Analysis of chromospheric flux-flux relationships of M Dwarfs using visible and near-infrared CARMENES spectra

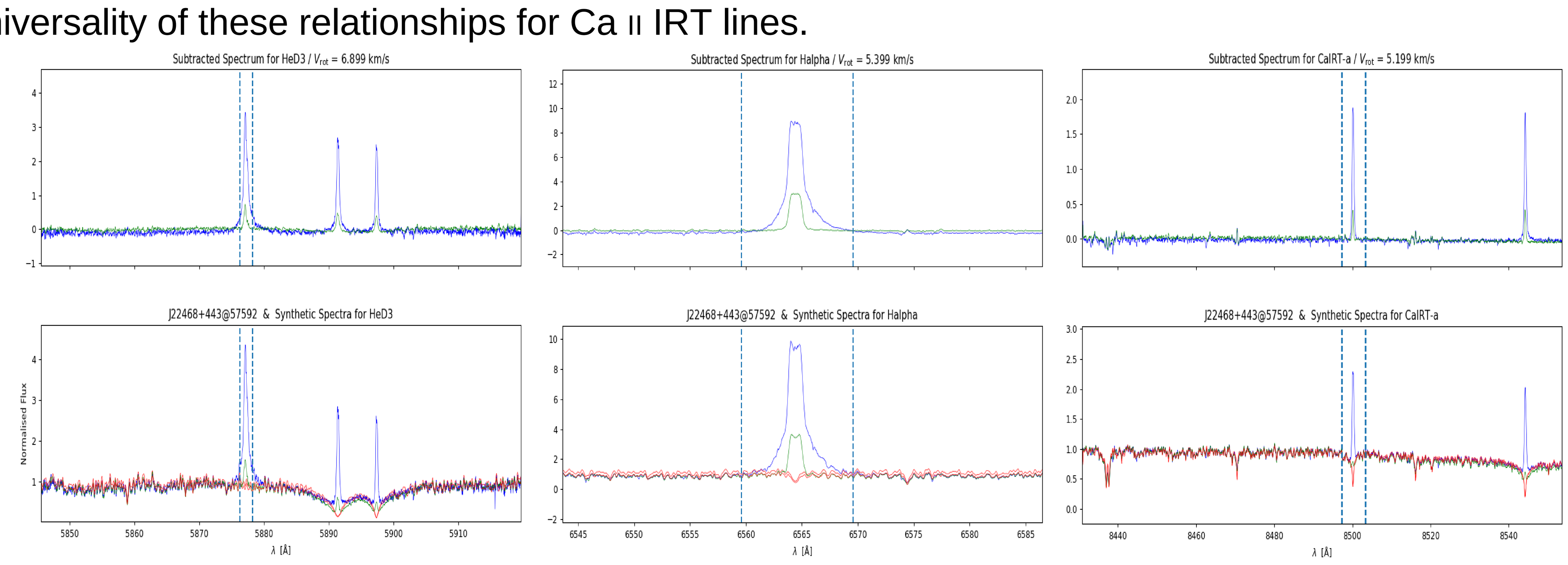
F. Labarga[1]; D. Montes[1]; C. Duque-Arribas[1]; A. López-Gallifa[1]; J. A. Caballero[2]; S. V. Jeffers[3]; A. Reiners[4]; I. Ribas[5]; A. Quirrenbach[6]; P. J. Amado[7]; and the CARMENES Consortium

1 Dpto. Física de la Tierra y Astrofísica & IPARCOS-UCM (Instituto de Física de Partículas y del Cosmos UCM), Fac. CC Físicas, Univ. Complutense de Madrid, Spain
2 Centro de Astrobiología (CSIC - INTA), ESAC campus, camino bajo del castillo s/n, 28691, Villanueva de la Cañada, Madrid, Spain
3 Max Planck Institute for Solar System Research, Göttingen, Germany
4 Institut für Astrophysik, Georg-August-Universität, Göttingen, Germany
5 Institut de Ciències de l'Espai & IEEC-CSIC, Campus UAB, c/ de Can Magrans s/n, E-08193 Bellaterra, Barcelona, Spain
6 Zentrum für Astronomie der Universität Heidelberg, Landessternwarte, Heidelberg, Germany
7 Instituto de Astrofísica de Andalucía (IAA, CSIC), Glorieta de la Astronomía s/n, E-18008 Granada, Spain

