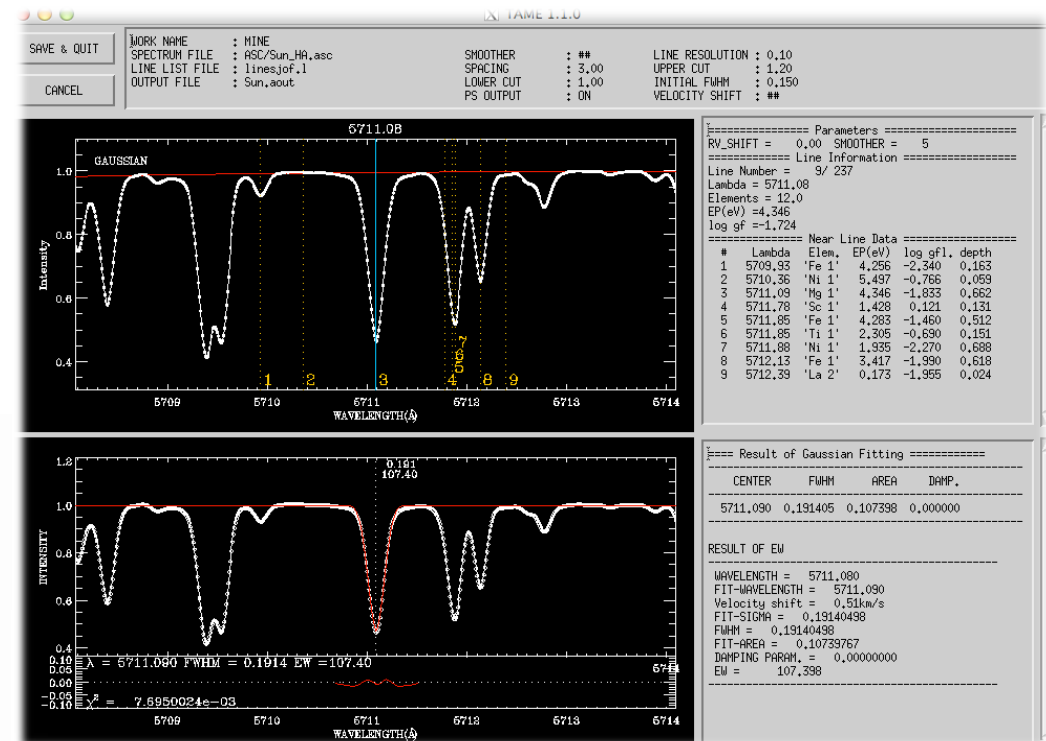
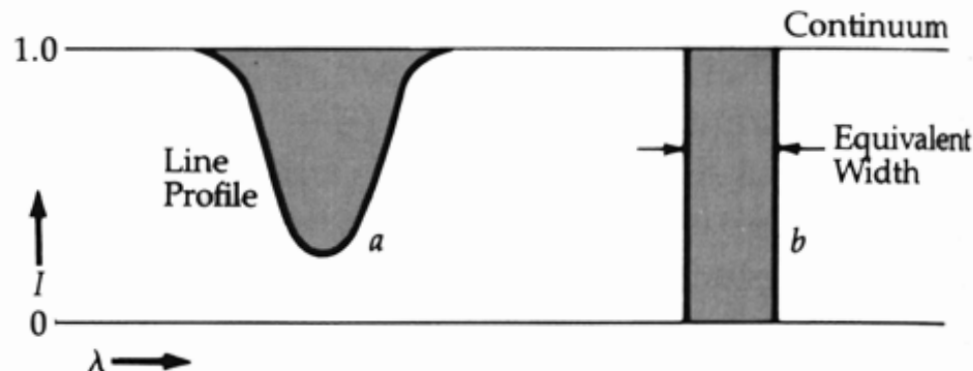
To apply this method, we use two different pieces of software:

- ➔ TAME (Kang et al., 2012, MNRAS 425, 3162-3171)
- ➔ StePar (Tabernero et al., 2012, A&A, 547, A13).

TAME is used for measuring the EW of the lines under analysis on each of our spectra.

