CARMENES Survey
Exoplanet discoveries and insights into stellar astrophysics

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- **C**alar **A**lto
- High-**R**esolution Search for
- **M** Dwarfs with
- **E**xo-Earths
- With **N**ear-Infrared and Optical
- **E**chelle **S**pectrographs

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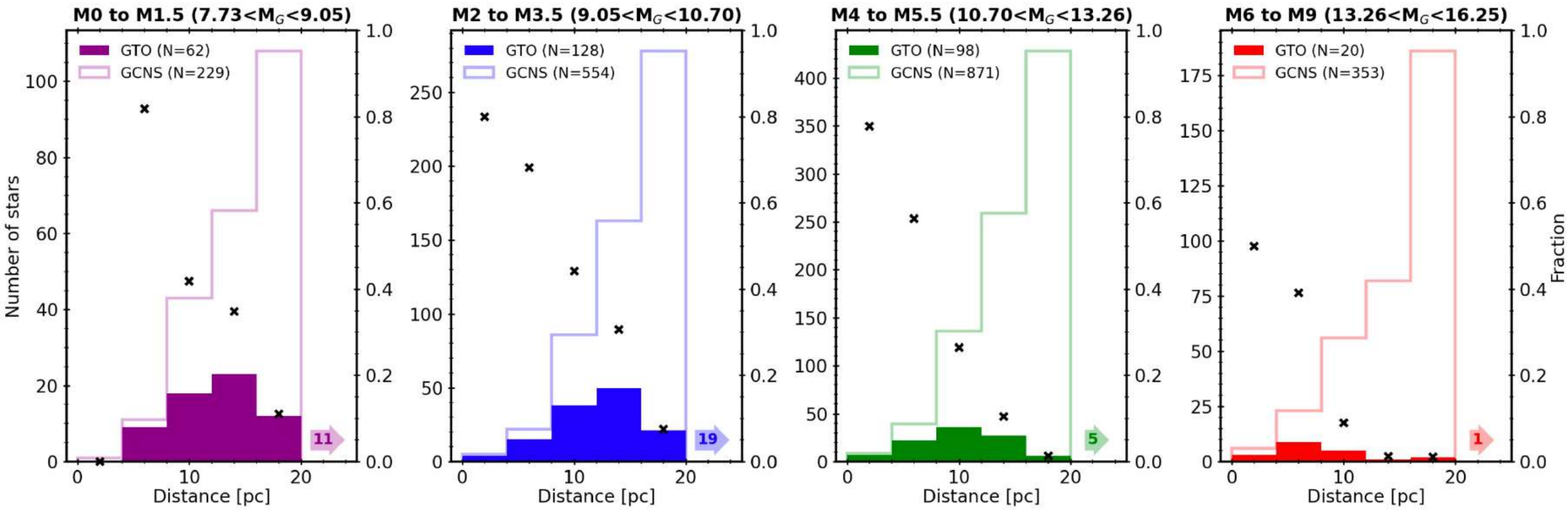
- Mounted on 3.5-m @ CAHA
- Consortium: 11 Spanish and German institutions
- GTO: 2016-2020 (750 un)
- CARMENES Legacy-Plus: 2021-2026+ (370 un)

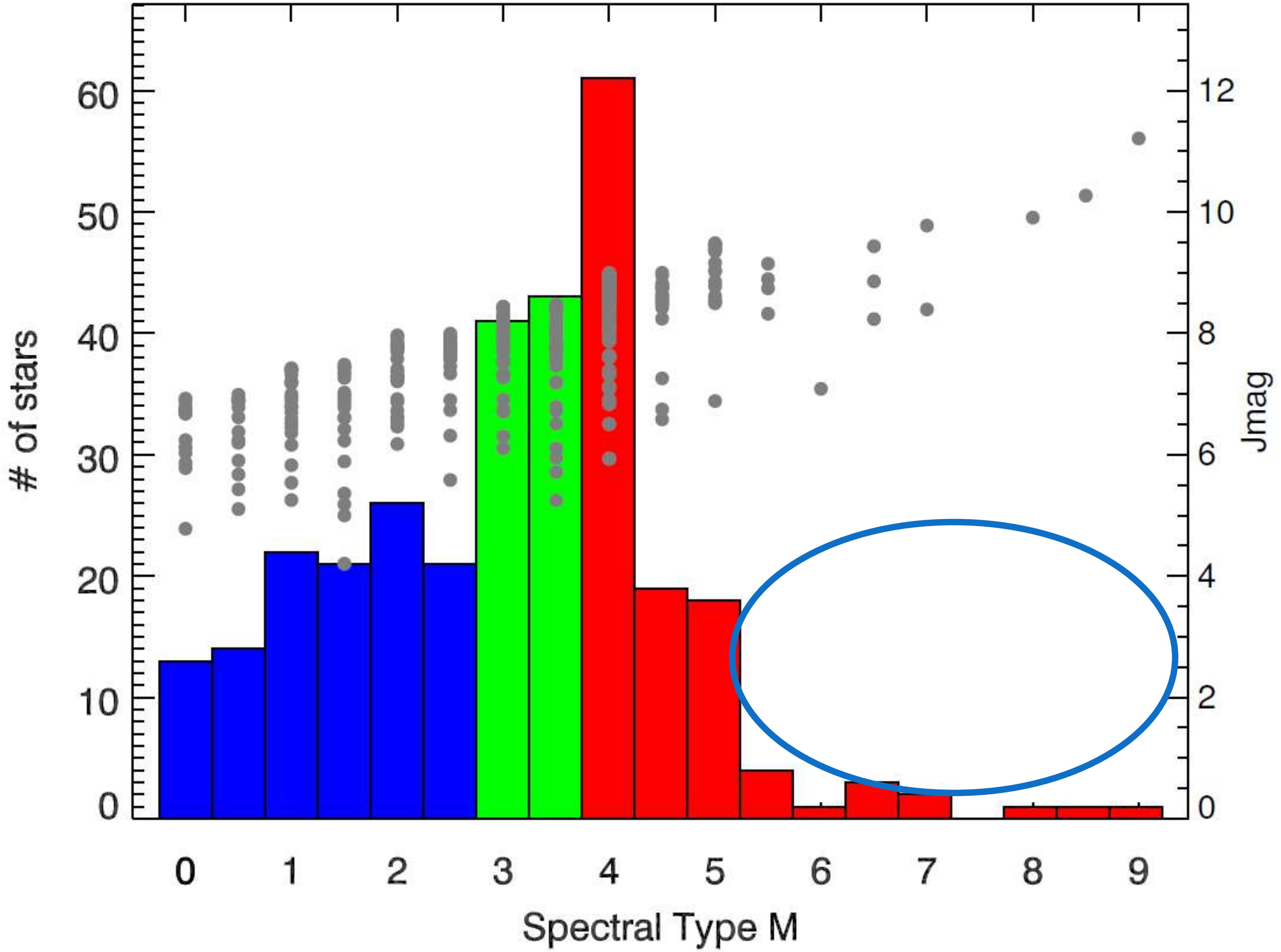
- VIS (520-970 nm) & NIR (970-1710 nm) channels
- Goal: detecting low-mass planets in M-dwarf habitable zones (focus on >M4) ➜ architecture & statistics