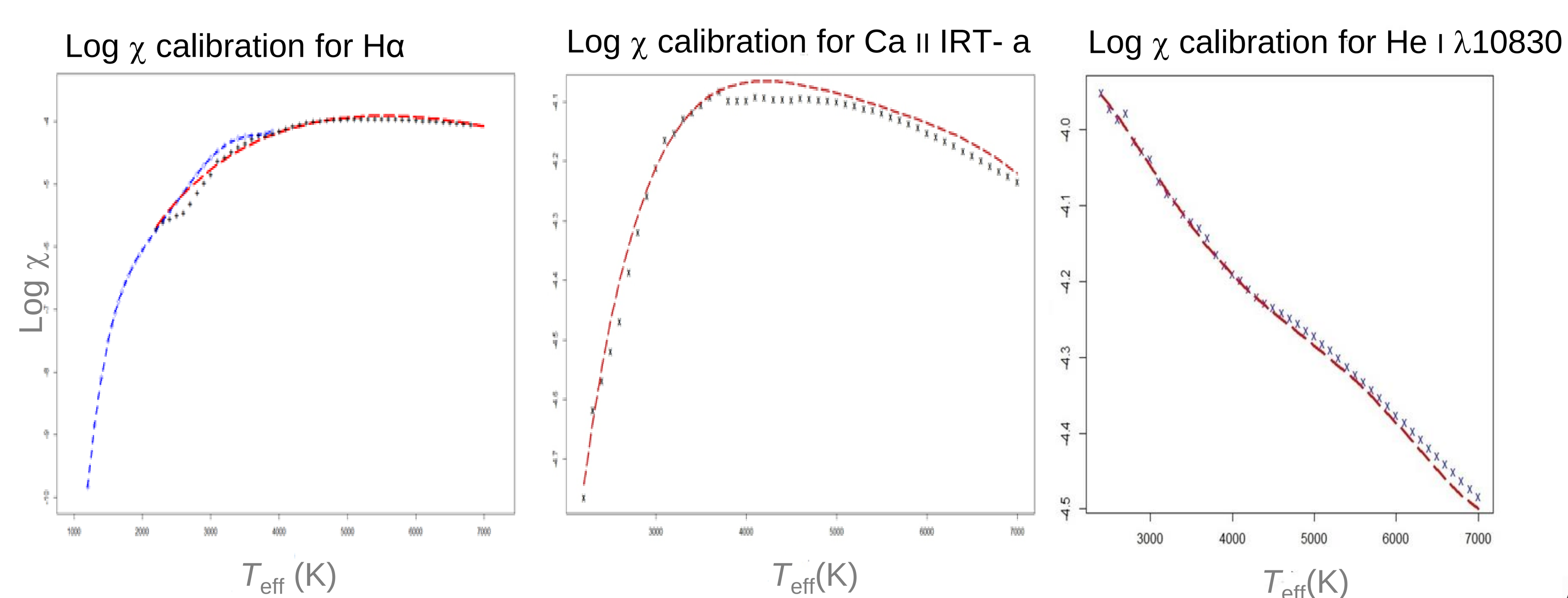
ABSTRACT: Exploiting the huge amount of data provided by the **CARMENES** survey, this work aims to study the chromospheric activity of M dwarfs based on a sub-sample (active RV-loud M dwarfs) of CARMENES GTO sample. Using the spectral subtraction technique and calibrations of the continuum-flux near the line of interest, the available information on the chromospheric activity flux is extracted. Most of the chromospheric indicators included in the spectral range of the spectrograph, ranging from visible (VIS) - that include the Na I D_1&D_2 He I D_3, and Hα lines - to near-infrared (NIR) - that include the Ca II IRT, He I λ10830, Paschenα and Paschenβ lines - are used. For the implementation of the spectral subtraction technique, a Python code (*iSTARMOD*) based on a previous FORTRAN one, formerly used by the research group, is used. The synthetic spectra for effective temperatures in the range [2400, 7000] K, allows through the calibrations a comparison of the flux-flux relationships with previous works performed for F, G and K dwarfs. The studies of flux-flux relationships of lines formed at different chromosphere layers seek for a better understanding of the magnetic activity of M-type dwarf stars and try to determine the number of different chromospheric emitters populations, deduced from the non-universality of these relationships for Ca II IRT lines.