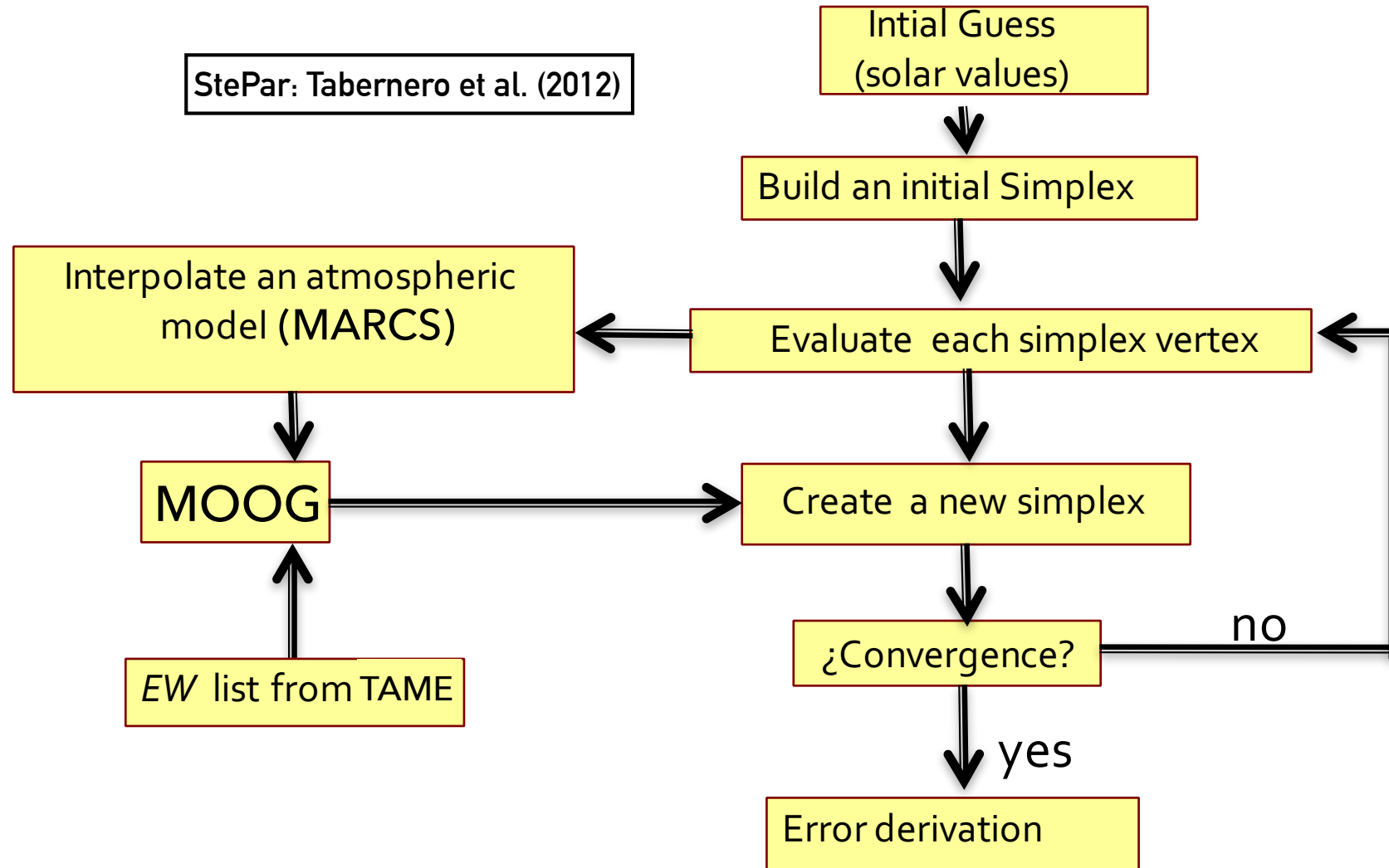
Formal definition of the Equivalent Width:

$$W_{\lambda} = \int \left(1 - \frac{F_{\lambda}}{F_0} \right) d\lambda$$



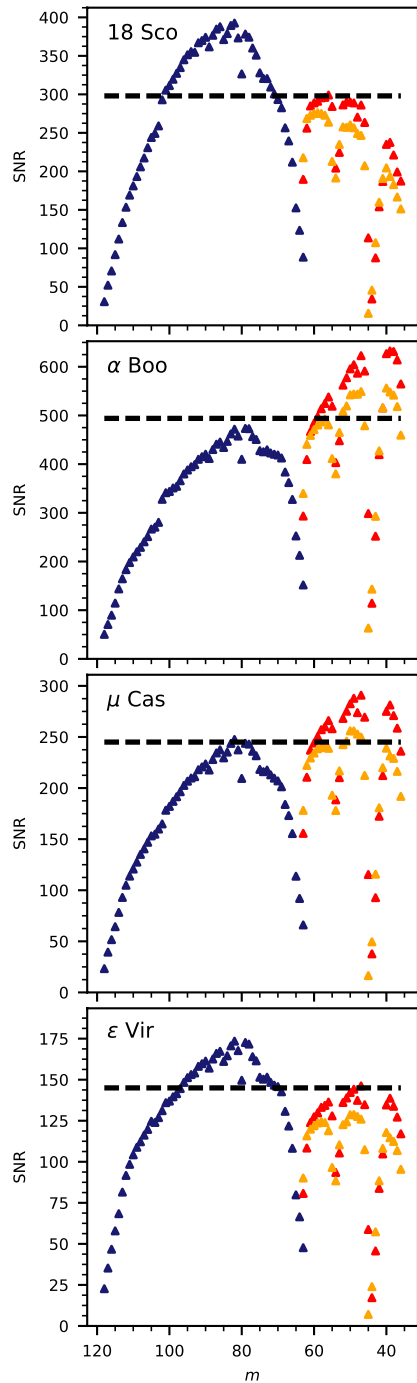
StePar programme flow

StePar uses a grid of MARCS model atmospheres (Gustafsson et al. 2008) and the 2017 version of MOOG radiative transfer code (Snedden et al. 2017) to compute the stellar atmospheric parameters, imposing both ionization and excitation equilibria on a set of Fe I and Fe II.