The CARMENES sample

- 362 stars in total – 11 SB2 & SB3
- Completeness at 20 pc: 15%
- 48% of M dwarfs within 10 pc
- Up to 10 pc, ratio >50% except late Ms (28%)



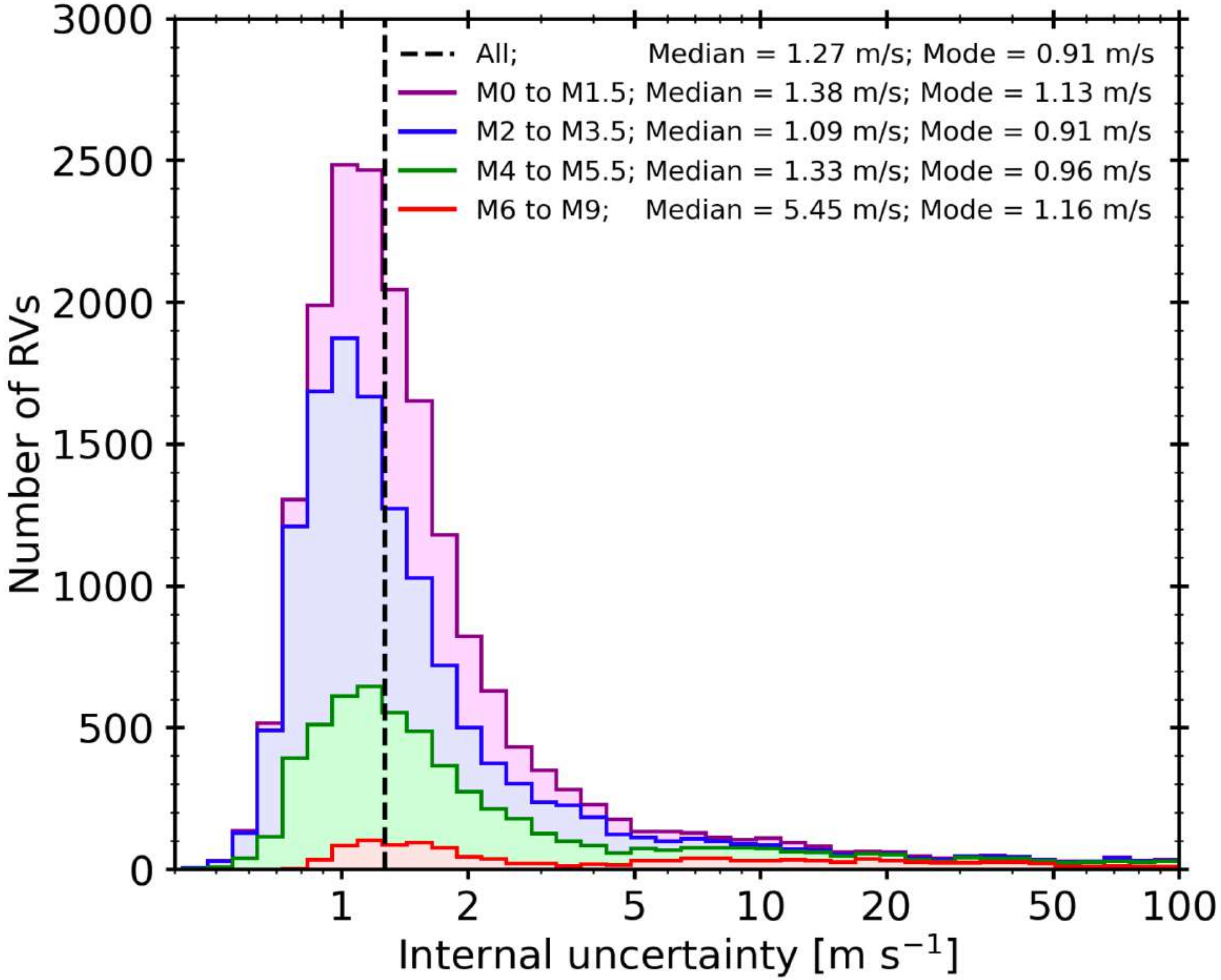
The CARMENES sample



<d> = 13 pc

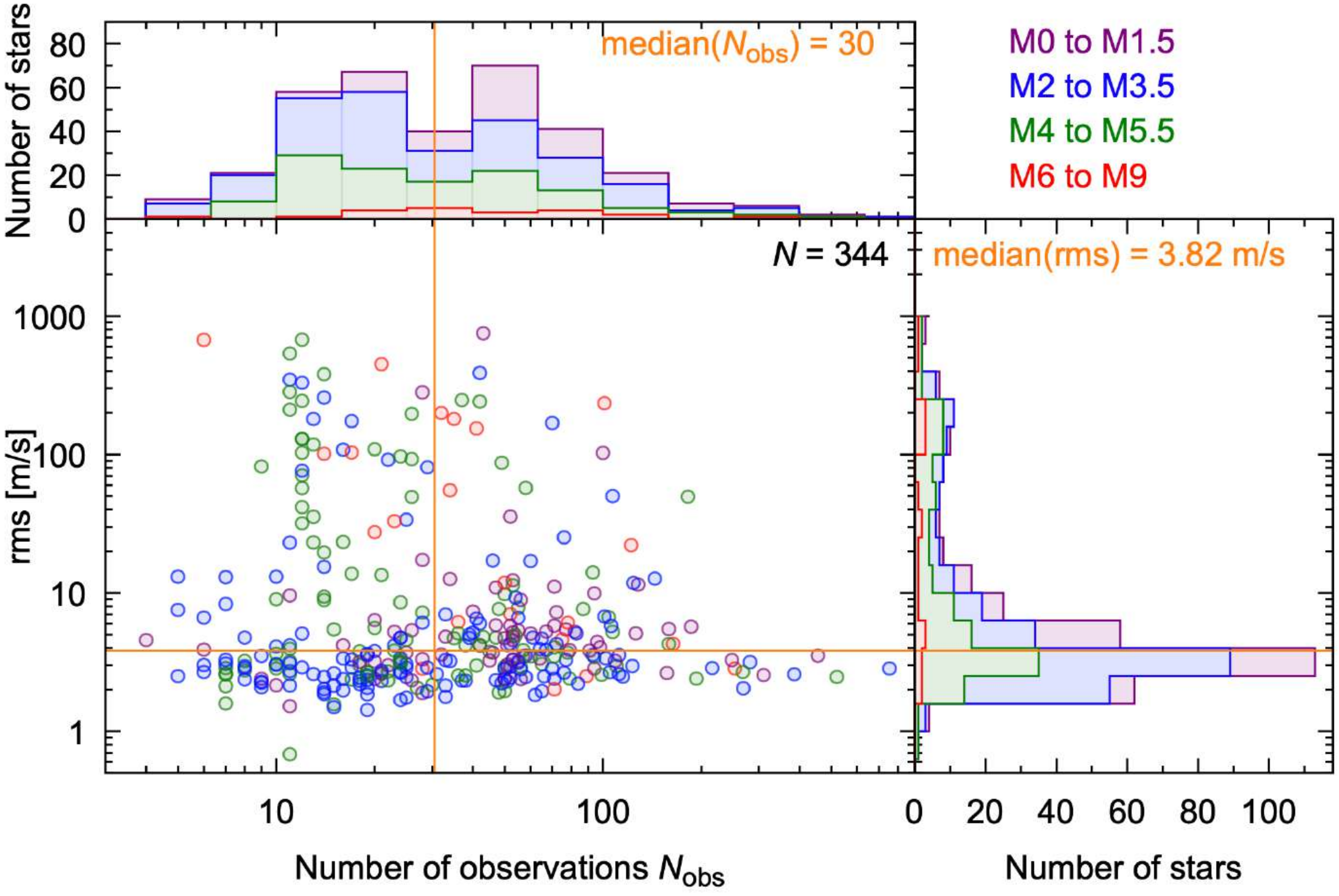
Typical target:
M3-M4 & J=7-9
(50% of all)