The spectral subtraction technique (Barden, SC; 1985, Montes et al., 2000) is well suited for the study of chromospheric activity in M-dwarfs, given that this type of stars does not have a well-defined continuum, especially in its late-types. The detailed analysis of the activity indicators is important from one side in order to confirm or discard all the possible planets around these stars and by the other studying its dependency with other stellar parameters as rotation, age and depth of the convective zone. This is the case for the stars of the **CARMENES** survey (Quirrenbach et al. 2020), where a WG on stellar activity, elaborating on its characterization in order to discount the jamming effect on stellar spectra of activity and rotation in the detection of exoplanet candidates. The CARMENES has the aim of detecting Earth-mass planets orbiting in the habitable zones of their host stars, focusing on over 300 M-type dwarf stars, spread over the complete M spectral range.

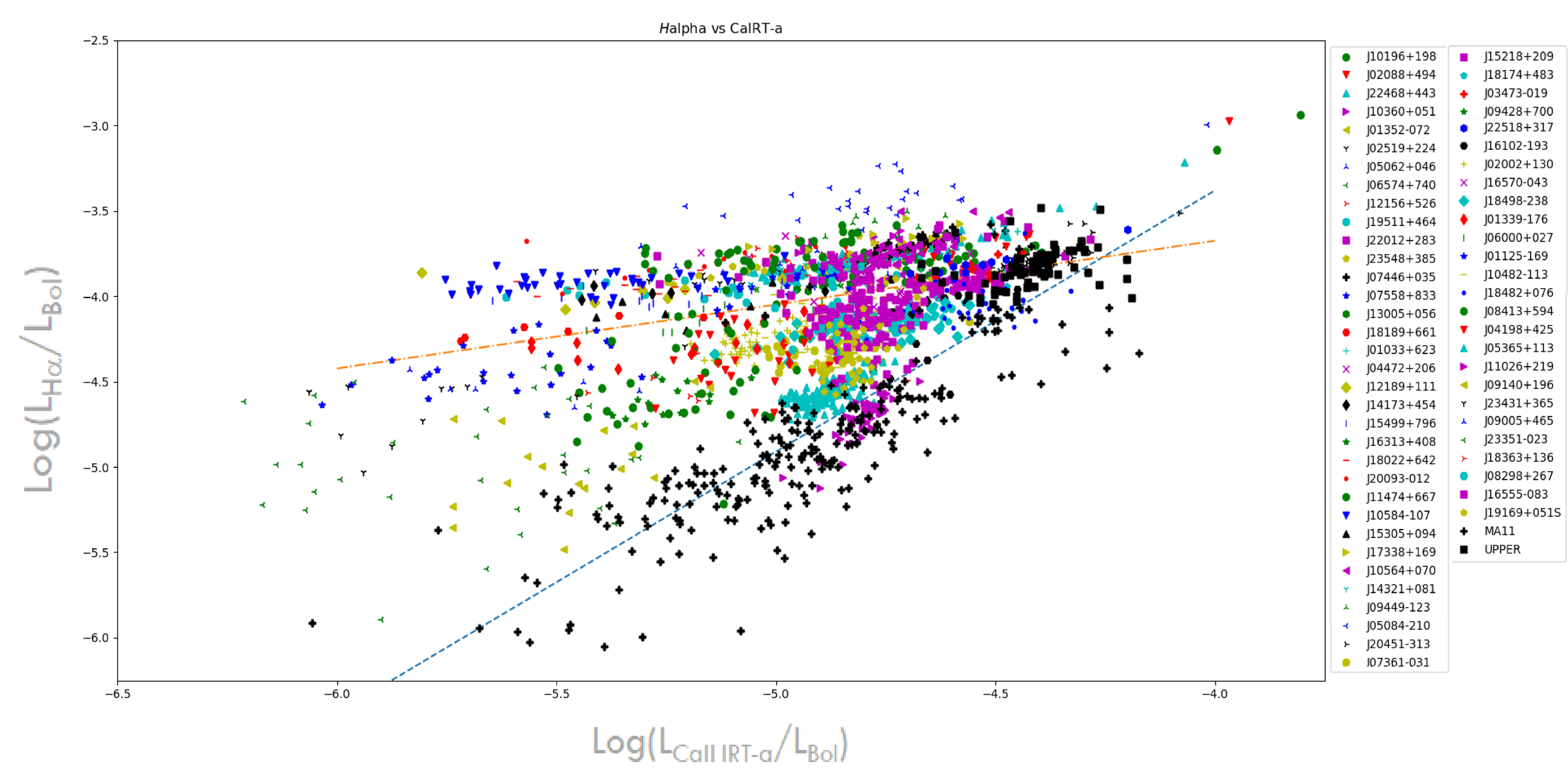
For the work carried out in this study, the spectral subtraction technique (see Fig. 1) has been applied using the *Python* code ***iSTARMOD*** (Labarga & Montes, 2020).