Preliminary results

(Marfil et al., A&A, in prep.)



◀ SNR of the reference spectra as a function of spectral order. Black, dashed lines represent the SNR estimation by iSpec.

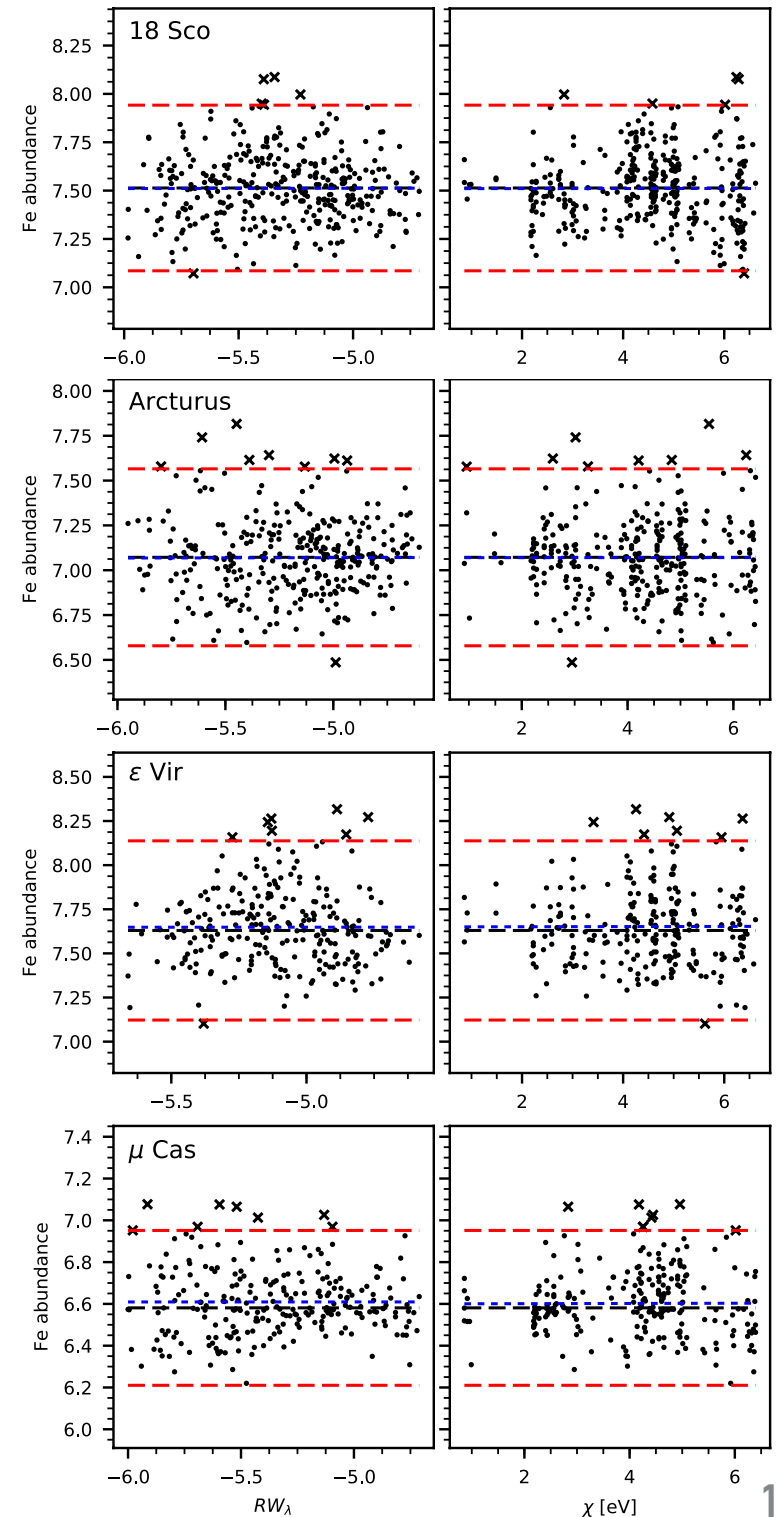
StePar inner sigma-clipping process: Fe I lines that yield an Fe abundance exceeding 3σ with respect to the median Fe abundance are rejected.