The CARMENES Data Release 1 (2016-2020)



- Ribas et al. (2023, A&A, 670, A139)
- 19623 GTO spectra – 19161 useful RVs
- 18893 spectra with full set of data products (SB2 & SB3 excluded)
- **VIS**: Raw data, calibrated spectra, and high-level data products (RVs and indicators)

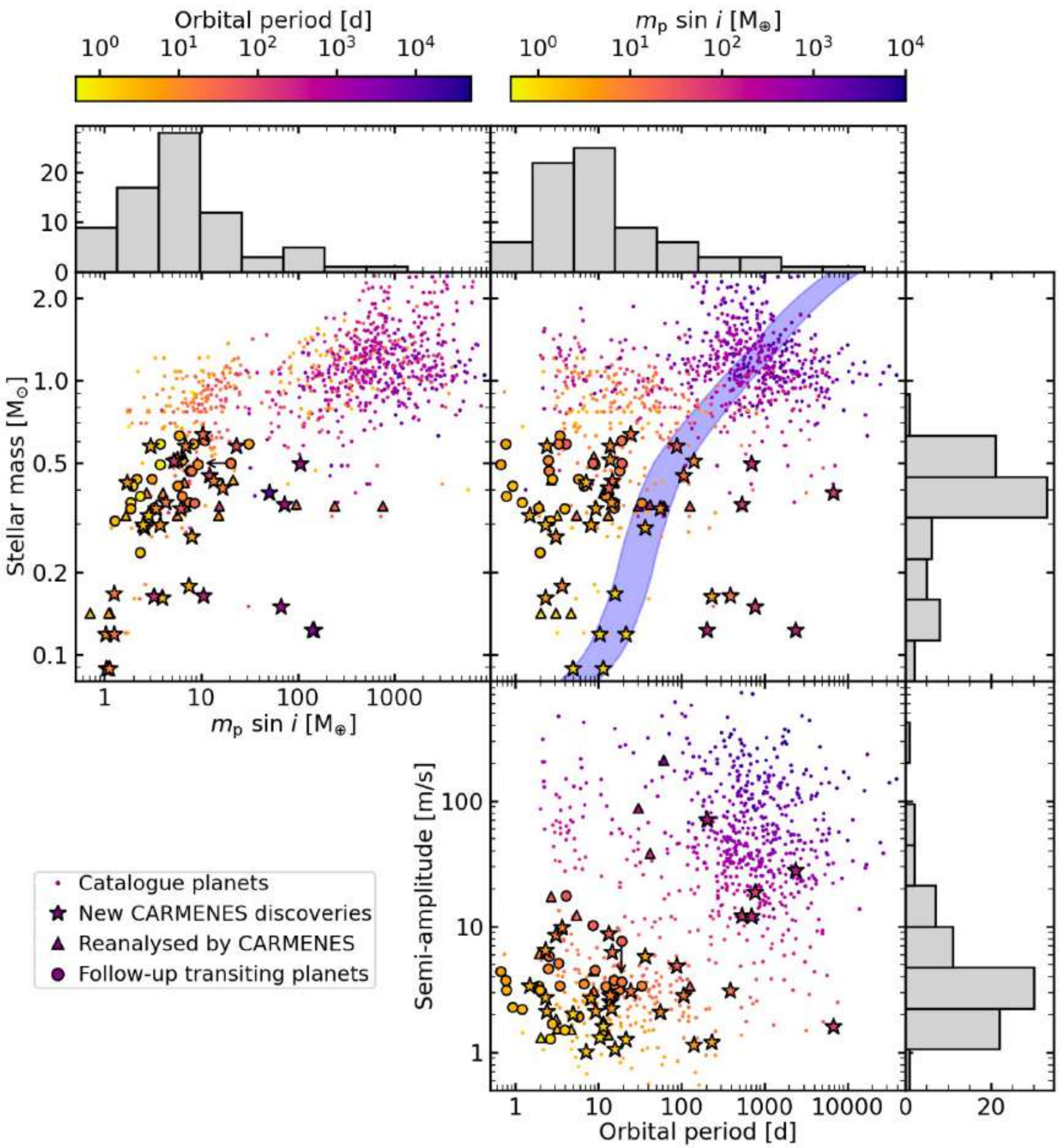
The CARMENES Data Release 1: External precision