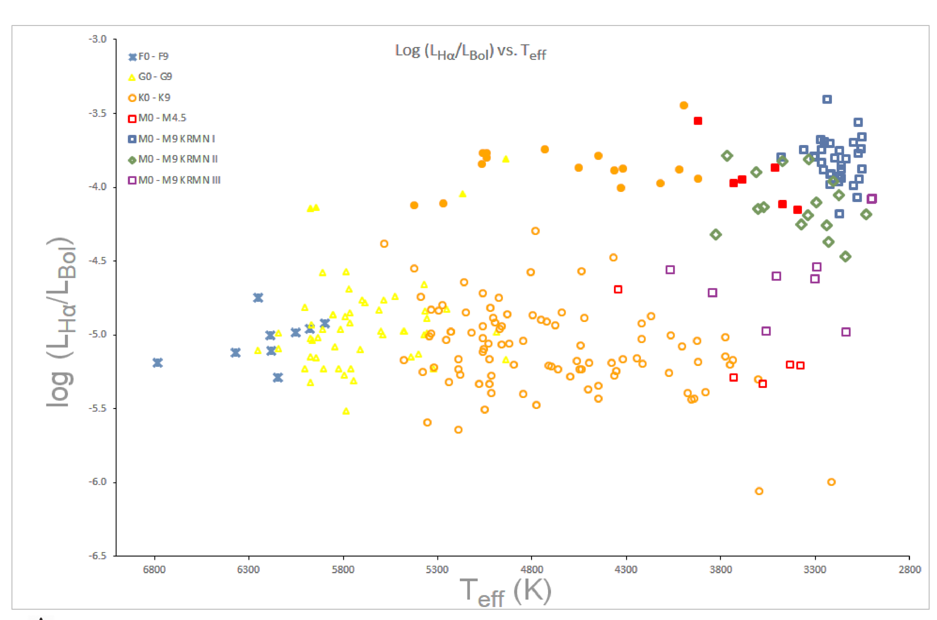
▲ **Fig. 1:** Results of applying the spectral subtraction for selected chromospheric activity indicators (He I D_3, Na I D_1, D_2, Hα and the first two of three Ca II IRT lines in the VIS) with the CARMENES spectra of J22468+443 **(EV Lac)** at the **maximum level** of chromospheric activity (Flare) and in a previous **quiescent phase** as well as the **synthetic spectrum** obtained with a M3.5 V reference star (J22096-046). The spectra to perform the subtraction are shown at the bottom and the obtained subtracted spectra at top from where we derived the *EW* of the chromospheric contribution. The algorithm makes use of the python code ***iSTARMOD*** as described in Labarga & Montes (2020).