$$\chi \equiv \text{excitation potential [eV]}$$

$$RW_\lambda = \log_{10} \left(\frac{W_\lambda}{\lambda} \right) \equiv \text{reduced equivalent width}$$

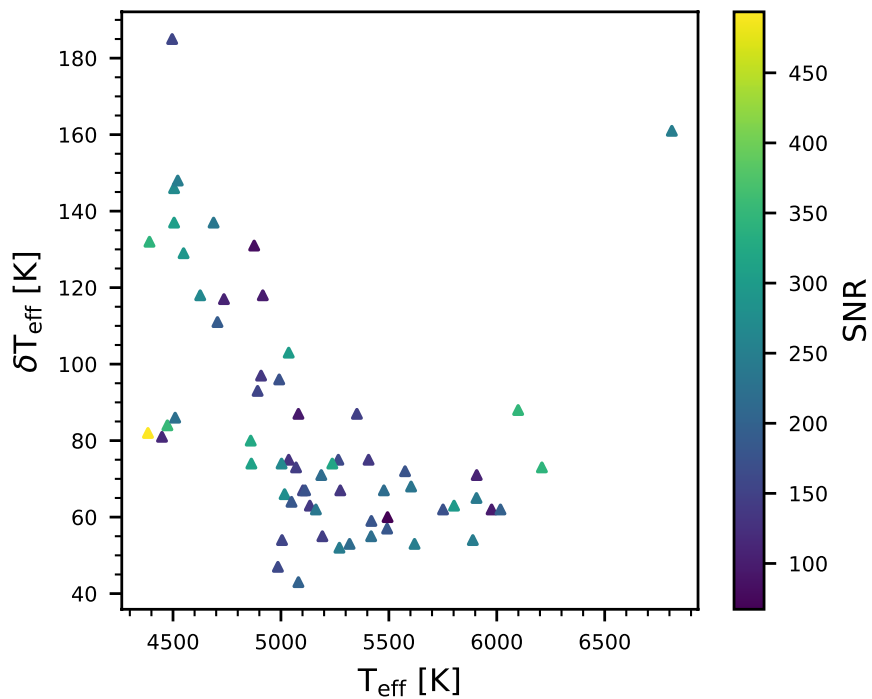
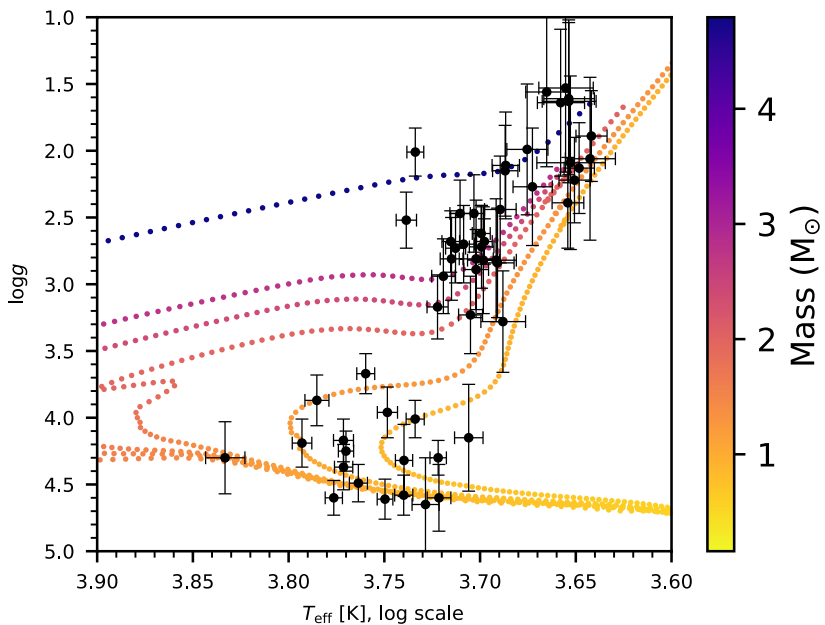
MOOG abundances are computed in an "absolute scale":