vs. 1.27 m/s internal precision

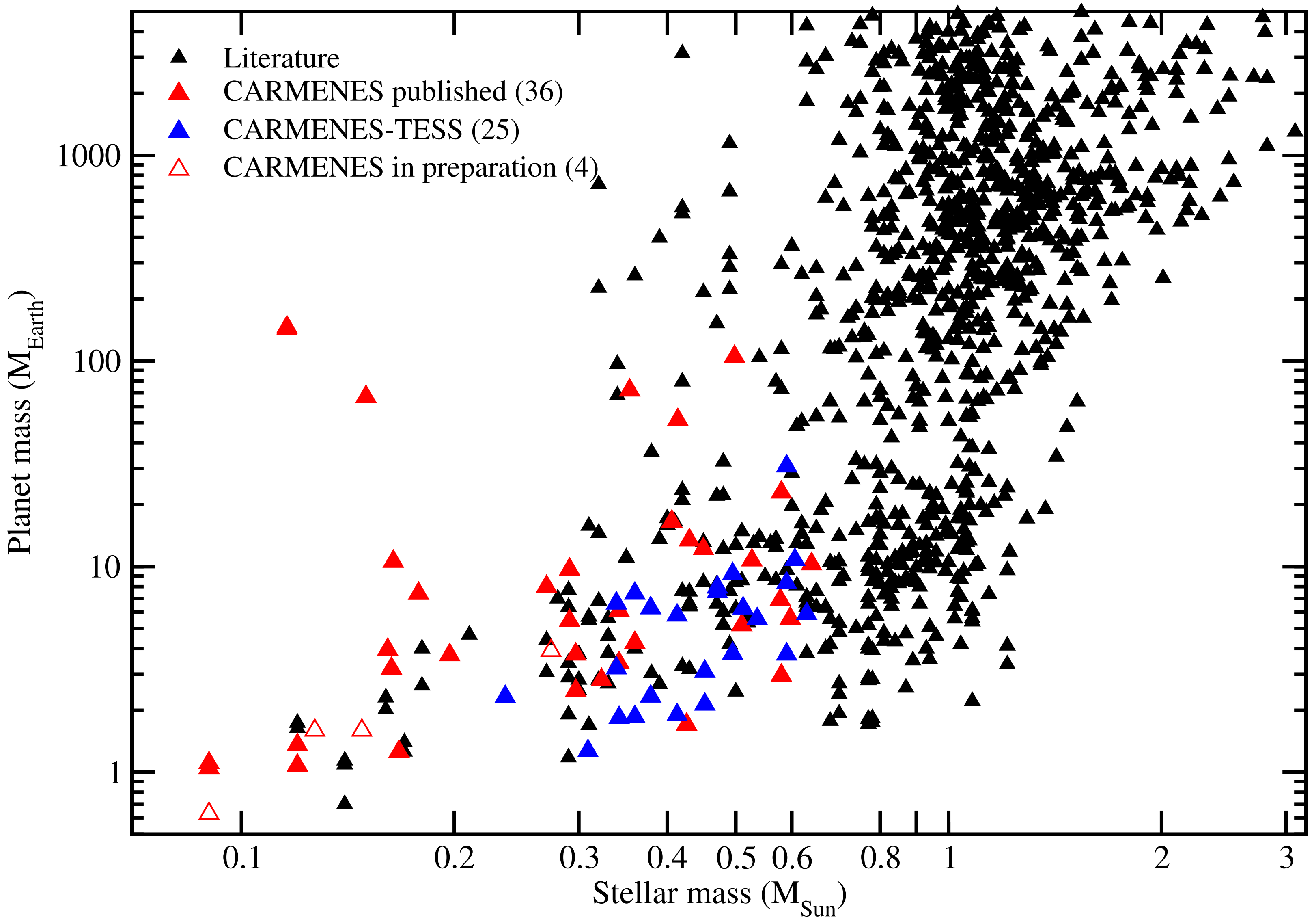
Stellar activity & planets!

The CARMENES Data Release 1: Planets



- 50% of all known RV planets with stellar hosts below 0.2 M$_\odot$ have been discovered by CARMENES
- Majority of CARMENES planets are super-Earth to Neptune-mass
- In spite of low occurrence rate, CARMENES has discovered 6 Saturn- and Jupiter-mass planets
- Most CARMENES planets have P from a few days to a few 10s of days
- 5 new CARMENES low-mass planets orbit within the liquid-water HZ
- Killed a few planets…