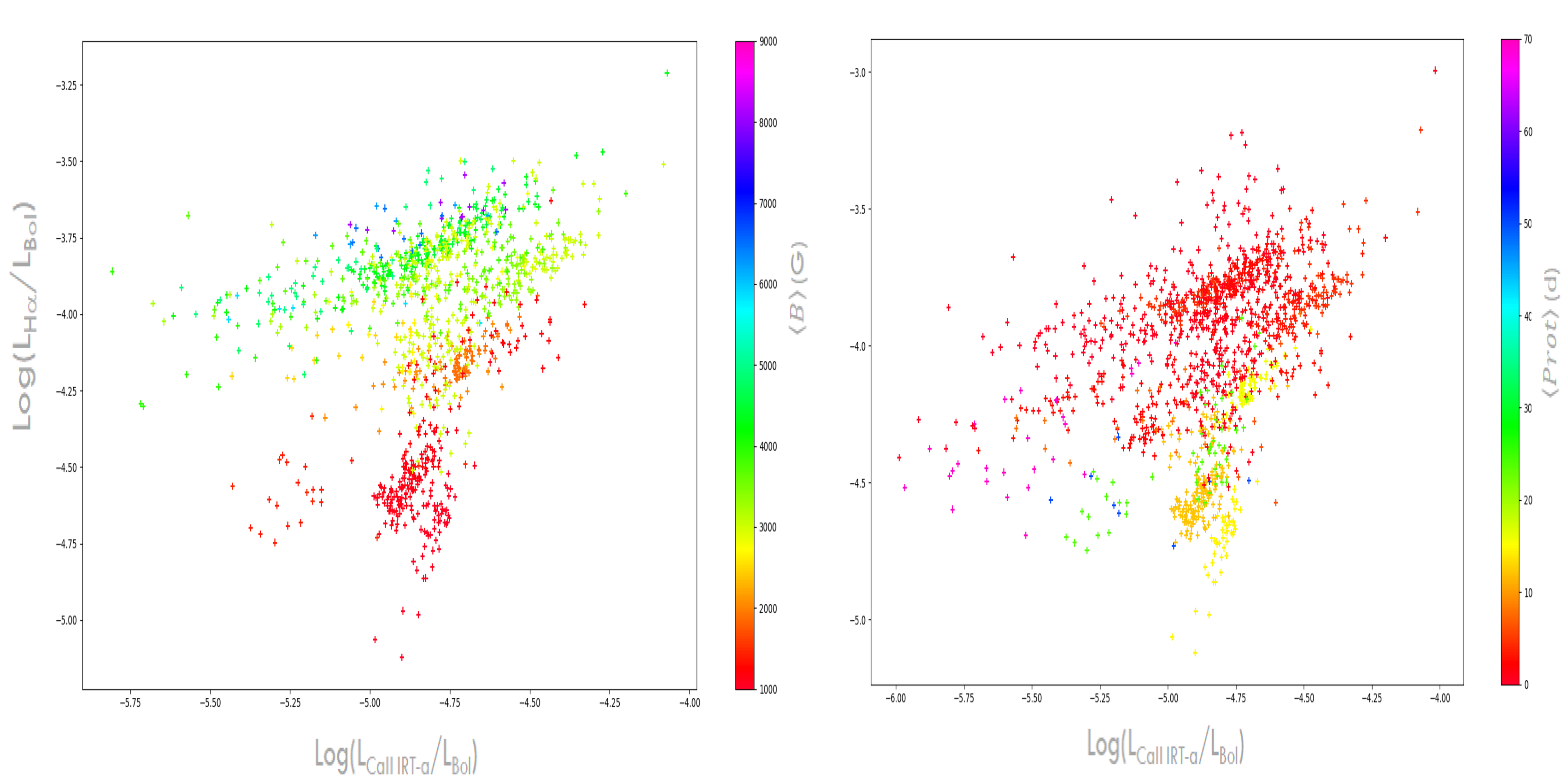
▲ **Fig. 2:** Example of the calibrations for χ factor Walkowicz, L. M., et al. (2004) and Reiners & Basri (2008) with effective temperature ($T_{\rm eff}$) for **Hα, Ca II IRT, HeI λ10830 Å** (dashed red lines) performed for $T_{\rm eff}$ in the range [2400, 7000 K], except the case of the Hα line that covers the range [1200, 7000 K] for comparison with the fit obtained in Reiners & Basri (2008) (dashed blue line).



▲ **Fig. 3: Flux-flux** relationship of **Hα vs. Ca II IRT-a** for the CARMENES RV loud sample of M stars. Data provided in Martinez-Arnáiz et al. (2011) for FGKM stars (**black** squares and asterisks in the right-hand side of the image) are included for comparison, as well as the fits of flux-flux relationships for these points. As can be seen, the existence of different emitter populations on the flux-flux relationships points out to the existence of different dynamos in the interior of stars (e.g.: Böhm-Vitense, 2007) or to differences due to age/rotation, producing a saturation in the chromospheric emission of younger and faster rotating stars (see e.g.: Hartmann et al., 1984; Hartmann & Noyes, 1987). Both hypothesis has not been put into test extensively with the whole range of **M-type stars**, and now this has been done with the RV loud sample (Tal-Or et al, 2018) within the **CARMENES** survey.



▲ **Fig. 4 Hα** flux vs $T_{\rm eff}$ using the mean values calculated from the data provided by **CARMENES** and Martinez-Arnáiz et al. (2011). The points coming from our study are represented as empty squares in **blue**, **green** and **purple.** The remaining points are provided in Martinez-Arnáiz et al. (2011) for FGKM stars. The points of the upper branch of this study are clearly completed by the values provided by **CARMENES** data.



▲ **Fig. 5:** In order to explore evidences for the above mentioned different dynamos, here the same flux-flux relationships are shown as in Fig. 3 but with colours indicating the magnetic field (**B**) values (left) derived by Reiners et al. (2022), and the data of rotation periods (right) by Shan et al. (2022 in prep.). Note the gradient of magnetic field between the distinct emitters populations. **At least two branches** are clearly visible in both figures, confirming the results of Martinez-Arnáiz et al. (2011) and showing the non-universality of flux-flux relationships, providing evidence to the existence of distinct chromospheric emitter populations.

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