$$\log_{10} \epsilon(\text{Fe}) = \log_{10} N(X) / N(H) + 12$$

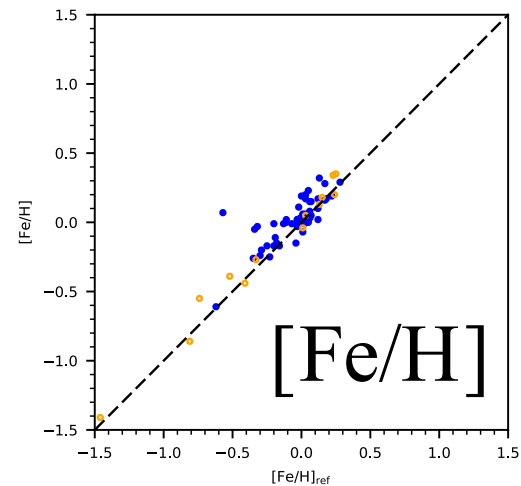
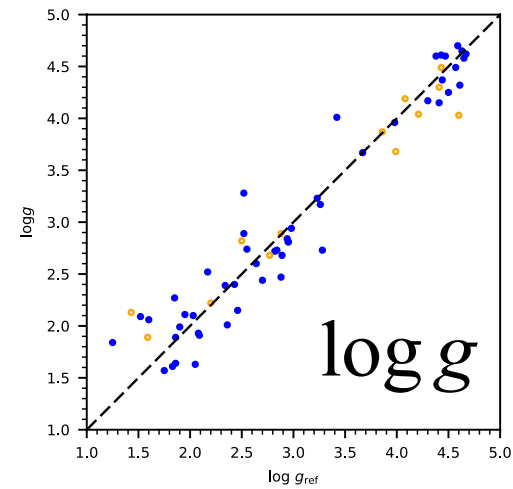
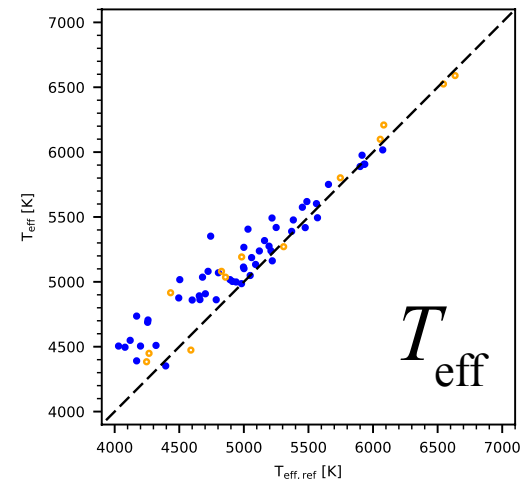
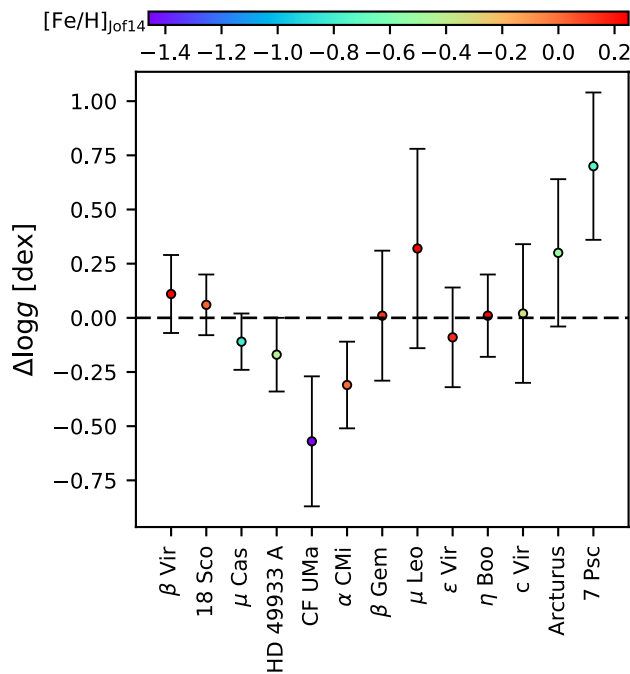
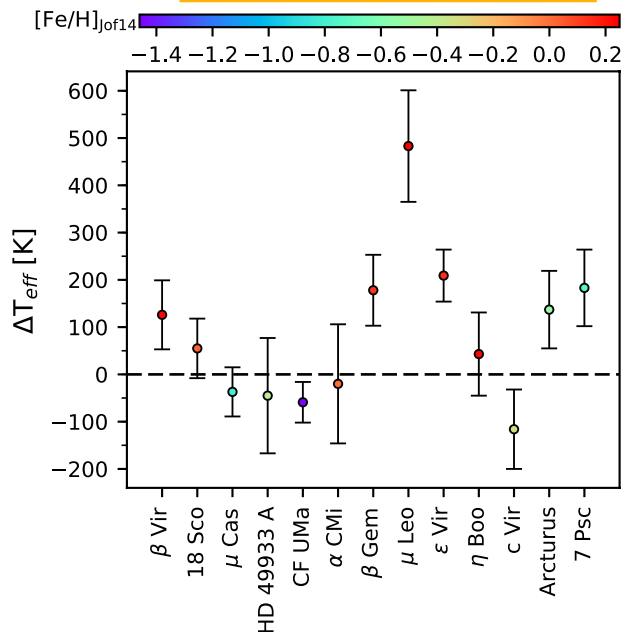