CARMENES GTO + Legacy-Plus planets

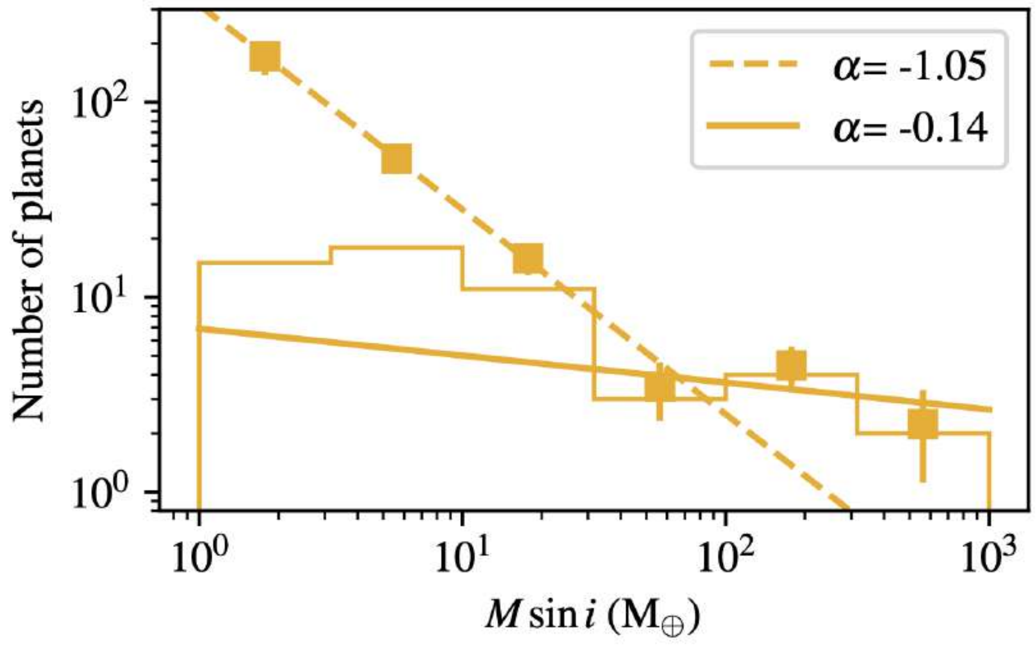


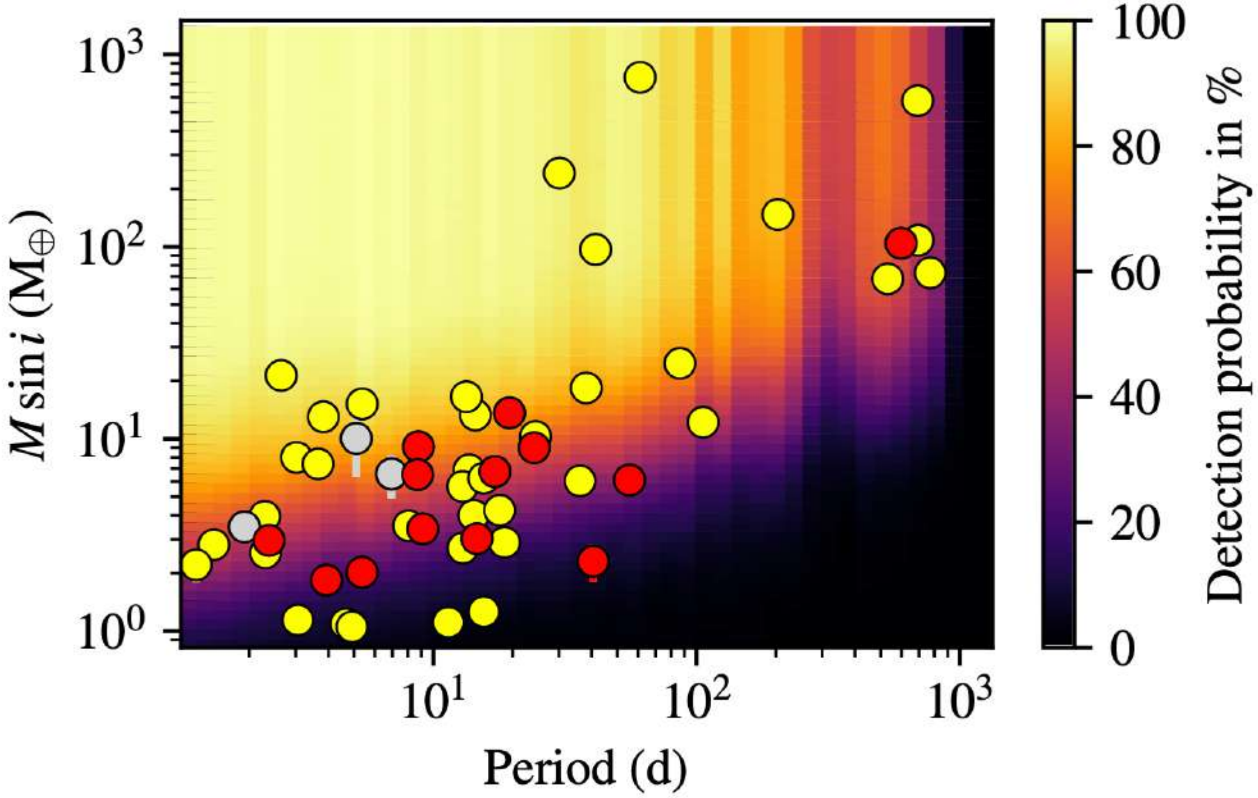
Planet zoo

- Neptunes in temperate orbits
- Close-in eccentric
- With active star hosts
- Nearby systems with transits
- …

The CARMENES Survey: Occurrence rates

- Update to Sabotta et al. (2021) – from 71 to 238 stars
- Signal retrieval and vetting to identify periodicities (P_{orb} < timespan/1.5)
- 53 planets in 43 systems
- Lower rates than Sabotta et al. (2021) ➜ human intervention bias





Ribas et al. (2023, A&A)

The CARMENES Survey: Occurrence rates

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	P (d)			
	1–10	10–100	100–1000	1–1000
(a) Planets with $100\,M_\oplus < M_{pl} \sin i < 1000\,M_\oplus$				
$N_{pl,det}$	0	2	4	6
$\bar{n}_{pl}$	<0.006	$0.010^{+0.010}_{-0.005}$	$0.03^{+0.01}_{-0.01}$	$0.03^{+0.02}_{-0.01}$
N_h	0	1	4	5
F_h	<0.006	$0.006^{+0.005}_{-0.005}$	$0.03^{+0.01}_{-0.01}$	$0.03^{+0.01}_{-0.01}$
(b) Planets with $10\,M_\oplus < M_{pl} \sin i < 100\,M_\oplus$				
$N_{pl,det}$	4	7	3	14
$\bar{n}_{pl}$	$0.02^{+0.02}_{-0.01}$	$0.04^{+0.02}_{-0.01}$	$0.04^{+0.02}_{-0.02}$	$0.09^{+0.03}_{-0.02}$
N_h	4	7	2	13
F_h	$0.02^{+0.02}_{-0.01}$	$0.04^{+0.02}_{-0.01}$	$0.03^{+0.02}_{-0.02}$	$0.09^{+0.02}_{-0.03}$
(c) Planets with $1\,M_\oplus < M_{pl} \sin i < 10\,M_\oplus$				
$N_{pl,det}$	18	15	0	33
$\bar{n}_{pl}$	$0.39^{+0.10}_{-0.07}$	$0.67^{+0.18}_{-0.15}$	< 0.40	$1.37^{+0.24}_{-0.24}$
N_h	15	10	0	25
F_h	$0.33^{+0.08}_{-0.07}$	$0.47^{+0.13}_{-0.13}$	< 0.40	$0.89^{+0.08}_{-0.11}$
(d) Planets with $1\,M_\oplus < M_{pl} \sin i < 1000\,M_\oplus$				
$N_{pl,det}$	22	24	7	53
$\bar{n}_{pl}$	$0.37^{+0.09}_{-0.07}$	$0.63^{+0.14}_{-0.12}$	$0.54^{+0.23}_{-0.17}$	$1.44^{+0.20}_{-0.20}$
N_h	19	18	6	43
F_h	$0.32^{+0.07}_{-0.07}$	$0.47^{+0.13}_{-0.09}$	$0.47^{+0.20}_{-0.16}$	$0.94^{+0.04}_{-0.09}$

- Planets of any mass (1-1000 $M_\oplus$) & period (1-1000 d) around M dwarfs:
  - 1.44 planets per star
  - 94% of stars have planets
- Results in good agreement with Bonfils et al. (2013), Pinamonti et al. (2022) but more precise (larger sample)
- Excess of giant planets compared with theoretical expectations

Ribas et al. (2023, A&A)