Preliminary results

(Marfil et al., A&A, in prep.)



Gaia Benchmark Stars



The log gf calibration

It is a known issue that VALD3 provides inaccurate log gf values for some Fe lines (see e. g. Andreasen et al. 2016).

This problem can be circumvented by means of a log gf calibration, which yields the so-called astrophysical log gf values. This technique consists in the minimisation of the difference between the EW of a spectral line measured on a reference spectrum (typically, the Sun) and its theoretical EW (= given by the solution of the radiative transfer equations) when different log gf are taken as input values.

Since the CARMENES stellar library originally lacked a solar spectrum, we made a DDT proposal at CAHA to obtain a CARMENES spectrum of the Sun (observing Ceres).

This calibration can be done through MOOG's *ewfind* driver, which computes the theoretical EW given the line parameters.



Spectral Synthesis on M stars

Passegger et al., 2018, A&A, in press

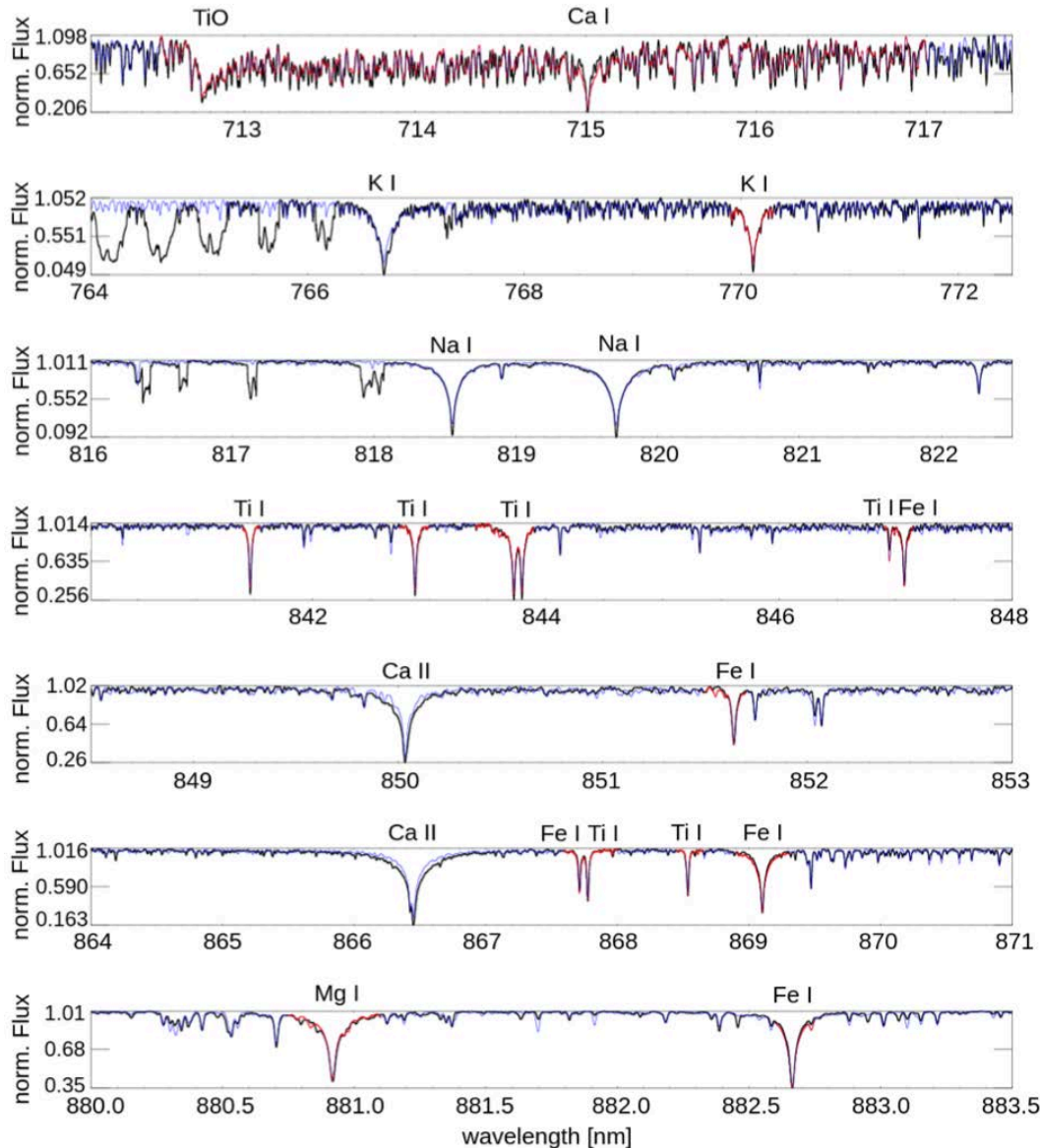


Fig. 4. Co-added CARMENES spectrum of the M1 V star GX And (black) and the best-fit model (blue: whole fit, and red: regions used for χ^2 minimisation).

It is based on a χ^2 minimization on selected spectral regions (around astrophysically interesting lines) between the observed and synthetic spectra.