The CARMENES Survey: Occurrence rates

	P (d) 1–10	10–100	100–1000	1–1000
(a) Planets with 100 $M_\oplus \sin i < M_{\rm pl} < 1000\ M_\oplus$				
$N_{\rm pl,det}$	0	2	4	6
$\bar{n}_{\rm pl}$	<0.006	$0.010^{+0.010}_{-0.005}$	$0.03^{+0.01}_{-0.01}$	$0.03^{+0.02}_{-0.01}$
$N_{\rm h}$	0	1	4	5
$F_{\rm h}$	<0.006	$0.006^{+0.005}_{-0.005}$	$0.03^{+0.01}_{-0.01}$	$0.03^{+0.01}_{-0.01}$
(b) Planets with 10 $M_\oplus < M_{\rm pl} \sin i < 100\ M_\oplus$				
$N_{\rm pl,det}$	4	7	3	14
$\bar{n}_{\rm pl}$	$0.02^{+0.02}_{-0.01}$	$0.04^{+0.02}_{-0.01}$	$0.04^{+0.02}_{-0.02}$	$0.09^{+0.03}_{-0.02}$
$N_{\rm h}$	4	7	2	13
$F_{\rm h}$	$0.02^{+0.02}_{-0.01}$	$0.04^{+0.02}_{-0.01}$	$0.03^{+0.02}_{-0.02}$	$0.09^{+0.02}_{-0.03}$
(c) Planets with 1 $M_\oplus < M_{\rm pl} \sin i < 10\ M_\oplus$				
$N_{\rm pl,det}$	18	15	0	33
$\bar{n}_{\rm pl}$	$0.39^{+0.10}_{-0.07}$	$0.67^{+0.18}_{-0.15}$	< 0.40	$1.37^{+0.24}_{-0.24}$
$N_{\rm h}$	15	10	0	25
$F_{\rm h}$	$0.33^{+0.08}_{-0.07}$	$0.47^{+0.13}_{-0.13}$	< 0.40	$0.89^{+0.08}_{-0.11}$
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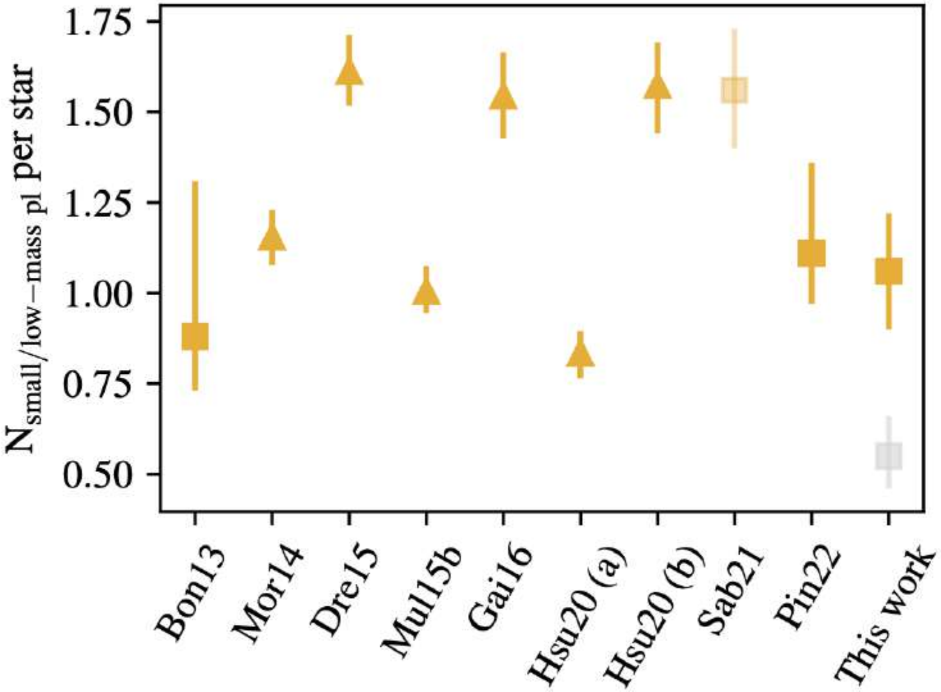
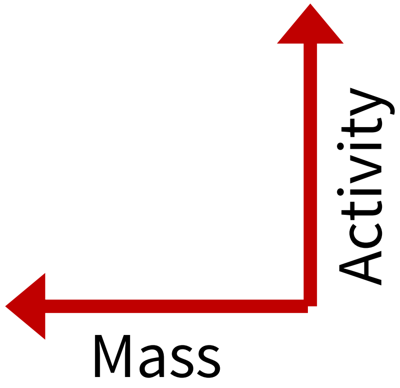
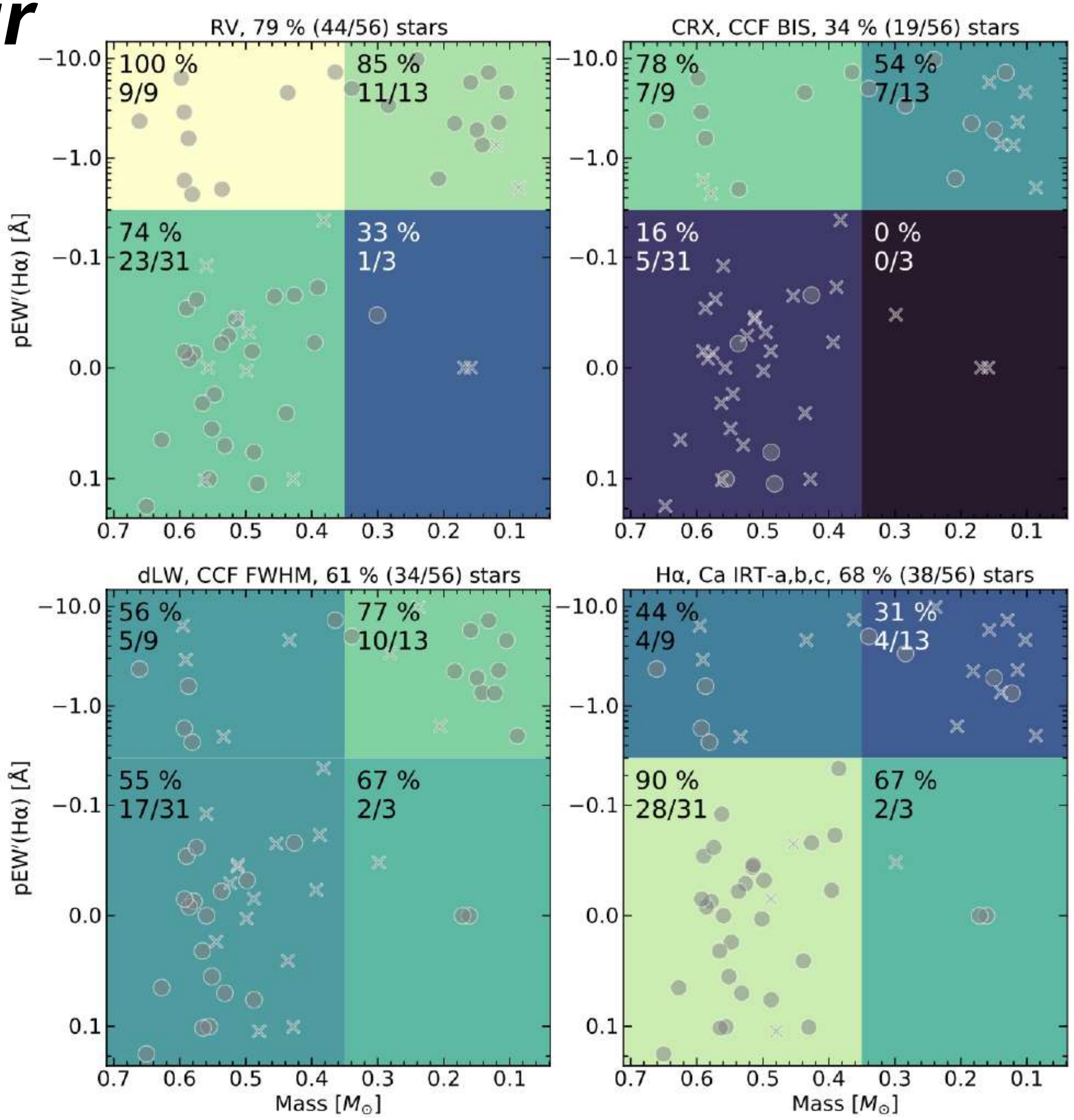
- Discrepancies in number of small/low-mass planets
- Criteria: 1 d < P_{orb} < 100 d, 1 $M_\oplus$ < M sin i < 10 $M_\oplus$ or 1.3 $R_\oplus$ < R < 3.7 $M_\oplus$
- Different assumptions on planet mass distribution: log-uniform vs. power law



Ribas et al. (2023, A&A)