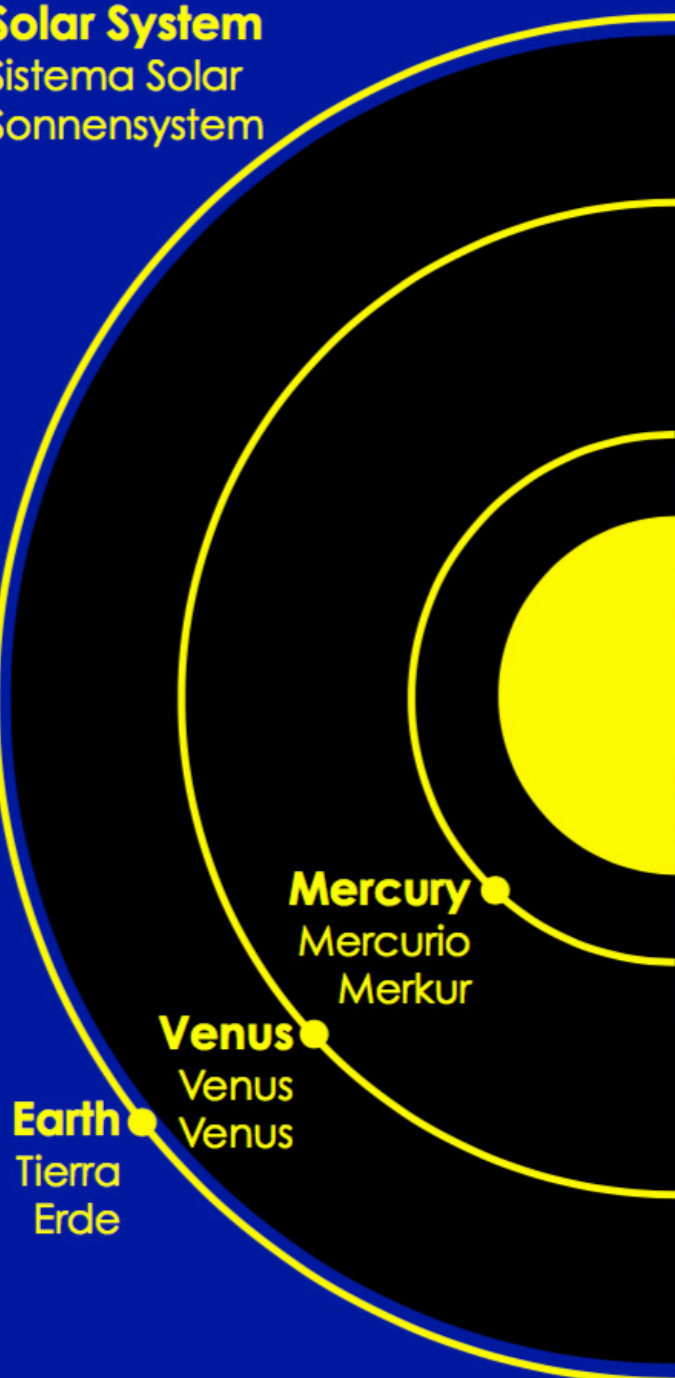
The PHOENIX-ACES model grid (Husser et al. 2013 and references therein) is especially adequate for modelling spectra of cool dwarfs since it uses a new equation of state to improve the calculations of molecule formation in cool stellar atmospheres.

Our spectral synthesis method is based on a modified version of StePar which relies upon spectral synthesis instead of equivalent widths (Tabernero et al., MNRAS, 2018, in press).

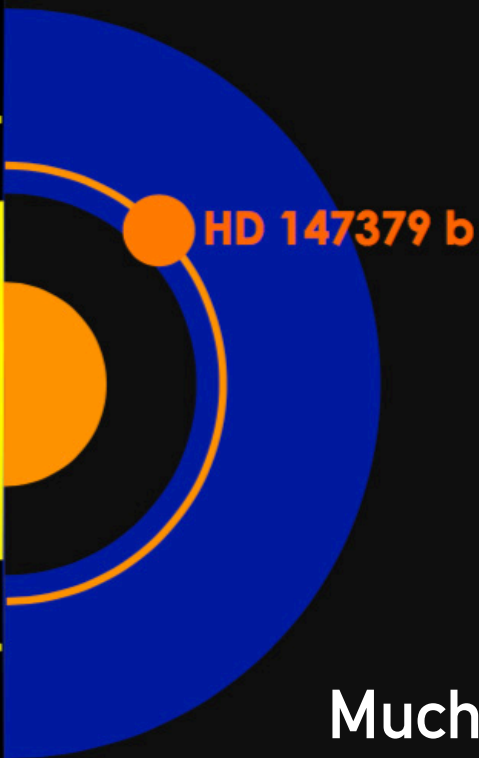
The original optimization method is also replaced by a Metropolis-Hastings algorithm using Markov chains (Metropolis et al. 1953). Our method generates a Markov-Chain of 20 000 points starting from an arbitrary point. To be able to evaluate any point within the stellar parameter space, we employ a bilinear interpolation scheme. As objective function we used a χ^2 in order to fit any previously selected spectral features.

Solar System

Sistema Solar
Sonnensystem



HD 147379
J16167+672S
GJ 617 A



Muchas gracias por vuestra atención

Star and planet sizes *not* to scale
Estrellas y planetas *no* a escala
Größen *nicht* maßstabsgetreu

HD 147379 b

CARMENES • Reiners et al. • 2017



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