Understanding stellar activity indicators

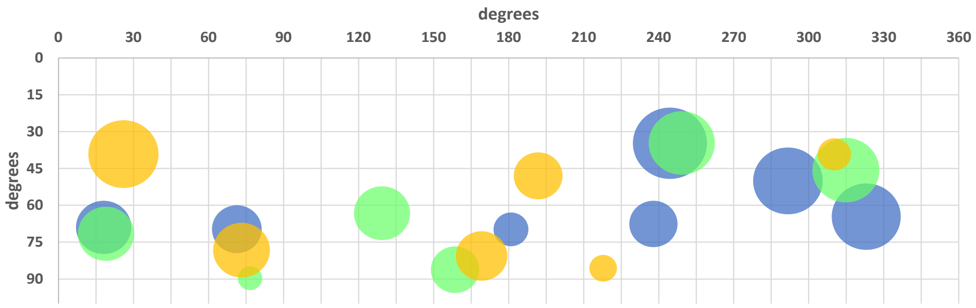




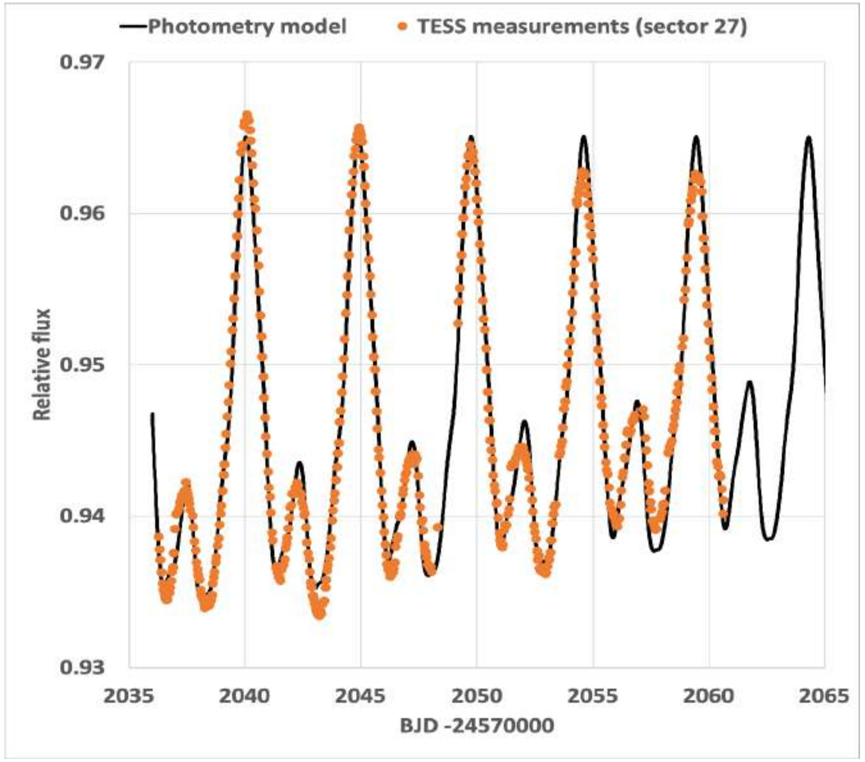
Lafarga et al. (2021, A&A)

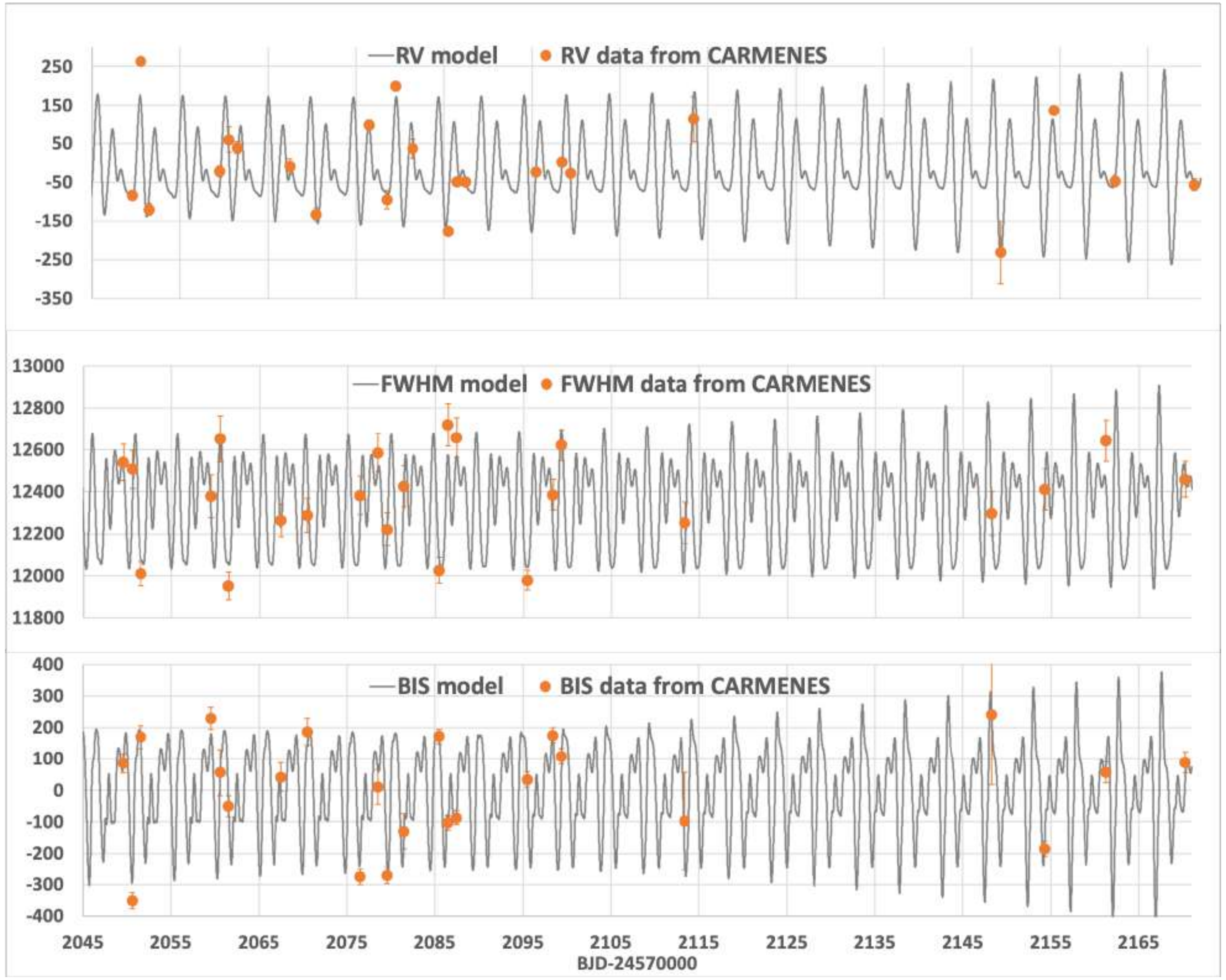
Also soon Kemmer et al. (A&A, subm.)

AU Mic: Simultaneous fit of photometry & spectroscopy

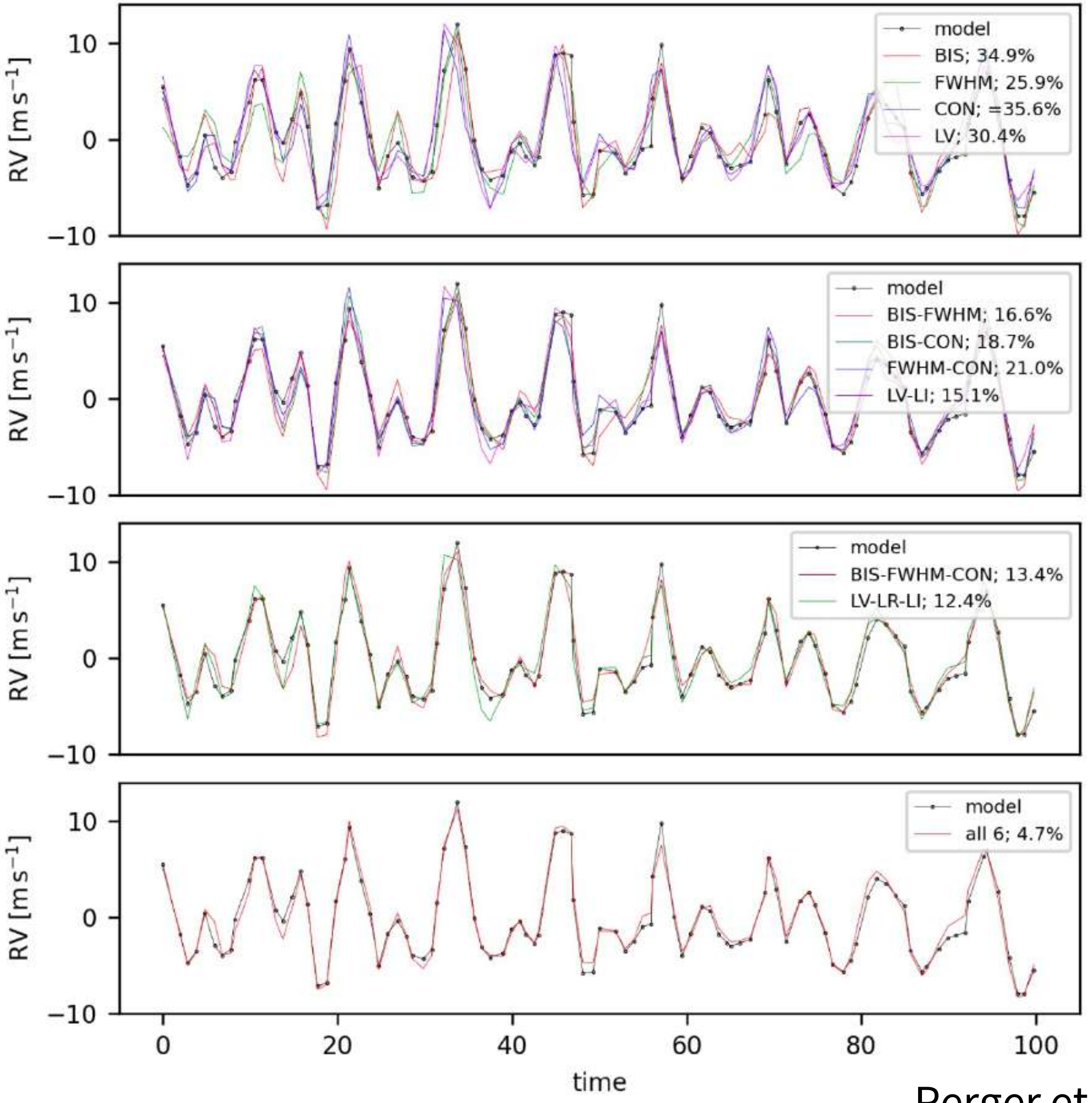


- Inversion of simple spot model with StarSim (Herrero et al. 2016; Rosich et al. 2020)
- PhD Thesis of Carles Blázquez



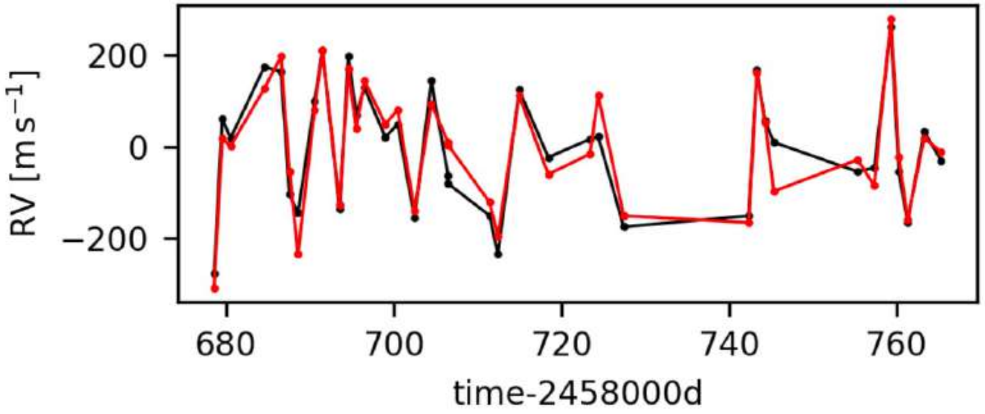


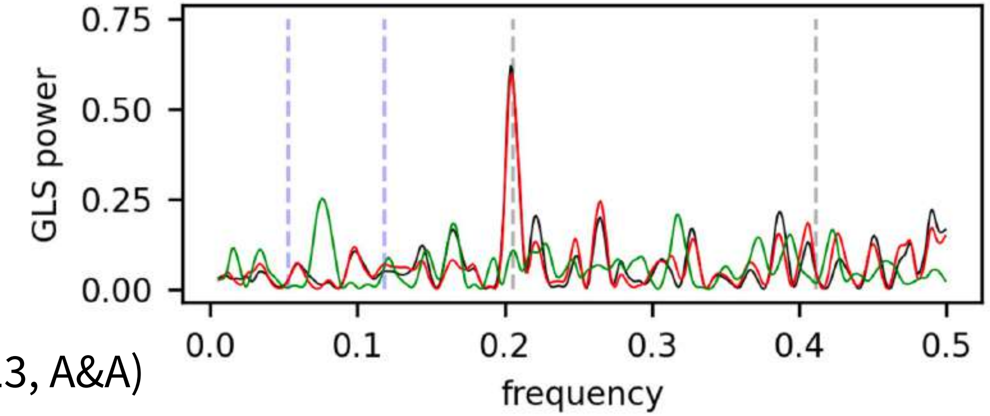
ML approach to RV activity correction



- Deep Neural Network trained with StarSim models (10^6) using different observables
- Fits to StarSim simulated data using a DNN (relative residual error in % ➜ 1/20 of original)

AU Mic – CARMENES data (black) & ML model (red)





Perger et al. (2023, A&A)

And many more science topics…

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- Planetary atmospheres
- Stellar atmospheric parameter determination
- Stellar activity (rotation, lines, magnetic fields)
- Planetary dynamics
- Transit detection follow-up (K2, TESS)
- Spectroscopic binaries
- Methodology (tellurics, cross-correlation, LBL)

Poster 21
M. Lafarga et al.

Poster 44
D. Montes et al.

Poster 43
C. Duque-Arribas et al.

Poster 29
P. Chaturvedi et al.

Take-home messages

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- The CARMENES DR1 is out (Ribas et al. 2023, A&A) and the survey continues until 50 measurements for all 345 targets are reached (2026)
- Not quite volume-limited but close (48% of all Ms within 10 pc)
- Updated planet occurrence rates (238 stars & 53 planets)
- Found one (or more!) new planet(s) around Teegarden's Star
- Lots of data available for many applications (19,000 measurements with up to 5 yr baseline; median n_{obs} = 30)
- More to come in a few years
- Enjoy!